Academic Report (2018–19)

Harish - Chandra Research Institute
Chhatnag Road, Jhunsi
Prayagraj (Allahabad), India
211019

Contents

About The Institute

History: The Harish-Chandra Research Institute is one of the premier research institutes in the country. It is an autonomous institution fully funded by the Department of Atomic Energy (DAE), Government of India. The Institute was founded as the Mehta Research Institute of Mathematics and Mathematical Physics (MRI). On 10th Oct 2000 the Institute was renamed as Harish-Chandra Research Institute (HRI) after the acclaimed mathematician, the late Prof Harish-Chandra.

MRI started with the efforts of Dr. B. N. Prasad, a mathematician at the University of Allahabad, with initial support from the B. S. Mehta Trust, Kolkata. Dr. Prasad was succeeded in January 1966 by Dr. S. R. Sinha, also of Allahabad University. He was followed by Prof. P. L. Bhatnagar as the first formal Director. After an interim period, in January 1983 Prof. S. S. Shrikhande joined as the next Director of the Institute. During his tenure the dialogue with the DAE entered into decisive stage and a review committee was constituted by the DAE to examine the Institute's future. In 1985 Shri N. D. Tiwari, the then Chief Minister of Uttar Pradesh, agreed to provide sufficient land for the Institute and the DAE promised financial support for meeting both the recurring and non-recurring expenditure. In January 1990, about 66 acres of land was acquired in Jhunsi, Allahabad, and the Institute came up at this site.

Prof. Shrikhande was followed by Prof. H. S. Mani who took over as the Director in January 1992. With his joining, and the shift to the new campus at Jhunsi in 1996, the Institute's activities picked up pace. After a distinguished tenure of about nine years Prof. Mani retired in August 2001 and the charge was taken over by Prof. R. S. Kulkarni. After Prof. Kulkarni's tenure, Prof. Amitava Raychaudhuri was the Director from July 19, 2005 to May 15, 2011. After him Prof. Sumathi Rao officiated as Acting Director till April 28, 2012. Prof. Jayanta Kumar Bhattacharjee was the next Director and continued till April 9, 2017. Prof. Pinaki Majumdar, the current Director, took over on April 10, 2017.

The Institute has a residential campus in Jhunsi, Allahabad, with a library, state of the art computational facility and fast internet link to the outside world. There is an active Ph.D program, an M.Sc program in Physics that started in 2017, and a large traffic of visiting scientists and students.

Research: The Institute continues to be devoted to fundamental research in diverse areas of mathematics and theoretical physics. Research is carried out by faculty members, visiting scientists, post-doctoral fellows and Ph.D. students.

The mathematics group at HRI carries out research in several areas. In algebra, work is done on algebraic groups and related structures, the theory of groups and group rings, representation theory, and infinite-dimensional Lie algebras. Work in analysis is in the field of harmonic analysis of Lie groups. Activity in geometry includes discontinuous groups and Riemann surfaces, algebraic topology, variational problems on manifolds, Chow groups of rational surfaces, and moduli of vector bundles. The number theory group works on algebraic, analytic and combinatorial number theory, automorphic forms and cryptography.

The areas of research in physics are astrophysics, condensed matter physics, quantum information and computing, high energy phenomenology and string theory. In

astrophysics, work is done on the cosmic microwave background, large scale structure formation, and galaxy evolution. Main areas of activity in condensed matter physics are strongly correlated systems, mesoscopic systems, and the study of clusters and nanomaterials. In string theory, perturbative and non-perturbative aspects of string theory and quantum field theory are being actively investigated. Research in neutrino physics, strong interactions, lattice gauge theory, supersymmetry and various aspects of physics beyond the standard model is done in high-energy phenomenology. The Institute is a member of the India-based Neutrino Observatory (INO) collaboration.

Recognition: Since 1992 the Institute has attracted worldwide attention, as is evident from the recognition received by many of its members. Several members of the Institute have been recognised for their scientific contribution. Prof. Ashoke Sen, Prof. B. Mukhopadhyaya, Prof. Pinaki Majumdar and Prof. Rajesh Gopakumar have been awarded the Shanti Swarup Bhatnagar prize and in 2018 Prof. Aditi Sen De became the first woman scientist in India to be awarded the Bhatnagar prize in Physical Sciences. The outstanding contribution of Prof. Ashoke Sen has been recognised by a Fellowship of the Royal Society, the award of Padmashri and Padmabhushan and the award of one of the first Fundamental Physics Prize (2012) from the Yuri Milner Foundation. He was the only recipient of the prize from all of Asia. In 2017 the Institute was recognised as being among the top 10 research centers in India by the Nature journal.

Director's Report

We start with a report on celebrations. Despite its small size HRI continues to maintain a leadership position in theoretical physics. This year a major honour went to the quantum information and computation (QIC) group at HRI. Dr. Aditi Sen De was awarded the S. S. Bhatnagar Award in Physical Sciences, the first ever physics Bhatnagar award to a woman scientist. Dr. Arun Pati, also of the QIC group, was awarded a J. C. Bose Fellowship.

The year had its share of scientific meetings and outreach activities. This included an international conference on "Class Groups of Number Fields" a School on "Group Cohomology", an Advanced Instructional School on Lie Algebras, and the outreach activity "Summer Programme in Mathematics". In physics we had a meeting on "Quantum Information Processing and Applications". We made extensive use of our Infosys grant to support the visits of distinguished physicists and mathematicians. These included Jean-Marc Deshouillers, Francois Hennecart, Yuval Gefen, David Logan, and Kaoru Hagiwara.

We have also progressed in our Masters teaching program. Our laboratory is fully functional, with a scanning tunneling microscope (STM) and a physical property measurement system (PPMS), equipments which are standard in research laboratories but a novelty in a theory institute. We plan to use these extensively as pedagogical tools.

As usual we held our annual Talent Search examination for school level children in Allahabad, and a week long Vaigyanik Karyashala in hindi to encourage dissemination of science in the vernacular. We continue to have a vibrant Visiting Students Program for undergraduate and Masters students.

Given our isolated location and the small academic community it was felt necessary to have regular HRI Colloquia which expose our students to a broad set of ideas not only in Science but also in the Humanities and Social Sciences. These included lectures on the history of science, environmental policy, and the evolution of Indian art.

Fourteen students submitted their thesis during the year. A large batch, of about twenty five students, joined the Ph.D program, while eight students joined the Physics Masters program. About 130 research papers were published during the year.

Various aspects of campus infrastructure have undergone improvement. We have completed work on our VRF-VRV central air conditioning system, replacing our twenty year old - and progressively inefficient - AC system. Parallely, our computing facility is now served by 'precison AC's' which provide more focused cooling. Both these systems are expected to reduce our electricity consumption. On the housing front we are still subject to a ban on new constructions, so to increase the on campus accommodation we have partitioned some of our D type apartments. These can be used for our regular students and also conference accommodation. Finally, the physics laboratory is a fully functional and self contained space.

Pinaki Majumdar

Director

List of Governing Council Members (2018 -19)

1 - Prof. M. S. Raghunathan (Chairman)
503, Atlantis Raheja Acropolis - 1
Deonar Pada Road, Deonar,
Mumbai - 400 088

2 - Prof. R. Balasubramanian
Institute of Mathematical Sciences
CIT Campus, Taramani,
Chennai - 600 113

3 - Joint Secretary (Finance) DAE
Govt. of India, Chhatrapati Shivaji
Maharaj Marg, Mumbai - 400 001

4 - Joint Secretary (R & D) DAE,
Govt. of India, Anushakti Bhavan,
Ch. Shivaji Maharaj Marg
Mumbai - 400 001

5 - Dr. J. N. De,
BH - 135, Sector - II
Salt Lake, Kolkata - 700 091

6 - Prof. S.M. Chitre
Chair, Academic Board
University of Mumbai
Department of Atomic Energy
Centre for Excellence in Basic
Sciences , (UM - DAE - CBS)
Health Centre Building
University of Mumbai
Kalina Campus,
Mumbai - 400 098

7 - Prof. H. S. Mani
2, Fourth Cross Street
Durga Colony, Sembakkam
Chennai - 600 073

8 - Director, (Ex - officio)
Higher Education Department,
U.P., Near G.P.O., Civil Lines,
Allahabad - 211 001

9 - Shri S. L. Mehta
4, Clive Row,
Kolkata - 700 001

10 - Shri Avnish Mehta
4, Penn Road,
Kolkata - 700 027

11 - Mr. Rajnish Mehta
4, Penn Road,
Kolkata - 700 027

12 - Prof. Pinaki Majumdar
(Ex - Officio)
Director,
Harish - Chandra Research
Institute (Ex - Officio)
Chhatnag Road, Jhunsi
Allahabad - 211 019

ACADEMIC STAFF

Faculty Members (Mathematics)

1. Batra, Punita
2. Chakraborty, Kalyan
3. Dalawat, Chandan Singh
4. Dubey, Umesh Kumar V.
5. Kumar, Manoj
6. Prakash, Gyan
7. Raghavendra, N.
8. Ramakrishnan, B.
9. Ramana, D. Surya
10. Ratnakumar, P.K.
11. Shah, Hemangi M.
12. Thangadurai. R.

Faculty Members (Physics)

1. Basu, Anirban
2. Choubey, Sandhya
3. Das, Tapas Kumar
4. Datta, AseshKrishna
5. Sen(De), Aditi
6. Gandhi, Raj
7. Jatkar, Dileep
8. Maharana, Anshuman
9. Majumdar, Pinaki
10. Mukhopadhyaya, B.
11. Naik, S.
12. Pareek, T. P.
13. Pati, Arun Kumar

14. Rai, Santosh Kumar
15. Rao, Sumathi
16. Sen, Ashoke
17. Sen, Prasenjit
18. Sen, Ujjwal

Administrative Staff

1. Shri Ravindra Singh [Registrar]
2. Shri Rajkumar Gulati [Accounts Officer]
3. Shri Manish Sharma [Scientific Officer 'E']
4. Shri K.K. Suresh Kumar [Librarian]
5. Shri Amit Roy [Internal-Audit-cum Administrative officer]
6. Shri Sanjai Verma [Systems Manager]
7. Shri A.K. Srivastava [SO(C)]
8. Shri V.K. Srivastava [SO(C)]
9. Shri R.P. Sharma [Manager Guest House]
10. Ms. Anju Verma [Scientific Assistant]
11. Shri U.K. Dwivedi [Cashier]
12. Shri D. Malhotra [Upper Division Clerk]
13. Shri K.K. Srivastava [Upper Division Clerk]
14. Shri Yashpal Singh Sr. [Stenographer]
15. Ms. Sumitra [Upper Division Clerk]
16. Ms. Seema Agarwal [Receptionist]
17. Shri Sudheer Kumar Singh [Accountant]
18. Shri Sanjeev Nagar [Hindi Typist]
19. Shri Vivek Kumar [Junior Library Assistant]
20. Shri Kamlesh Thakur [Bearer (Canteen Cadre)]
21. Shri Kamta Prasad [Peon/Watchman]
22. Shri Rajesh Kumar [Sweeper]
23. Shri Munna Lal [Gardener]

Visiting Fellow

Mathematics

1. Arunachalam, Umamaheswaran
2. Banerjee, Kalyan
3. Choudhury, Snigdha Bharati
4. Hoque, Azizul
5. Juyal, Abhishek
6. C. P. Anil
7. Kumari, Rani
8. Laxmi, Jai
9. Taha, Ebtsam Hassan
10. Podder, Shubhankar
11. Pradhan, Soham S.
12. Raundal, Hitesh Ramesh
13. Singh, Rajesh Kumar
14. Subramani, M

Physics

1. Abdallah, Waleed Mohammed
2. Chatterjee, Atreya
3. Chouhan, Rajiv Kumar
4. Das, Debmalya
5. Dhargyal
6. Fernandes, Karan
7. Gupta, Manish Kumar
8. Gupta, Manjari
9. Lahiri, Jayita
10. Mal, Shiladitya
11. Pramanick, Soumita

12. Saha, Arnab Priya
13. Samui, Tousik
14. Prasad, Yogeshwar
15. Sazim, S.K.
16. Sehrawat, Arun
17. Singh, S. Nilakash

Visiting Scientist

1. Deo, Satya (Maths)
2. Saha, Pratishruti (INSPIRE Faculty)
3. Banerjee, Rudra

Research Scholar

Mathematics

1. Agnihotri, Rishabh
2. Bhowmick, Kushal
3. Chakraborty, Priyanshu
4. Chattopadhyay, Jaitra
5. Choudhury, Srijonee Shabnam
6. Das, Mithun Kumar
7. Das, Pradeep
8. Gupta, Shubham
9. Karmakar, Debasish
10. K, Krishnarjun
11. Kaushik, Rahul
12. Keshari, Parul
13. Kumar, Veekesh
14. Maity, Arup Kumar
15. Manikandan, S.
16. Mishra, Mohit
17. Nishant
18. Pal, Souvik
19. Pandey, Manish Kumar
20. Patil, Bhuwanesh Rao
21. Pramod, E.
22. Roy, Bidisha
23. Sahoo, Gopinath
24. Sarkar, Subha
25. Singh, Anup Kumar
26. Singh, Anoop
27. Tantubay, Shantanu
28. Vaishya, Lalit

Physics

1. Abdulla, Faruk
2. Alam, Khorsed
3. Bakshi, Sankha Subhra
4. Bandyopadhyay, Subhodip
5. Banerjee, Ratul
6. Barik, Anjan Kumar
7. Basak, Nirnoy
8. Bhattacharya, Ritabrata
9. Bhattacharya, Sauri
10. Bhowmik, Swapnil
11. Bose, Debraj
12. Das, Sreetama
13. Datta, Satadal
14. De, Suman Jyoti
15. Dey, Atri
16. Dey, Shyamashish
17. Dutta, Arijit
18. Dutta, Juhi
19. Garg, Parveen
20. Ghosh, Avirup
21. Ghosh, Srijon
22. Ghoshal, Ahana
23. Grover, Sachin
24. Haldar, Stav
25. Joshi, Abhishek
26. Kadge, Samrat Suresh
27. Kar, Arpan
28. Khan, Sarif

29. Kumar, Abhass
30. Mahanta, Ratul
31. Maity , Susovan
32. Mohan, Brij
33. Md., Abhishek
34. Mondal, Tanmoy
35. Mukhopadhyay, Chiranjib
36. Pal, Kalyanbrata
37. Pandey, Vivek
38. Pramanik, Dipyaman
39. Roy, Samiran
40. Roy, Saptarshi
41. Roy, Shubhojit
42. Roy, Tanaya
43. Roychoudhury, Shouvik
44. Sahoo, Biswajit
45. Sanyal, Sanjeev
46. Sen, Arpita
47. Sen, Kornikar
48. Md. Shaikh, Arif
49. Sharma, Gautam
50. Shrimali, Divyansh
51. Singh, Kajal
52. Sohail
53. Srivastav, Abhay
54. Srivastava, Chirag
55. Tripathi, Krashna Mohan

M.Sc. Students

Physics

1. Boxi, Sovan
2. Chauhan, Ankur
3. Choudhary, Swati
4. Das, Manojit
5. Dipanshu
6. Ghorui, Arnab
7. Mal, Sourav
8. Nanda, Ayan
9. Pal, Amartya
10. Paul, Aritra
11. Reddy, Vemula Suneel Chandra
12. Sisodiya, Durgesh Singh

Academic Report - Mathematics

Punita Batra

Research Summary:

In a joint work with H. Yamane, we gave elements in the center of the generalized quantum group corresponding to its irreducible finite dimensional modules and gave a conjecture that these elements must form a basis of the center. With Rao and Sharma, we modified the results on the paper twisted toroidal extended affine Lie algebras.

Publications:

1. Punita Batra and S. Eswara Rao, *On integrable modules for the twisted full toroidal Lie algebra,* Journal of Lie Theory **Vol.28**, No.1, 79-105 (2018)

2. Punita Batra, Hiroyuki Yamane, *Natural elements of center of generalized quantum groups,* Accepted to appear in Contemporary Mathematics

Preprints:

1. (With S. Eswara Rao and Sachin S. Sharma) Integrable modules for twisted toroidal extended affine Lie algebras, arXiv:1802.09823v1 Feb 2018, Submitted.

Conference/Workshops Attended:

1. *"Interactions of quantum affine algebras with cluster algebras, current algebras and categorification, A conference celebrating the 60th birthday of Vyjayanthi Chari"* at The Catholic University of America, Washington D.C., USA, June 2-8, 2018.

Visits to other Institutes:

1. Department of Mathematics, The Catholic University of America, Washington D.C. USA during June 2-8, 2018.

2. Department of Mathematics, University of Lucknow on January 8, 2019.

Invited Lectures/Seminars:

1. *Classification of Integrable modules of twisted full toroidal Lie algebras* , **Invited short talk,** The Catholic University of America, Washington D. C. USA, June 5, 2018.

Other Activities:

1. Coordinator for SPIM(Summer Programme in Mathematics) at HRI in June 2018.

2. Gave six lectures on " Galois Theory" in Summer Programme in Mathematics(SPIM) at HRI in June, 2018.

3. Coordinator - HRI's Science Talent Search exam 2018(Mathematics part).

4. Organised AIS(Advanced Instructional School) on "Lie Algebras" at HRI during December 10-29, 2018 and also gave 6 lectures in this school on semisimple Lie algebras.

5. Convener of the Outreach Programme(Mathematics). Also serving as a member in the Sports and Entertainment Committee and the Rajbhasha Committee.

Kalyan Chakraborty

Research Summary:

Class number and related topics: Exploiting the close relationship between class number of number fields with the values of Dedekind zeta functions of the number field in question, we have recently characterised class groups of order $2, 3$ and 4 of certain family of real quadratic fields in terms these zeta values. We intend to explore these relationship into more depth and expand our research into higher degree number fields and also to other families of real quadratic fields.

Solutions of certain Diophantine equations: Studied solutions certain Lebesgue-Ramanujan-Nagell type of equations and using class number of quadratic fields, arithmetic of elliptic curves and that of Pell type equations, we could find complete solutions of these equations when the related class number is 1. We also studied certain Mordell - type equations by using basic arithmetic of elliptic curves and found its rational solutions. Work is on to study these equations in the ring of integers of imaginary quadratic fields.

Chow groups and class groups; Tate-Shafarevich groups and Selmer groups: Recently Kalyan Banerjee and Azizul Hoque completed a project relating Picard group of algebraic curves or surfaces to the class groups of number fields and they used this connection to study some arithmetic of these two groups. Continuing on similar lines we are involved in a project to prove the weak Mordell-Weil type theorem for Chow groups of abelian varities defined over number fields and its consequences. The basic tool is to study the analogously defined 'Selmer and 'Tate-Shafarevich groups' associated with the Chow group of an abelian variety.

Post Quantum ECC (Isogeny - based crypto): Quantum computers are no more a far fetched reality as IBM has been able to produce small - scale quantum computing models. In the advent of quantum computers the EC-DLP and RSA would be rendered unsafe owing to Shor's Algorithm. We intend to study the rational homomorphisms along with the mathematical structure of elliptic curves. The under lying hard problem for isogeny- based cryptography is -"Given two isogenous super singular elliptic curves, Find an isogeny between them". This problem seems to be intractable for quantum computers. The objective is to study in depth this intractability as well as various other parameters involved in developing such crypto systems. This would need plenty of questions to be answered both from the theoretical as well as from the computing point of view.

Publications:

1. K. Chakraborty, A. Hoque, Y. Kishi and P.P. Pandey, *Divisibility of class numbers of imaginary quadratic fields,* J. Number Theory **185**, 339–348, (2018)

2. K. Chakraborty and A. Hoque, *Pell-type equations and class number of the maximal real subfield of a cyclotomic field,* Ramanujan J **46**, 727–742, (2018)

3. K. Chakraborty and A. Hoque, *Divisibility of class number of certain families of quadratic fields,* J. Ramanujan Math. Soc. (To appear)

4. K. Chakraborty and A. Hoque, *Class groups of imaginary quadratic fields of 3 - rank at least 2,* Annales UMCS Mathematica **47** 179–183, (2018)

5. K. Chakraborty, S. Kanemitsu and T. Kuzumaki, *Seeing the invisible : Kubert identities,* Annales UMCS Mathematica **47** 185–195, (2018)

6. Sarthak Gupta and Kalyan Chakraborty, *A problem related to prime numbers,* The Mathematics Student **87** (2018)

7. S. Banerjee and K. Chakraborty, *Asymptotic behaviour of a Lambert series a La Zagier: Maass case,* Ramanujan J., **48** 567–575 (2019)

8. K. Chakraborty, A. Hoque and M. Mishra, *A note on certain real quadratic fields with class number upto three,* Kyushu J. Math. (To appear)

9. K. Chakraborty, A. Hoque and R. Sharma, *Divisibility of class numbers of quadratic fields: Qualitative approach,*Advances in Mathematical inequalities and Application. Trends in Mathematics. Birkhauser,/Springer, Singapore, 247–264 (2018)

10. K. Chakraborty, A. Hoque and P.P. Pandey, *Class groups of number fields and related topics,*Springer, **Conference Proceedings, Edited** (2019)

Preprints:

1. K. Chakraborty, A. Hoque, S. Kanemitsu and A. Laurincikas, *Complex powers of L-functions and integers without large prime factors* Pre-print

2. S. Banerjee, K. Chakraborty and A. Hoque, *An analogue of Wilton's formula and values of Dedekind zeta functions,* arXiv:1611.08693

3. K. Chakraborty and A. Hoque, *On the plus part of the class numbers of cyclotomic fields,* Pre-print

4. K. Chakraborty and A. Hoque, *Exponents of class groups of certain imaginary quadratic fields,* arXiv:1801.00392

5. K. Chakraborty, A. Hoque and R. Sharma, *Complete solutions of certain Lebesgue-Ramanujan-Nagell type of equations,* arxiv:1812.11874

6. K. Chakraborty, A. Hoque and M. Mishra, *A classification of order 4 class groups of* $\mathbb{Q}\sqrt{n^2+1}$, arxiv:1902.05250

7. K. Chakraborty and R. Sharma, *On the rational solutions of* $y^2 = x^3 + k^n$, Pre-print

8. K. Chakraborty, A. Hoque, H.K. Saikia and Y. Kishi, *Divisibility of class numbers of quadratic fields whose discriminant has exactly* n*- distinct prime factors,* in preparation

Conference/Workshops Attended:

1. *International conference in number theory*, China, May 2018.
2. *International meet on random matrix theory, its application in number theory and extreme values*, Hong Kong, May 2018.
3. *Canadian number theory meet*, Canada, July, 2018.
4. *International conference in mathematics and mathematics education for developing nations*, Laos, November 2018.
5. *International conference on special functions and applications*, India, November 2018.
6. *International conference on areas influenced by S. Ramanujan*, India, December 2018.
7. *International conference on number theory*, India, February 2019.

Visits to other Institutes:

1. Yangling University, Yangling, China, May 2018.
2. North West University, Xian, China, May 2018.
3. Hong Kong University, Hong Kong, May 2018.
4. University of Calgary, Calgary, Canada, July 2018.
5. Laval University, Quebec, Canada, July 2018.
6. Queen's University, Kingston, Canada, July 2018.
7. National University of Laos, Laos, November 2018.
8. Mahodol University, Bangkok, Thailand, November 2018.
9. SASTRA University, Kumbhakonam, India, December 2018.
10. KSOM, Kochi, India, February 2019.
11. IIT BHU, Varanasi, India, March 2019.

Invited Lectures/Seminars:

1. *Asymptotic behaviour of a Lambert series {'a la Zagier: Maass case*, 14-th International Conference on Number Theory, Northwest University, Yangling, April 2018.
2. *Class numbers of Quadratic fields*, Northwest University Number Theory, Northwest university, Xian, April 2018.
3. *Class numbers quadratic fields*, Shaanxi Normal university, Xian, April 2018.
4. *Pell-type equations and class numbers of cyclotomic fields*, CNTA-2018, Laval university, July 2018.

5. *An analogue of Wilton's formula and values of Dedekind zeta functions*, 11-th international Conference on Mathematics and Mathematics education for Developing Countries, The National university of Laos, November 2018.

6. *On the Barnes multiple zeta- and gamma function*, Mahidol University Number Theory Seminar, Mahidol University, Bangkok, November 2018.

7. *Seeing the invincible: Around generalised Kubert functions*, International Conference on Special Functions and Applications, Amal Jyothi College of Engineering, October 2018.

8. *Dedekind zeta values*, 16-th Annual international conference on the mathematics influenced by Ramanujan, SASTRA University, December 2018.

9. *Certain real quadratic fields with class numbers upto three*, International conference on number theory, KSOM, February 2019.

Other Activities:

1. Organised ICCGNFRE-2018, October, 2018.

2. Coordinator (Zone 2): Written and interviews for NBHM fellowships, 2018-19.

3. Mentor: INSPIRE Camp at Burdwan and Raipur, 2018-19.

4. Vice President: SSFA (Society for special functions and applications).

5. 4 Undergraduate students visited and did month long projects.

Chandan Singh Dalawat

Research Summary:

An effort was made to give a coherent exposition of our parametrisation of primitive solvable extensions of an arbitrary field F and the primitive p-extensions (where p is a prime) of a p-field K. The latter involves a parametrisation of the irreducible $\mathbf{F}_p$-representations of the absolute Galois group of K and the determination of the Galois module structure of $L^\times/L^{\times p}$ in characteristic 0 and $L^+/\wp(L^+)$ in characteristic p, for suitable extensions L of K.

Notes on the beginning of group cohomology were written and distributed to the students of a minicourse. Starting from the definitions, they give a complete proof that every extension of a finite group by a finite commutative group of relatively prime order splits, and any two splittings are conjugate.

Publications:

1. *The ramification filtration in certain p-extensions*, Rocky Mountain Journal of Mathematics **49** (2), 487–492. `arXiv:1508.02228`.

Conference/Workshops Attended:

1. *Gauge Theory Ideas for Number Theory*, International Centre for Theoretical Sciences, 17–21 December, 2018.

Visits to other Institutes:

1. International Centre for Theoretical Sciences, Bangalore, 26 November–8 December 2018.
2. Tata Institute of Fundamental Research, Bombay, 17–25 February 2019.

Invited Lectures/Seminars:

1. *Some footnotes to Galois's memoirs on solving equations by radicals*, Colloquium, International Centre for Theoretical Sciences, Bangalore, 28 November 2018. `https://youtu.be/_2YBsJsgVHA`
2. *Wildly primitive extensions of p-adic fields*, Seminar, International Centre for Theoretical Sciences, Bangalore, 5 December 2018. `https://youtu.be/Cm0I_mByfvQ`

Other Activities:

Gave a set of two lectures in Hindi in the outreach programme. Refereed papers for international journals. Taught the graduate course Topology I. Gave a set of four lectures in the Annual Foundation School at Kishangarh. Gave a set of four lectures in a school on group cohomology at HRI. Mentored a student from NISER Bhuvaneshwar and a student from IISER Poona. Acted as a reviewer in some promotion cases.

Umesh Kumar Vanktesh Dubey

Research Summary:

The Chow group of scheme is widely studied geometric invariant in Algebraic Geometry. P. Balmer introduced the notion of tensor triangular (tt-) Chow group and S. Klein computed it for some class of tt-categories. In joint work with Vivek M. Mallick, we described the tt-chow group of another class of tt-categories with an action of a finite group G. Along the way, we also improved our earlier results on the computation of the Balmer spectrum for such a class of tt-categories. More precisely, we prove that the rational tt-chow group (for some class of equivariant tt-categories) is the G-invariant part of the rational tt-chow group of original tt-category. As an application, we also studied some examples coming from Algebraic Geometry and Modular Representation Theory. We also generalised some results of A. Vistoli related to equivariant Chow group of schemes.

We extended, in joint work with Sanjay Amrutiya, the moduli construction of A. King from representations to filtered representations of the quiver. Since the category of filtered representations is rarely an abelian category, we used results of Y. André to extend the moduli construction to the quasi-abelian category of filtered representations. We also gave the construction of determinant theta functions on such moduli spaces using the results of H. Derksen and J. Weyman. In the second joint work with Sanjay Amrutiya, we used the moduli of filtered representations to answer the question of V. Balaji and C. S. Seshadri related to the functorial construction of moduli of parabolic sheaves without using the Biswas-Seshadri correspondence.

We developed, in joint work with Sarang Sane, necessary tools for classification of thick sub-categories of graded singularity category for some class of graded algebras which are a locally complete intersection. This classification is also required to understand the structure of subcategories of the bounded derived category of graded modules.

Preprints:

1. Umesh V. Dubey and Vivek M. Mallick, *On differential graded Eilenberg - Moore construction,* arXiv:1510.07453v2 [math.AG] (under review).

2. Umesh V. Dubey and Sanjay Amrutiya, *Moduli of filtered quiver representations,* arXiv:1808.02003 [math.AG] (under review).

3. Umesh V. Dubey and Vivek M. Mallick, *Tensor triangular Chow group of tt-equivariant categories,* (in preparation).

4. Umesh V. Dubey and Sanjay Amrutiya, *On functorial construction of moduli space of parabolic sheaves and filtered-Kronecker modules,* (in preparation).

5. Umesh V. Dubey and Sarang Sane, *Classification of thick subcategories of some graded singularity categories,*(in preparation).

Conference/Workshops Attended:

1. *Conference on Geometry: Local and Global*, Tifr, Mumbai, INDIA, October, 2018.
2. *Conference on Algebraic Geometry and related areas*, IMSc, Chennai, INDIA, July, 2018.

Visits to other Institutes:

1. Indian Institute of Science Education and Research, Pune, INDIA, January, 2019 and May, 2018.
2. Central University of Rajasthan, Ajmer, INDIA, December , 2018.
3. Tata Institute of Fundamental Research, Mumbai, INDIA, October, 2018.
4. Institute of Mathematical Sciences, Chennai, INDIA, July, 2018.
5. Indian Institute of Science Education and Research, Mohali, INDIA, June, 2018.

Invited Lectures/Seminars:

1. *Stability of representations and semi-invariants*, Maths seminar, Indian Institute of Science Education and Research, Mohali, June, 2018.

Other Activities:

1. Graduate Course on *Topology - II*, Harish-Chandra Research Institute, January - May, 2019.
2. Seminar series on *Topics in Homological Algebra*, Harish-Chandra Research Institute, August - December, 2018.
3. Academic co-organiser and speaker in AFS-II, Central University of Rajasthan, Ajmer, December, 2018.
4. 6 hrs lectures and 4 hrs tutorials on Algebra, AFS-I, IISER Pune, May, 2018.
5. Supervising two research scholars, mentoring one NPDF, refereed few manuscripts for Mathematics Journal.
6. Member of Mathematics Graduate Programme Committee, Transport, Admission and Outreach Committee. Helped in SPIM and Talent search Exam.

Manoj Kumar

Research Summary:

Let G be a finite group and w be a word. The word w defines a map into G, called a word map. We investigated power maps, that is, maps corresponding to the word $w = X^p$, for the lower-triangular matrix group $T(n,q)$ and lower unitriangular matrix group $U(n,q)$ over a finite field of q elements, where q is a p-power for a fixed prime p. It is known that $T(n,q)$ is a Borel subgroup of $GL(n,q)$ and $U(n,q)$ is a Sylow p-subgroup of $GL(n,q)$. In the finite groups of Lie type, the regular semisimple elements play an important role as they constitute a dense subset. Considering the image of a word map on maximal tori has turned out to be useful in getting asymptotic results. Thus, we aim at considering the large size conjugacy classes in $U(n,q)$, and try to understand if they are in the image under the power map $w = X^p$.

Let G^p denote the image $w(G)$ of a group G under the word map given by $w = X^p$. So, $G^p = \{g^p \mid g \in G\}$ is the *set* consisting of the p-powers of the elements of G. It is known that $U(n,q)^p$ is contained in the subgroup

$$U_{p-1}(n,q) = \{(a_{ij}) \in U(n,q) \mid a_{ij} = 0, \text{ for all } i-j \leq p-1\}$$

consisting of the lower triangular matrices with the first $p-1$ sub-diagonals having zero entries. Moreover, $U(n,q)^p = 1$ if and only if $n \leq p$, and $U(n,q)^p = U_{p-1}(n,q)$ if and only if $n = p+1$ and $p+2$. We prove the following: Let q be a power for a prime p and n an integer such that $n \geq p+3$. Then, the set $U(n,q)^p$ is a proper generating subset of $U_{p-1}(n,q)$ and $|U(n,q)^p| > \frac{1}{3}|U_{p-1}(n,q)|$ when $q \geq n-p-1$. For for $T(n,q)$ we prove: Let q be a p-power and suppose $q > 2$. Then for the group $T = T(n,q)$ we have,

$$|T^p| = \sum_{(a_1,\ldots,a_k)\vdash n, k<q} \left(\frac{(q-1)\cdots(q-k)n!}{\prod_{b=1}^{n} m_b!(b!)^{m_b}}\right)\left(\prod_{i=1}^{k}|U(a_i,q)^p|\right) q^{\binom{n}{2}-\sum_{i=1}^{k}\binom{a_i}{2}}$$

where the m_b's are obtained by writing the partition $(a_1,\ldots,a_k)$ in power notation as $1^{m_1}\ldots n^{m_n}$.

In a different work, we have started working on a new topic, called *skew left braces*. This has direct connection with set theoretic solutions of the quantum Yang-Baxter equation. A multiplicatively written group G, with multiplicative structure on G given by $(g_1,g_2) \mapsto g_1g_2$, is said to be a *skew left brace* if it admits an additional group structure given by $(g_1,g_2) \mapsto g_1 \circ g_2$ satisfying

$$g_1 \circ (g_2g_3) = (g_1 \circ g_2)g_1^{-1}(g_1 \circ g_3) \tag{1}$$

for all $g_1,g_2,g_3 \in G$, where g_1^{-1} denotes the multiplicative inverse of g_1. A skew left brace G is said to be a *left brace* if G is an abelian groups under multiplicative structure. We have improved an algorithm for computing skew left braces and left braces developed in [*Skew braces and the Yang-Baxter equation*. Math. Comp. **86** (2017), 2519-2534]. Using the improved algorithm, we computed skew left braces and left braces of small orders (up to orders 447 except some cases) using computer algebra system MAGMA.

Publications:

1. Rahul D. Kitture and Manoj Kumar Yadav, *Finite p-groups with abelian automorphism groups - A survey,* Group Theory and Computation, Indian Statistical Institute Series, Springer, Singapore, 119-140, (2018).
2. IBS Passi, Mahender Singh and Manoj Kumar Yadav, *Automorphisms of finite groups,* Springer Monographs in Mathematics, Springer, Singapore, xix + 217, (2018).
3. NSN Sastry and Manoj Kumar Yadav (editors), *Group Theory and computation,* Indian Statistical Institute Series, Springer, Singapore, xi + 206, (2018).

Preprints:

1. Silvio Dolfi, Anupam K. Singh and Manoj Kumar Yadav, *p-Power conjugacy classes in $U(n, q)$ and $T(n, q)$,* preprint, arXiv:1905.04244.
2. Valeriy Bardakov, M. Neschadim and Manoj Kumar Yadav, *Enumeration of Skew left braces of small orders,* (in preparation).

Conference/Workshops Attended:

1. *All Russia conference*, Russia, October, 2018.
2. *International Conference on Algebra and Continuum Mechanics*, India, November, 2018.
3. *Conference of mathematical sciences and development*, India, December 2018.
4. *Workshop in group theory*, India, February 2019.

Visits to other Institutes:

1. Central University of Rajasthan, Kishangarh, India, August, 2018.
2. Sobolev Institute of Mathematics, Novosibirsk, Russia, October, 2018.
3. IISER, Mohali, India, January 2019.
4. IISER, Pune, India, February, 2019.

Invited Lectures/Seminars:

1. *Schur multiplier of central product of groups*, All Russia Conference, Tomsk State University, Tomsk, Russia, October, 2018.
2. *Finite groups with few conjugacy class sizes*, International Conference on Algebra and Continuum Mechanics, HP University, Shimla, November, 2018.
3. *Groups with maximal central quotient*, Conference of mathematical sciences and development, IBS Khandari, Dr. BR Ambedkar University, Agra, December, 2018.
4. *The left braces*, Workshop in group theory, IISER, Pune, February, 2019.

Academic recognition:

- Member of the editorial board, Proc. Math. Sci., I.A.Sc., Bangalore (w.e.f. January 2019 for 3 years).

Other Activities:

1. Delivered three lectures on representation theory of finite groups at Central University of Rajasthan, Kishangarh, August, 2018.
2. Delivered a public lecture on "Group theory in the living room" at IBS Khandari, Dr. BR Ambedkar University, Agra, August, 2018.
3. Conducted a workshop on computer algebra system GAP at Ambedkar University, Delhi, February, 2019.
4. Refereed research papers for many national and international journals. Also refereed a book for Springer.
5. Served as a member of several committees at HRI.

Gyan Prakash

Research Summary:

Given s natural numbers $k_1, \ldots k_s$, with $s \geq 2$, in a joint work with François Hennecart and E. Pramod, we study the question of how "thin" a subset A of natural numbers can be such that $A^{k_1} + \ldots + A^{k_s}$ contains all natural numbers. Here $A^{k_1} + \ldots + A^{k_s}$ denotes the set consisting of those n which can be written as $n = b_1 + \ldots + b_s$ where $b_i = a_1 \ldots a_{k_i}$ with $a_i \in A$ for each i. For any subset B of natural numbers and a real number x, we write $B(x)$ to denote the number of natural numbers belonging to B which does not exceed x. An elementary combinatorial argument shows that for any A as above, $A(n)$ must be at least $cn^{\frac{1}{\sum_i k_i}}$. When $k_1 = \ldots = k_s = 1$, there are known examples of A as above with $A(n)$ not exceeding $cn^{1/s}$. We study the question for general $k_1, \ldots, k_s$ and show that $A(n)$ must be at least $c\frac{n^{1/s}}{\log^{\alpha(k_1,\ldots,k_n)} n}$ for infinitely many n, where we may take $\alpha(k_1, \ldots, k_n) = 1 - \frac{1}{\max_i k_i}$. For general s, when $\min(k_1, k_2) \geq 2$, we also show the existence of A such that $A^{k_1} + \ldots + A^{k_s}$ contains all natural numbers and $A(n)$ is $o(\sqrt{n})$. The arguments used are a combination of combinatorial, probabilistic and those from elementary analytic number theory.

Preprints:

1. François Hennecart, Gyan Prakash and E. Pramod, *On sum-product basis*, https://arxiv.org/abs/1904.05908

Conference/Workshops Attended:

1. *International conference in Number theory, KSOM*, India, December 2018.

Visits to other Institutes:

1. Ashoka University, India, March 2019,
2. IMSc Chennai, India, January 2019,
3. KSOM Kozhikode, India, December 2018,
4. University of Bordeaux, France, June 2018,
5. University of Saint-Etienne, France, June 2018.

Invited Lectures/Seminars:

1. *On sum-product basis*, Mathematics seminar, Ashoka University, Delhi, March 2019.
2. *On sum-product basis*, CEFIPRA final meeting, IMSc, Chennai, January 2019.
3. it On sum-product basis, International Conference in Number theory, KSOM, Kozhikode, December 2018.

Raghavendra Nyshadham

Research Summary:

I have been working with my student Pradeep Das and my colleague Umesh Dubey on tensor products of representations of quivers. We have shown that the tensor product of two semistable complex representations of a finite quiver is semistable. This fact gives rise to a canonical morphism from the product of the corresponding moduli spaces of representations to another such moduli space. We are studying the properties of this morphism. With another student Anoop Singh, I have been working on the moduli spaces of logarithmic connections on a compact Riemann surface.

Ramakrishnan Balakrishnan

Research Summary:

1. **Determining modular forms of half-integral weight (with Manish Kumar Pandey)**:
One of the interesting problems in the theory of automorphic forms is to find criterions for the determination of Hecke eigenforms. It is known that a normalized modular form of integral weight, which is a normalized Hecke eigenform, is determined by its Fourier coefficients (which are nothing but the eigenvalues) indexed by prime numbers. There are many works which consider this question of determination of a Hecke eigenform of integral weight by the special values of the L-functions twisted by a family of modular forms. In this joint work, we show that a Hecke eigenform g of half-integral weight on $\Gamma_0(4)$ which belongs to the Kohnen plus space is uniquely determined by the central values of the family of convolution (Rankin-Selberg) L-functions $L(s, f \otimes g)$, where f runs over an orthogonal basis of Hecke eigenforms of weight $k + 1/2$ on $\Gamma_0(4)$ which lie in the Kohnen plus space with k varying over an infinite set of integers.

2. **Triangular Numbers, forms of mixed type and their representation numbers (with Lalit Vaishya)**: In 1995, K. Ono, S. Robins and P.T. Wahl considered the problem of determining formulas for the number of representations of a natural number n by a sum of k triangular numbers and derived many applications, including the one connecting these numbers with the number of representations of n as a sum of k odd square integers. They also obtained an application to the number of lattice points in the k-dimensional sphere. In this work, we consider triangular numbers with positive integer coefficients. First we show that if the sum of these coefficients is a multiple of 8, then the associated generating function gives rise to a modular form of integral weight (when even number of triangular numbers are taken). We then use the theory of modular forms to get the representation number formulas corresponding to the triangular numbers with coefficients. We also obtain several applications concerning the triangular numbers with coefficients similar to the ones obtained by Ono et. al. In the second part of the work, we consider more general mixed forms (as in the work of Xia-Ma-Tian (IJNT 2016)) and derive modular properties for the corresponding generating functions associated to these mixed forms. Using our method we deduce all the 21 formulas proved by Xia et. al. Finally, we show that our method of deriving the above mentioned 21 formulas together with the (p, k) parametrization of the generating functions of the three mixed forms imply the (p, k) parametrization of the Eisenstein series $E_4(\tau)$ and its duplications. It is to be noted that the (p, k) parametrization of E_4 and its duplications were derived using a different method by K. S. Williams and his co-authors.

3. **Construction of Shimura and Shintani correspondences between certain subspaces (with Manish Kumar Pandey and Anup Kumar Singh)**: In 1985, W. Kohnen constructed explicit Shintani lifts from the space of cusp forms of weight $2k$ on $\Gamma_0(N)$, which are mapped into the plus space $S^+_{k+1/2}(\Gamma_0(4N))$, where N is an odd integer. This lifting is adjoint to the (modified) Shimura map defined by him with respect to the Petersson scalar product. Using this construction along with the theory of newforms on $S^+_{k+1/2}(\Gamma_0(4N))$ (where N is an odd square-free natural number), he derived explicit Waldspurger theorem for the newforms belonging to the space $S^+_{k+1/2}(\Gamma_0(4N))$. Fur-

ther in this work, Kohnen considered the ± 1 eigen subspaces corresponding to the Atkin-Lehner involution and showed that the intersection of this $\pm$ spaces with the corresponding newform spaces are isomorphic under the Shimura correspondence. A natural question is whether a similar result can be obtained for the intersection of this (± 1) subspaces with the oldforms. In this direction, in 2017, S. Choi and C.H. Kim constructed similar Shimura and Shintani maps between subspaces of forms of half-integral and integral weights when N is an odd prime. The subspaces considered by Choi and Kim are nothing but $+1$ eigenspace under the Fricke involution. Our work generalises the results of Choi and Kim to the case where N is an odd square-free natural number.

Preprints:

1. Manish Kumar Pandey and B. Ramakrishnan, *Determining modular forms of half-integral weight by central values of convolution L-functions*, 2018.
2. B. Ramakrishnan and Lalit Vaishya, *On triangular numbers, forms of mixed type and their representation numbers*, 2019.
3. Manish Kumar Pandey, B. Ramakrishnan and Anup Kumar Singh, *Shimura and Shintani liftings of certain cusp forms of half-integral and integral weights*, 2019.

Conference/Workshops Attended:

1. *Workshop on Number Theory*, NISER, Bhubaneswar, India, December 2018.
2. *International Conference on Number Theory*, Kerala School of Mathematics, Kozhikode, December 2018.
3. *Conference on Algebra and Number Theory (CANT-2018)*, Central University of Tamil-nadu, Thiruvarur, India, December 2018.
4. *33rd Automorphic Forms Workshop*, Duquesne University, USA, March 2019.

Visits to other Institutes:

1. The Institute of Mathematical Sciences, Chennai, India, April to August, 2018.
2. Kerala School of Mathematics, Kozhikode, India, September to December, 2018.

Invited Lectures/Seminars:

1. *On Shimura and Shintani maps on the Kohnen plus space*, Workshop on Number Theory, NISER, Bhubaneswar, December 2018.
2. *On a theorem of Hurwitz*, CANT-2018, CUTN, Thiruvarur, December 2018.
3. *On Shimura and Shintani lifts for certain subspaces of modular forms*, 33rd Automorphic Forms Workshop, Duquesne University, Pittsburgh, USA, March 2019.

Other Activities:

1. Supervising four Ph. D students, two of them submitted their theses during March 2019.

2. Convener, Board of Studies in Mathematical Sciences, HBNI, Mumbai.

3. Honorary Treasurer, National Academy of Sciences, Prayagraj.

4. Lectured in a Faculty Development Programme conducted by the Department of Mathematics, PSGR Krishnammal College for Women, Coimbatore during September 2018.

5. Co-organised and lectured in the school on "Modular Forms-Phase II", Kerala School of Mathematics, Kozhikode, October, 2018.

6. Co-organised and lectured in the school on "Analytic Number Theory", Kerala School of Mathematics, Kozhikode, November 2018.

7. Co-organised an international conference on Number Theory at Kerala School of Mathematics, Kozhikode, December, 2018.

8. Co-organised a Conference on Algebra and Number Theory at the Central University of Tamilnadu, Thiruvarur, December 2018.

D. Surya Ramana

Research Summary:

Much of my work over the last few years has been concerned with investigating if large but otherwise arbitrary subsets of "interesting subsets" of the natural numbers retain certain properties of these interesting sets. A specific theme has been to obtain sharp analogues of the classical theorems of Lagrange, Vinogradov and Hua on expressing integers as sums of squares, primes and prime squares respectively, from the point of view of Ramsey theory. In particular, the preprint listed below, which a revised version of earlier work, gives a close to optimal upper bound for the smallest number $r(K)$ such that given any colouring in K colours of the set of prime squares, every large enough integer can be written as a sum of no more than $r(K)$ prime squares, all of the same colour. Here K is any positive integer.

Together with my collaborators, I have also considered other problems which are related to the aforementioned theme. One such problem whose solution is likely to be of great interest is the problem of obtaining an optimal version of the large sieve inequality with square moduli.

Preprints:

1. K. Mallesham, Gyan Prakash and D.S. Ramana, *Monochromatic Sums of Prime Squares,* (to be submitted).

Conference/Workshops Attended:

1. *International Conference on Number Theory,* KSOM Calicut, 10 to 14, December 2018.

2. *CEFIPRA Conference*, IMSc Chennai, 14 to 18 January, 2019.

Visits to other Institutes:

1. Institute of Mathematical Sciences, Chennai, 28 December, 2017 to 27 January 2018.

Other Activities:

1. Thesis supervision at HRI: Ritika Sharma (defence scheduled), E. Pramod (synopsis submitted, co-guide Dr. Gyan Prakash), Mithun Kumar Das (to complete by July 2020).

2. Courses : Algebra II, HRI Graduate Programme, Jan. - July, 2019.

3. Co-organised and lectured (6 hrs) in AFS I, HRI, 6 May to 1 June, 2019. Lectured (6 hrs) in AFS II, Central University Rajasthan, Dec. 2018. Lectured (6 hrs) in AIS on Galois Theory at IIT Mandi in June 2018.

4. Served on a number of academic and administrative committees of HRI including the Mathematics Graduate Committee (as member), Library Committee (as convenor), Local Works Committee (as member).

Ratnakumar Peetta Kandy

Research Summary:

I have initiated the work on three problems during 2018-19, with my Ph. D. student Arup Kumar Maity and the two post doctoral fellows Dr. Rajesh Kumar Singh and Dr. Anupam Gumber. These concerns the study of Hörmander's type multipliers and singular multipliers on $\mathbb{R}^n$ and also on Weyl multipliers in the context of modulation spaces, respectively.

In the study of Weyl multipliers on Modulation spaces, we are able to obtain a characterisation in certain twisted modulation spaces, which we believe is natural in terms of the structure of the Weyl transform. This work is almost complete. The work on singular multipliers concerms the study of multiplier operators associated to certain surfaces, the well known cone multiplier theorem being an example. We are exploring analogous result in the context of quadratic sufaces to begin with. In the wrok on Hörmander's type multipliers on Euclidean spaces, we are presently exploring the optimal regularity assumption on the multiplier function. These two works are in progress.

Publications:

1. Ramesh Manna and P.K. Ratnakumar, *Maximal functions along hyper-surfaces*, J. Ramanujan Math. Soc. **Vol33-No. 3**, 283-296, (2018).

Other Activities:

1. Serving in the Math Graduate Committee as convener, and also as a member in the mathematics PDF committee.

Hemangi Madhusudan Shah

Research Summary:

Almost maximal volume entropy: Chen, Rong, and Xu recently established quantitative volume space form rigidity conjecture. This is one of the important conjectures in Differential Geometry. The conjecture shows that a closed Riemannian manifold of bounded diameter, Ricci curvature bounded from below and volume entropy close to the entropy of a compact hyperbolic manifold upto an error of $\epsilon > 0$, is Gromov-Hausdorff close (that is close upto an error which is function of ϵ, diameter and dimension of the close manifold), to the compact hyperbolic manifold. It is natural to ask if their result generalizes to the case where the diameter bound is replaced by some volume bound. In my joint published result in (2018), we give examples that this is not the case. And the result established by Chen, Rong, and Xu is optimal. Towards this we mainly proved the existence of manifolds with almost maximal volume entropy which are not hyperbolic.

Geometry of Asymptotically harmonic manifolds with minimal horospheres: Let (M^n, g) be a complete, simply connected Riemannian manifold without conjugate points. If M is harmonic manifold with minimal horospheres, then the (second order) flatness was proved in my joint paper with A. Ranjan. Asymptotically harmonic manifolds are asymptotic generalization of harmonic manifolds. It is a challenging question in the theory of asymptotically harmonic manifolds whether asymptotically harmonic manifold with minimal horospheres are flat. We resolved this *challenging question* by showing that asymptotically harmonic manifold with minimal horospheres are first order flat by the strongest criterion. Consequently, asymptotically harmonic manifolds can have either polynomial or exponential volume growth, generalizing the corresponding result of Nikolayevsky for harmonic manifolds. In case of harmonic manifold with minimal horospheres, the (second order) flatness was proved in my paper on: *Harmonic manifolds with minimal horospheres*. We concluded that the results obtained in my paper are the strongest and wider in comparison to harmonic manifolds, which are known to be asymptotically harmonic.

Asymptotically harmonic manifolds of dimension 4*:* In the theory of harmonic manifolds the central question is the Lichnerowicz conjecture: *Any simply connected harmonic manifold is either flat or a rank one symmetric space*. Lichnerowicz proved this conjecture for harmonic manifolds of dimension 4. It follows from my joint work that *an asymptotically harmonic manifold of dimension* 3 *is flat or a rank one symmetric space*, thus proving the conjecture in dimension 3. We proved that *asymptotically harmonic and Einstein manifolds of dimension* 4 *are either flat or are rank one symmetric spaces*. Thus, we proved the Lichnerowicz type conjecture for asymptotically harmonic manifolds of dimension 4. We also recover the Lichnerowicz conjecture for harmonic manifolds of dimension 4. The strong merit of our proof is that we *constructed* a Singer-Thorpe basis for asymptotically harmonic and Einstein manifold M of dimension 4, in which M is a symmetric space. On the other hand the proof of Besse for harmonic manifolds of dimension 4 used Singer-Thorpe basis to prove its symmetry. We also strengthened a result of Heber that an asymptotically harmonic homogeneous and Einstein manifolds are ei-

ther flat or rank one symmetric space of non-compact type in dimension 4.

Geometry of a special class of Finsler Manifolds: This is a joint work with Dr. E. Taha, HRI post-doctoral fellow, working under my mentorship on the study of a special class of Finsler Manifolds, since February 2019. We generalized some results of my joint work by (Akhil Ranjan and Hemangi Shah, Busemann functions in a harmonic manifold, Geom. Dedicata 101 (2003), 167-183) from Riemannian to Finsler geometry. In fact, Finsler manifolds are rich and contain 33 special spaces for example, Riemannian, Berwald, Rander and Landsberg manifolds. So, we set a goal to investigate harmonic and asymptotic harmonic manifold in Finslerian setting. It should be noted that theories and applications of either of these two manifolds are substantially mature in setting of Riemannian geometry but neither of them have been yet studied in Finslerian setting. In order to define and study such spaces, we shall naturally use Finsler Laplacian, but non uniqueness of it, contrary to Riemannian case (Laplace-Beltrami operator) and for certain reason we choose Shen's Laplacian. We studied such spaces using Busemann function and Finsler distance function which is not symmetric in general. We also work without the assumption of compact quotient and without any restriction on the flag curvature. In these spaces we proved: smoothness of Busemann function and established that asymptotically harmonic Finsler spaces having minimal horospheres have the bi-asymptotic property, consequently they are reversible. We also gave general construction of these type of spaces and studied them in the Berwald settings as well.

Publications:

1. V. Schroeder and H. Shah, *Almost maximal volume entropy*, Arch. Math. **110** (2018), no. 5, 515-521.

Preprints:

1. H. Shah, *Geometry of asymptotically harmonic manifolds with minimal horospheres*, arXiv:1703.00341 [math.DG], REVISED IN MAY 2019, under review.

2. H. Shah, *Asymptotically harmonic manifolds of dimension* 4, REVISED IN JUNE 2019, under review.

3. H. Shah and E. Taha, *Geometry of a special class of Finsler manifolds*, in preparation, 2019.

Conference/Workshops Attended:

1. Invited to present a paper at the International conference, Newyork, US, September 2018.

2. Invited to present a paper at the International conference, Washington, US, January 2019.

Visits to other Institutes:

1. Universität Zürich, Switzerland, April - May, 2018.

Invited Lectures/Seminars:

1. *Geometry of asymptotically harmonic manifolds with minimal horospheres*, International conference, Newyork, US, September 2018.

2. *Geometry of asymptotically harmonic manifolds with minimal horospheres*, International conference, Washington, US, January 2019.

Academic recognition/Awards:

- The article 'Almost maximal volume entropy', selected as the distinguished scientific article by the editors of Archiv der Mathematik, April 2018.

- Invited to join the panel of reviewers for Mathematical Reviews, August 2018. Mathematical Reviews/MathSciNet Reviewer number: 035736.

- Invited speaker at "The International Conference of Differential Geometry and Dynamical Systems", University Politechnica of Bucharest, Romania, June 2018.

- Invited to present a talk at 23rd international summer school on Global Analysis and Applications, Brasov, Romania, August 2018.

- Invited to present a talk on at the international conference, University of Southampton, UK, July 2018.

Other Activities:

1. MR3826825: Reviewed the article: *Hausdorff stability of the round two-sphere under small perturbations of the entropy*, Math. Res. Lett., **25** 347-365, (2018); October 2018.

2. MR3846037: Reviewed the article: *Harmonic Finsler manifolds with minimal horospheres*, Commun. Korean Math. Soc. **33** (2018), 929-933; January 2019.

3. MR3850961: Reviewed the article: *A rigidity result on Finsler surfaces*, Balkan J. Geom. Appl., **23** 34-40, (2018); January 2019.

4. MR3893269: Reviewed the article: *The topological entropy of non-dense orbits and generalized Schmidt games*, Ergod. Th. & Dynam. Sys., **39** (2019), 500-530; March 2019.

5. MR3874991: Reviewed the article: *Geometric structures on Riemannian and Finsler manifolds - Integral formulae, minimal entropy*, Folia Mathematica, **20** (2019), 3-16; March 2019.

6. August 2018: HRI Peer Review report, on work done on asymptotically harmonic manifolds, of the committee formed by faculty of Tata Institute of Fundamental Research, Mumbai, India: Interesting work in classical differential geometry is being carried out. This is complemented by other work overlapping with complex algebraic geometry, through Kähler geometry. The scope of the work in differential geometry could be expanded into other areas, of current interest, and also of potential interest to some physicist colleagues. This may need the induction of new faculty.

Ravindranathan Thangadurai

Research Summary:

For an odd prime number p, it is well-known that there are exactly $(p-1)/2$ number of quadratic residues as well as quadratic non-residues modulo p. Using Polya-Vinogradov Theorem, one can obtain the number of quadratic residues (respectively, non-residues) in the subset of all multiples of k in $\{1, 2, \ldots, p-1\}$ as $\frac{1}{2}\left[\frac{p-1}{k}\right] + O(\sqrt{p}\log p)$ for any positive integer k. However, it may happen that some intervals contains more number of quadratic residues than that of non-residues. In our preprint, we explored this phenomena and get a finer information using Dirichlet's class number formula for the quadratic field $\mathbf{Q}(\sqrt{-p})$.

In another preprint, we dealt with bounded gaps between primes. We had a series study on group cohomology and applications to number theory. In this connection, we organised a workshop in this subject which is a prelude to the forthcoming lecture series on Galois cohomology.

Publications:

1. R. Thangadurai and J. M. Deshouillers, *A sufficient condition for $(\theta^N)_N$ to have a distribution modulo one, when θ is in $F_2(X)$*, Integers **17**, 11pp, (2018).

2. R. Thangadurai and S. S. Rout, *On ℓ-th order gap balancing numbers*, Integers **18**, 12pp, (2018).

3. R. Thangadurai and Bidisha Roy, *On zero-sum subsequences in a finite abelian p-group of length not exceeding a given number*, J. Number Theory **191**, 246-257, (2018).

4. R. Thangadurai, Jaitra Chattopadhyay and Veekesh Kumar, *Set Equidistribution of subsets of $(\mathbf{Z}/n\mathbf{Z})^*$*, Hardy-Ramanujan Journal **41**, 104-112, (2018)

5. R. Thangadurai and Veekesh Kumar, *Distribution of a subset of non-residues modulo p*, Geometry, algebra, number theory and their information technology applications, Springer Proc. Math. Stat. **251**, 445-459, (2018).

6. R. Thangadurai, Jaitra Chattopadyay, Bidisha Roy and Subha Sarkar, *Quadratic nonresidues and nonprimitive roots satisfying a coprimality condition*, Bull. Aust. Math. Soc. **99** 177-183, (2019).

7. R. Thangadurai, V. P. Ramesh and R. Thatchaayini, *A note on Gauss's theorem on primitive roots*, Amer. Math. Monthly, **126**, 252-254, (2019).

Preprints:

1. R. Thangadurai, Jaitra Chattopadyay, Bidisha Roy and Subha Sarkar, *Distribution of residues modulo p using the Dirichlet's class number formula,* (in preparation).

2. R. Thangadurai, *A remark on bounded gaps between primes,* (in preparation).

Conference/Workshops Attended:

1. *Refresher course in Mathematics*, India, July, 2018.
2. *Summer school in Mathematics (Nurture)*, India, August, 2018.
3. *Workshop and Conference in Number Theory*, India, December, 2018.
4. *Conference on Number Theory*, India, December, 2018.
5. *Workshop and Conference in Dynamical Systems and Combinatorial Number Theory*, India, January, 2019.
6. *CEFIPRA meeting*, India, January, 2019.
7. *Workshop on 'Introduction to Group Cohomology'*, India, March, 2019.

Visits to other Institutes:

1. Central University of Hyderabad, Hyderabad, India, July, 2018.
2. Chennai Mathematical Institute, Chennai, India, July, 2018.
3. Central University of Tamilnadu, Thiruvarur, India, August, 2018.
4. Delhi University, Delhi, India, November, 2018
5. National Institute of Science and Research, Bhubaneshwar, India, December, 2018.
6. Kerala School of Mathematics, Kozhikode, India, December, 2018.
7. RKMVERI, Belur, India, January, 2019.
8. Institute of Mathematical Sciences, Chennai, India, January, 2019.
9. Shiv Nadar University, Noida, India, February, 2019.

Invited Lectures/Seminars:

1. *Introduction to Transcendental Number Theory: Rational approximations*, Mathematics Seminar, Shiv Nadar University, Noida, February, 2019.

Other Activities:

1. CSIR - NET Examination, July, 2018 and February, 2019.
2. Guided Dr. Nabin Kumar Meher's Ph. D thesis, May, 2018.
3. Guided Mr. Veekesh Kumar's Ph. D thesis, February, 2019.
4. Dean (Students' Affair), since January, 2017.
5. Served as M.Phil thesis external examiner in Delhi University, November, 2018.

6. Served as Ph. D thesis external examiner in Shiv Nadar University, February, 2019.

7. Member of Library Committee and Transport Committee.

8. Conducted workshop on 'Introduction to Group Cohomology', March, 2019.

Rishabh Agnihotri

Research Summary:

During this academic year, I have studied the following topics as reading courses: Theory of Modular forms (both integral and half-integral weights), Theory of newforms (as developed by Atkin-Lehner and W.W.Li), Topics in the theory of eta-quotients. Also, I did a reading project on Transcendental number theory and Algebraic number theory, particularly the subspace theorem and the n-stage euclidean algorithm.

Conference/Workshops Attended:

1. AIS on Algebraic number theory, IIT Guwahati, May 14 - June 02, 2018.
2. ICCGNFRT, HRI Prayagraj, Oct 7-11, 2018.
3. Workshop and Confrence on Number theory, NISER, Bhubaneswar, Nov 30- Dec 6, 2018.
4. School on Introduction to Group Cohomology, HRI Prayagraj, March 22-31, 2019.

Priyanshu Chakraborty

Research Summary:

In the academic year 2018-2019, I learnt some aspects of finite dimensional Lie algebras and its representation from "Introduction to Lie Algebras and Representation Theory by James E. Humphreys". In particular, I have read finite dimensional representation of semisimple Lie algebra.

Conference/Workshops Attended:

1. AIS on Lie Algebras, (Dec 10 - 29, 2018), HRI, Prayagraj, India.

Invited Lectures/ Seminers:

1. Classification of finite dimensional irreducible representation of semisimple Lie algebra, (30-05-19), HRI,Prayagraj, India.

Jaitra Chattopadhyay

Research Summary:

In this academic year, I have worked simultaneously on a few projects. In a joint work with Dr. M. Subramani, we studied the problem of the existence of a non-principal Euclidean ideal class in an algebraic number field and we could extend a previously known family of biquadratic fields having an Euclidean ideal class.

With Ms. Bidisha Roy and Mr. Subha Sarkar, we studied the literature of fractionally dense sets and obtained some new results for number fields that are natural generalizations of results known for the ring of integers $\mathbb{Z}$.

We proved a theorem on quadratic non-residues and non-primitive roots satisfying a certain co-primality condition which is a variant of a question addressed by Levin et al. in 2010. This is a joint work with Dr. R. Thangadurai, Ms. Bidisha Roy and Mr. Subha Sarkar. In another work, we used Dirichlet's class number formula to study the distribution of quadratic residues and non-residues in some intervals. We compared the number of residues with that of non-residues modulo a prime p, depending upon the residue class of the prime modulo 4 and 8.

I, jointly with Mr. Pranendu Darbar, worked on a problem on divisor function defined over number fields. There has been a great deal of research in this area in recent years. We considered the divisor function defined over the compositum of finitely many number fields and obtained an asymptotic formula of it over the square integers.

Publications:

1. Jaitra Chattopadhyay, Veekesh Kumar, R. Thangadurai *Set Equidistribution of subsets of* $(\mathbb{Z}/n\mathbb{Z})^*$, Hardy-Ramanujan Journal **41**, 104-112, (2018)

2. Jaitra Chattopadhyay, *A problem related to prime powers,* Math. Student **87**, 135-136, (2018)

3. Jaitra Chattopadhyay, Bidisha Roy, Subha Sarkar, *On fractionally dense sets,* Rocky Mountain J. Math., Accepted for publication.

4. Jaitra Chattopadhyay, M. Subramani, *Biquadratic fields having a non-principal Euclidean ideal class,* J. Number Theory, Accepted for publication.

5. Jaitra Chattopadhyay, Bidisha Roy, Subha Sarkar, R. Thangadurai, *Quadratic non-residues and nonprimitive roots satisfying a coprimality condition,* Bull. Aust. Math. Soc. **99**, 177-183, (2019)

6. Jaitra Chattopadhyay, Bidisha Roy, Subha Sarkar, R. Thangadurai, *Distribution of residues modulo p using the Dirichlet's class number formula,* Conference proceedings of ICCGNFRT-2017, Accepted for publication.

Preprints:

1. Jaitra Chattopadhyay, Pranendu Darbar, *Mean values and moments of arithmetic functions over number fields,* RNTB-D-19-00037

Conference/Workshops Attended:

1. *International conference on class group of number fields and related topics*, India, October 2018.
2. *Workshop on Number Theory*, India, November 2018.
3. *AIS on Lie Algebra*, India, December 2018.
4. *Workshop and conference on Number Theory*, India, January 2019.
5. *International conference on Number Theory*, India, March 2019.
6. *Workshop on Cohomology of Groups*, India, March 2019.

Invited Lectures/Seminars:

1. *On biquadratic fields having a non-principal Euclidean ideal class*, International conference on class group of number fields and related topics, Harish-Chandra Research Institute, Prayagraj (Allahabad), October 2018.
2. *On biquadratic fields having a non-principal Euclidean ideal class*, Workshop on Number Theory, Ramakrishna Mission Vivekananda Education and Research Institute, Belur, January 2019.
3. *On the class numbers of quadratic fields*, International conference on Number Theory, IISER, Thiruvananthapuram, March 2019.

Pradeep Das

Research Summary:

I have been working on the tensor products of quivers and of their representations. Given a representation V of a quiver Q and a representation V' of another quiver Q', we defined the tensor product $V \otimes V'$ which is a representation of the quiver $Q \otimes Q'$. It was shown that the semistability of V and V' implies the semistability of $V \otimes V'$. We also gave a relation between certain natural line bundles on the moduli spaces of representations of Q, Q', and $Q \otimes Q'$. We are also studying the cohomologies of these moduli spaces.

Publications:

1. Pradeep Das, *A natural Hermitian line bundle on the moduli space of semistable representations of a quiver,* Indian Journal of Pure and Applied Mathematics, To appear

Conference/Workshops Attended:

1. *Thematic month programme, 2019: 'Complex Geometry'*, France, January, 2019.
2. *International Conference on Advances in Pure & Applied Mathematics*, India, September, 2018.

Other Activities:

1. Took tutorials for the course 'Topology' in Annual Foundation School–II at Central University of Rajasthan, December, 2018.

Mithun Kumar Das

Research Summary:

During the academic year 2018-2019, I was mainly involved in the problems concerning value distribution of higher derivative of Hardy's Z-function. Also, I did a project on trigonometric sum and it's relation with certain mean value of Dirichlet L-series .

Hardy's Z-function is the function defined on the real line by the relation

$$Z(t) = \zeta\left(\frac{1}{2} + it\right)\rho\left(\frac{1}{2} + it\right)^{-\frac{1}{2}} \tag{2}$$

for all $t \in \mathbf{R}$. Here $\rho(s) = \pi^{s-1/2}\frac{\Gamma((1-s)/2)}{\Gamma(s/2)}$ for any complex number $s = \sigma + it$ and ζ and Γ denote, respectively, the Riemann zeta function and the Gamma function. It follows from standard facts on the Riemann zeta function that the function Z is a smooth real valued function on the real line with the property that $Z(t) = 0$ if and only if $\zeta(\frac{1}{2}+it) = 0$. Hardy's classical theorem on the function Z is that this function has infinitely many zeros on the real line. In light of Hardy's result one may ask if the function Z takes positive and negative values on the real line in "equal measure". On this question S. M. Gonek and A. Ivić showed in 2016 that the Lebesgue measure of the subset of the real line on which the function Z takes positive values, and respectively negative values, in the interval $(T, T + H]$ is $\gg H$, when H is not too small relative to T, for all large enough T. In joint work with S. Pujahari, a Post-Doctoral Fellow at University of Hong Kong, an asymptotic is obtained for the "mollified" second moment of k-th derivative of Hardy's Z-function and as a application of it we show that the Lebesgue measure of the set on which the k-th derivative of Hardy's Z-function is of a given sign in the interval $(T, T + H]$ is at least $H/c_k(\theta)$ where $c_k(\theta)$ is explicit positive constant depend on θ and k where T^θ is the "mollifier length" with $0 < \theta < 1/2$ and $H = T^{1/2+\theta+\epsilon}$. This is extending the aforementioned result of Gonek and Ivic. As an another application of the "mollified" second moment of k-th derivative of Hardy's Z-function, we derived an upper bound of number of zeros of certain linear combination of derivatives of Riemann zeta function on the right hand side of half line.

In the second work with A. Juyal, a Post-Doctoral Fellow at HRI, we obtain a trigonometric identity for $sec^m 2x cot^{2n} x$ in terms of integers linear combination of powers of $sec2x$ and $cotx$. We have given two application of it. As the first application we have given a partial answer of a question raised A. Straub about the irrationality of the series

$$\sum_{n=1}^{\infty} \frac{\cot(\pi n\tau_1)\cdots\cot(\pi n\tau_k)}{n^s},$$

where $\tau_1, \ldots \tau_k$ are quadratic (or algebraic) irrationality. As another application of the trigonometric identity, we have derived some special values of Zagier's higher dimensional Dedekind sums. Next, for Dirichlet characters χ modulo an odd integer q, a positive integer c co-prime to q and any positive integers m, n, we have shown that the mean values

$$M(q, c, m, n) = \frac{2}{\phi(q)} \sum_{\chi \pmod q} \chi(c)L(m, \chi)L(n, \overline{\chi})$$

can be evaluate in terms of higher dimensional Dedekind sums. Using special values of Zagier's higher dimensional Dedekind sums we obtained some formulas of mean values $M(q, c, m, n)$. These formulas are generalize results of H. Liu (J. Number Theory 147 [2015], 172-183).

Publications:

1. Mithun Kumar Das, B. R. Patil, E. Pramod, *Combinatorial properties of sparsely totient numbers* (Accepted for publication in Journal of the Ramanujan Mathematical Society).

2. Mithun Kumar Das, B. R. Patil, E. Pramod, *Sparse subsets of the natural numbers and Eulers totient function* (Accepted for publication in Proc. Indian Acad. Sci. Sect. A Math. Sci.)

Preprints:

1. Mithun Kumar Das, Abhishak Juyal, *Trigonometric sums, higher dimensional Dedekind sums and twisted mean value of Dirichlet L-series* (submitted).

2. Mithun Kumar Das, Sudhir Pujahari, *Distribution of signs of Karatsuba's and generalized Davenport-Heilbronn Z-functions* (under review).

3. Mithun Kumar Das, Sudhir Pujahari, *Mollifying the k-th derivative of Hardy's Z-function and distribution of signs* (in preparation).

4. Mithun Kumar Das, K Mallesham, *Smooth numbers composed of primes in a arithmetic progression* (in preparation).

Conference/Workshops Attended:

1. Workshop on Number Theory, National Institute of Science Education and Research, India, November 30 - December 6, 2018.

2. International Conference on Class Groups of Number Fields and Related Topics, Harish-Chandra Research Institute, India, 08-11, October, 2018.

3. CMI-LMS Research School: New Trends in Analytic Number Theory, University of Exeter, United Kingdom, August 13 -17, 2018.

4. The Combinatory Analysis-2018, Penn State University, USA, June 21-24, 2018.

5. The 33rd Annual Conference of the Ramanujan Mathematical Society, University of Delhi, India, June 1-3, 2018.

Visits to other Institutes:

1. Indian Statistical Institute , Kolkata, India, November 10-16, 2018.

Debasish Karmakar

Research Summary:

I have studied the parametrisation of solvable primitive extensions of an arbitrary field F of degree p^n for some fixed prime p and some fixed positive integer n.

I have focused on giving explicit description of parametrisation of primitive extensions of degree p^2 of a local field F with finite residue field of prime characteristic p.

Conference/Workshops Attended:

1. *International Conference on Class Groups of Number Fields and Related Topics*, India, October, 2018.
2. *Workshop on Number Theory*, India, November, 2018.
3. *Advanced Instructional School on Lie Algebras*, India, December, 2018.
4. *International Conference on Number Theory*, India, March, 2019.
5. *School on Group Cohomology*, India, March, 2019.

Other Activities:

1. Tutor in Summer Programme in Mathematics at HRI, June 18 - July 07, 2018.

Rahul Kaushik

Research Summary:

I studied combinatorial techniques from the book 'Combinatorial Group Theory' by W. Magnus et. el. and advanced group theory from 'A Course in Group Theory' by D. J. S. Robinson. I started working on 'Word maps on finite groups' and read some papers on surjectiveness of commutator map in finite p-groups. Study of word maps requires the knowledge of Lie Algebras and Algebraic Groups, which has been extensively used as a tool. I studied Lie algebras from the book Lie Algebras and Representation Theory by James E. Humphreys".

I looked at the surjectiveness of the commutator map on groups of order p^6 and obtained some partial results. I observed that commutator map is surjective for 40 classes out 43 isoclinism classes of groups of order p^6. I'll now study Linear Algebraic Groups and look at commutator map more closely.

Conference/Workshops Attended:

1. AIS on Lie Algebras, (Dec 10 - 29, 2018), HRI, Prayagraj, India.
2. School on Introduction to Group Cohomology, (March 22 - 31, 2019), HRI, Prayagraj, India.

Parul Keshari

Research Summary:

The main focus in these semesters have been to understand different characteristic classes (mainly, Stiefel Whitney classes and Chern classes) associated to real and complex vector bundles on topological spaces (or manifold), which is one of the invariants for space classification. In this direction, I have studied the notion of fibre bundles, different homology and cohomology theory, and some concepts in Homological Algebra.

Besides this, I have been studying some basics of Algebraic Geometry, Commutative algebra and spectral sequences. I have attended a series of lectures on Ringed Spaces by Prof. N. Raghvendra and Derived Functors by Dr. Umesh V. Dubey.

Veekesh Kumar

Research Summary:

1. The problem of finding the transcendence nature of an infinite series is challenging and interesting. It has a very rich history. For instance, Mahlers method, one can prove the transcendence of certain infinite sums. In 2001, Adhikari et al., proved the transcendence of certain infinite series by an application of Bakers theory of linear forms in logarithms of algebraic numbers.

   In 1974, Erdos and Straus studied the linear independence of certain series. In particular, they proved the following result. *Let $Q = (b_n)_{n\geq 1}$ be a sequence of positive integers with $b_n \geq 2$ for all integers $n \geq 1$ and let $\delta > \frac{1}{3}$ be any positive real number. Suppose that for all sufficiently large values of N we have*

   $$(b_1 b_2 \cdots b_N)^{\delta} \leq b_{N+1}.$$

   Then the real numbers

   $$1, \quad \sum_{n=1}^{\infty} \frac{\sigma(n)}{b_1 b_2 \cdots b_n}, \quad \sum_{n=1}^{\infty} \frac{\phi(n)}{b_1 b_2 \cdots b_n}, \quad \sum_{n=1}^{\infty} \frac{d_n}{b_1 b_2 \cdots b_n}$$

   are $\mathbb{Q}$-linearly independent, where $\phi(n)$ denotes the Euler totient function, $\sigma(n) = \sum_{d|n} d$ and $(d_n)_n$ is any sequence of integers satisfying $|d_n| < n^{\frac{1}{2}-\delta}$ for all large n and $d_n \neq 0$ for infinitely many values n. In a joint work with B. Mance, we extend their result and we proved that at least one of the last three numbers is transcendental under some conditions on the sequence $(b_n)_n$.

2. In 2018, Elsner et.al., proved the followng: let τ be any complex number with $\mathrm{Im}(\tau) > 0$ such that $e^{i\pi\tau}$ is algebraic. Let $m, n \geq 1$ be distinct positive integers. Then the numbers $\theta_3(m\tau)$ and $\theta_3(n\tau)$ are algebraically independent over $\mathbb{Q}$. But on the other hand, C. Elsner and Y. Tachiya proved the following result: let ℓ, m and n be positive integers. Then, the numbers $\theta_3(\ell\tau), \theta_3(m\tau)$ and $\theta_3(n\tau)$ are algebraically dependent over $\mathbb{Q}$.

   Though these three values of Jacobi theta-constants are algebraicaly dependent over $\mathbb{Q}$, these may be linearly independent over $\mathbb{Q}$. I partially answer this question and proved the following result. *Let $k \geq 2$, $b \geq 2$ and $1 \leq a_1 < a_2 < \cdots < a_m$ be integers such that $\sqrt[k]{a_i/a_j} \notin \mathbb{Q}$ for any $i \neq j$. Then the real numbers*

   $$1, \quad \sum_{n=1}^{\infty} \frac{1}{b^{a_1 n^k}}, \quad \sum_{n=1}^{\infty} \frac{1}{b^{a_2 n^k}}, \ldots, \sum_{n=1}^{\infty} \frac{1}{b^{a_m n^k}}$$

   are $\mathbb{Q}(\sqrt{-D})$-linearly independent.

As an immediate consequence by putting $k = 2$, we can conclude that the m- Jacobi-theta values

$$\theta_3(a_1\tau), \quad \theta_3(a_2\tau), \ldots, \theta_3(a_m\tau)$$

are $\mathbb{Q}$-linearly independent with 1.

Currently, I am working along with C. Elsner and Y. Tachiya to generalize this problem for any $\tau \in \mathcal{H}$, under some mild condition on τ.

Publications:

1. Veekesh Kumar and B. Mance, *On the transcendence of certain real numbers,* Bull. Aust. Math. Soc., (doi.org/10.1017/S0004972719000194).

2. Veekesh Kumar, *Linear independence of certain numbers,* Arch. Math. (Basel), **112**, 377-385, (2019)

3. Veekesh Kumar, *Linear independence of certain numbers,* J. Ramanujan Math. Soc., (To appear).

Preprints:

1. C. Elsner, Veekesh Kumar and Y. Tachiya , *Linear independence results for certain values of jacobi theta-constants,* Preprint, 2018.

Conference/Workshops Attended:

1. *International Conference on Class Groups of Number Fields and Related Topics*, India, September 2018.

Visits to other Institutes:

1. Moscow State Universirty, Russia, October-November 2018 (three weeks). Worked with Prof. Yuri Nesterenko.

2. National National Institute of Science Education Research in Bhubaneswar, Odisha, India, December 2018 (three weeks). Worked with Dr. Senthil Kumar.

Invited Lectures/Seminars:

1. *On the transcendence of certain real numbers*, Moscow State University, Moscow, Russia, October, 2018.

Arup Kumar Maity

Research Summary:

In this academic year I mainly studied Mikhilin's multiplier theorem, its generalization Hormander's multiplier theorem and related topics. Then I studied a paper by Loukas Grafakos and Lenka Slavikova titled "A sharp version of the Hormander multiplier theorem"(arXiv:1706.06507v1).Now I am trying to find some problem in this direction.

Conference/Workshops Attended:

1. *Advanced Instructional School in Harmonic Analysis*, India, 17th December 2018-5th January 2019

Mohit Mishra

Research Summary:

(I) A note on certain real quadratic fields with class number upto three (joint work with Kalyan Chakraborty and Azizul Hoque)
It is interesting to find necessary and sufficient conditions that a real quadratic field has a given fixed class number h. Byeon and Kim [J. Number Theory **57** (1996)] established certain necessary and sufficient conditions for the class number of real quadratic fields of Richaud-Degert type to be 1. They obtained these conditions by comparing the special zeta values attached to a real quadratic field determined by two different ways. In [J. Number Theory **62** (1997)] they analogously obtained some necessary and sufficient conditions for the class number of the same family to be 2.

We consider all real quadratic fields of narrow Richaud-Degert type with two exceptions. More precisely, we consider the real quadratic fields $k = \mathbb{Q}(\sqrt{d})$, where $d = n^2 + r$ and $|r| \in \{1, 4\}$ with the exceptions when $n^2 \equiv 0 \pmod 4$ and $n^2 \equiv 1 \pmod 8$. We also consider wide Richaud-Degert type real quadratic fields $\mathbb{Q}(\sqrt{d})$, where $d = n^2 + r$ and $r \notin \{1, 4\}$ with $d \equiv 1 \pmod 8$. We obtain some criteria for the class number of these fields to be 3. We also obtain similar criteria for $\mathbb{Q}(\sqrt{n^2 + r})$, $r \in \{1, 4\}$ to have class number 2 which were not covered earlier.

(II) A classification of order 4 class groups of $\mathbb{Q}(\sqrt{n^2 + 1})$ (joint work with Kalyan Chakraborty and Azizul Hoque)
Here, we extend our previous work method to classify order 4 class groups of $\mathbb{Q}(\sqrt{n^2 + 1})$ and $\mathbb{Q}(\sqrt{n^2 + 4})$.

(III) We are trying to modify our method so that it can be used to get an effective lower bound for class number of real quadratic fields of Richaud-Degert type. We are are interested to work on an analogous problem for real quadratic fields other than Richaud-Degert type.

Publications:

1. Kalyan Chakraborty, Azizul Hoque and Mohit Mishra, *A note on certain real quadratic fields with class number upto three,* Kyushu J. Math. (2019) (To appear).

Preprints:

1. Kalyan Chakraborty, Azizul Hoque and Mohit Mishra, A Classification of order 4 class groups of $\mathbb{Q}(\sqrt{n^2 + 1})$, submitted for publication 2019.

Conference/Workshops Attended:

1. AIS on Algebraic Number Theory (May 13 - June 2, 2018), IIT Guwahati, Guwahati, India.
2. ICCGNFRT 2018 (Oct 8-11), HRI, Prayagraj, India.
3. Workshop on Number Theory (Nov 30 - Dec 06, 2018), NISER, Bhubaneswar, India.

4. School on Introduction to Group Cohomology, (March 22 - 31, 2019), HRI, Prayagraj, India.

Nishant

Research Summary:

In the academic year 2018-2019, I learnt some aspects of combinattorial group theory from "Combinatorial Group Theory by W.Magnus". In particular, solutions of word problem. I read techniques of Group theory from "A course in group theory by D.Robinson".

Also, I studied the work of "Wolfgang Rump" on the set theoretical solutions of quantum Yang-Baxter equation. In particular, cycle sets and its embedding in braces and study their interaction, in the context of quantum Yang-Baxter equation.

Conference/Workshops Attended:

1. AIS on Lie Algebras, (Dec 10 - 29, 2018), HRI, Prayagraj, India.
2. School on Introduction to Group Cohomology, (March 22 - 31, 2019), HRI, Prayagraj, India.

Souvik Pal

Research Summary:

In the academic year 2018-2019, I have learnt some aspects of representation theory of infinite dimensional Lie algebras. In particular, I have been studying the works of Vyjayanthi Chari and Eswara Rao on integrable representations of Affine Kac-Moody algebras and Toroidal Lie algebras with finite dimensional weight spaces.

Also, I am working on a project where I am trying to give a complete classification of irreducible integrable modules for Lie Tori where the zero degree central elements act trivially on the entire module.

Conferences/Workshops Attended:

1. Participated and served as one of the tutors in AIS on Lie Algebras, (Dec 10 - 29, 2018), HRI, Prayagraj, India.

Visits to other Institutes:

1. Visited IIT Kanpur, India for research collaboration, (June 06 - 12, 2019).

Manish Kumar Pandey

Research Summary:

1. **Determining modular forms of half-integral weight (with Ramakrishnan Balakrishnan)**: Determination of Hecke eigenforms is an interesting problem in the theory of automorphic forms. It is well known that modular forms of integral weight are determined by their Fourier coefficients indexed by prime numbers. The problem of determining modular forms of integral weight by the special values of the L-functions twisted by a family of modular forms have been considered in many aspects. In this joint work, we show that a Hecke eigenform g of half-integral weight on $\Gamma_0(4)$ which belongs to the Kohnen plus space is uniquely determined by the central values of the family of convolution (Rankin-Selberg) L-functions $L(s, f \otimes g)$, where f runs over an orthogonal basis of Hecke eigenforms of weight $k + 1/2$ on $\Gamma_0(4)$ which lie in the Kohnen plus space with k varying over an infinite set of integers.

2. **Construction of Shimura and Shintani correspondences between certain subspaces (with Ramakrishnan Balakrishnan and Anup Kumar Singh)**: W. Kohnen considered a canonical subspace of the space of modular forms of half integral weight called as the plus space $S^+_{k+1/2}(\Gamma_0(4N))$. He constructed explicit Shintani lifts from thespace of cusp forms of weight $2k$ on $\Gamma_0(N)$, which are mapped into $S^+_{k+1/2}(\Gamma_0(4N))$, where N is an odd integer. This lifting is adjoint to the (modified) Shimura map defined by him with respect to the Petersson scalar product. Using this construction along with the theory of newforms for $S^+_{k+1/2}(\Gamma_0(4N))$ (where N is an odd square-free natural number), he derived explicit Waldspurger theorem for the newforms belonging to the space $S^+_{k+1/2}(\Gamma_0(4N))$. Further in his work, Kohnen considered the eigen subspaces with eigenvalues $+1$ or -1 corresponding to the Atkin-Lehner involution and showed that the intersection of these spaces with the corresponding newform spaces are isomorphic under the Shimura correspondence. A natural question is whether a similar result can be obtained for the intersection of these $+1$ or -1 subspaces with the oldforms. In this direction, in 2017, S. Choi and C.H. Kim constructed similar Shimura and Shintani maps between subspaces of forms of half-integral and integral weights when N is an odd prime. The subspaces considered by Choi and Kim are nothing but $+1$ eigenspace under the Fricke involution. Our work generalises the results of Choi and Kim to the case where N is an odd square-free natural number.

Preprints:

1. Manish Kumar Pandey and B. Ramakrishnan, *Determining modular forms of half-integral weight by central values of convolution L-functions*, 2018.

2. Manish Kumar Pandey, B. Ramakrishnan and Anup Kumar Singh, *Shimura and Shintani liftings of certain cusp forms of half-integral and intgral weights*, 2019.

Conferece/Workshops Attended

1. *Building Bridges: 4th EU/US Workshop on Automorphic forms and Related topics*, Alfred Renyi Institute of Mathematics, Budapest, Hungary, July 2018.
2. *Workshop on Modular forms*, Kerala School of Mathematics, Kozhikode, October 2018.
3. *Workshop on Number Theory*, NISER, Bhubaneswar, India, December 2018.
4. *International Conference on Number Theory*, Kerala School of Mathematics, Kozhikode, December 2018.
5. *Conference on Algebra and Number Theory*, Central University of Tamilnadu, Thiruvarur, India, December 2018.

Visit to other Institutes

1. Institute of Mathematical Sciences, Chennai, India, May to June, 2018.
2. Kerala School of Mathematics, Kozhikode, India, September to December, 2018.

Invited Lectures/Seminars:

1. *Explicit Shimura image of certain forms*, 4th EU/US Workshop on Automorphic forms and Related topics, Budapest, Hungary, July 2018.
2. *Determining modular forms of half integral weight*, Workshop on Number Theory, NISER, Bhubaneswar, December 2018.
3. *Determining modular forms of half integral weight*, CANT-2018, CUTN, Thiruvarur, December 2018.

Other Activities

1. Submitted Thesis, *Explicit Shimura liftings of certain class of forms and some problems involving modular L-functions*, March, 2019.

Bhuwanesh Rao Patil

Research Summary:

Continuing the study of previous year, I was able to observe some special number patterns containing good additive or multiplicative structures in the set of natural numbers. One of these number patterns is related to l-syndetic sets. For $l \in \mathbb{N}$, a subset A of $\mathbb{N}$ is called an l-syndetic set if and only if it has non-empty intersections with every set of l consecutive natural numbers. We have observed the following properties related to syndetic sets.

1. Let H_0 be an infinite set of natural numbers such that any two elements of H_0 are co-prime. Then any additively syndetic set contains a 2-term geometric progressions with common ratio nr for some $n \in H_0 \setminus \{1\}$ and $r \in \mathbb{N}$ with $r \equiv 1 \pmod{n}$.

2. A 2-syndetic set contains infinitely many 2-term geometric progressions whose common ratios are perfect squares.

Details of these facts are presented in the article "Geometric progressions in syndetic sets".

Apart from the above research, some number patterns related to Euler's totient function $\phi\colon \mathbb{N} \to \mathbb{N}$ have been studied in a collaboration with Pramod Eyyunni and Mithun Kumar Das where $\phi(n)$ denotes the number of positive integers co-prime to n and less than or equal to n. For this, we define the following quantities:

$$\begin{aligned} N_1(m) &= \max\{n\colon \phi(n) \leq m\}, \\ N_2(m) &= \max(\phi^{-1}(m)), \\ N_3(m) &= \min(\phi^{-1}(m)) \text{ and} \\ N_i &= \{N_i(m)\colon m \in \phi(\mathbb{N})\}, i = 1, 2, 3. \end{aligned}$$

We have explicitly constructed infinitely many elements in each of the sets N_i and observed their properties. Some of the properties are the following.

(a) A natural number n is a squarefree integer if and only if all sufficiently large sparsely totient numbers are divisible by n.

(b) Every non-squarefree positive integer divides infinitely many sparsely totient numbers.

(c) The sets N_1, N_2 and N_3 contain arbitrarily long arithmetic and geometric progressions.

(d) The set of sparsely totient numbers contains patterns of the forms $\{x, y, x + y\}$ and $\{x, y, xy\}$. But we do not know whether it contains a pattern of the form $\{x + y, xy\}$. We have shown that a particular subfamily of sparsely totient numbers does not contain a pattern of this form.

(e) The set of sparsely totient numbers is an additive IP_0 and multiplicative IP set but not an additive IP set.

(f) The set of sparsely totient numbers is multiplicatively piecewise syndetic but not additively piecewise syndetic.

Details of these facts have been given in the articles "Sparse subsets of the natural numbers and Eulers totient function" and "Combinatorial properties of sparsely totient numbers".

Publications:

1. B. R. Patil, *Geometric progressions in syndetic sets,* Archiv der mathematik, https://link.springer.com/article/10.1007/s00013-019-01320-x
2. M. K. Das, P Eyyunni and B. R. Patil, *Sparse subsets of the natural numbers and Eulers totient function,* Proc. Indian Acad. Sci. (Math. Sci.), accepted for publication in 2019.
3. M. K. Das, P Eyyunni and B. R. Patil, *Combinatorial properties of sparsely totient numbers,* J. Ramanujan Math. Soc., accepted for publication in 2019.

Invited Lectures/Seminars:

1. *Geometric progressions in syndetic sets*, International Conference on Class Groups of Number Fields and Related Topics-2018, Harish-Chandra Research Institute, Prayagraj(Allahabad), October 2018.
2. *Geometric progressions in syndetic sets*, 84th Annual Conference of Indian Mathematical Society: An International Meet, School of Mathematics, Shri Mata Vaishno Devi University, Katra, November 2018.

Pramod Eyyunni

Research Summary:

Ramanujan's Notebooks contain many beautiful identities involving infinite series. In joint work with Atul Dixit, Bibekananda Maji and Garima Sood, we obtained a finite analogue of a recent generalization, due to Dixit and Maji, of an identity in Ramanujan's Notebooks. Differentiating it with respect to one of the parameters led to a result whose limiting case gave a finite analogue of Andrews' famous identity for spt(n). The latter motivated us to extend the theory of the restricted partition function $p(n, N)$, namely, the number of partitions of n with largest parts less than or equal to N, by obtaining the finite analogues of rank and crank for vector partitions as well as of the rank and crank moments. As an application of the identity for our finite analogue of the spt-function, we proved an inequality between the finite second rank and crank moments. The other results obtained include finite analogues of a recent identity of Garvan, an identity relating $d(n, N)$ and lpt(n, N), namely the finite analogues of the divisor and largest parts functions respectively, and a finite analogue of the Beck-Chern theorem.

The work with Mithun Kumar Das and Bhuwanesh Rao Patil, which was initiated during the previous academic year and described in last year's report, has led to two publications reported below. Also, the work with Gyan Prakash and François Hennecart reported about in last year's report has been submitted for publication.

Publications:

1. M. K. Das, P. Eyyunni and B. R. Patil, *Sparse subsets of the natural numbers and Euler's totient function,* Proc. Indian Acad. Sci. (Math. Sci.) (To appear)

2. M. K. Das, P. Eyyunni and B. R. Patil, *Combinatorial properties of sparsely totient numbers,* J. Ramanujan Math. Soc. (To appear)

Preprints:

1. A. Dixit, P. Eyyunni, B. Maji and G. Sood, *Untrodden pathways in the theory of the restricted partition function* $p(n, N)$, arXiv:1812.01424

2. F. Hennecart, G. Prakash and E. Pramod, *On Sum-Product Bases,* arXiv:1904.05908

Conference/Workshops Attended:

1. *84th Annual Conference of the Indian Mathematical Society*, Shri Mata Vaishno Devi University, Katra, Jammu & Kashmir, November, 2018.

Visits to other Institutes:

1. IIT Gandhinagar, Palaj, Gandhinagar, July 19 - August 2, 2018.

2. IIT Gandhinagar, Palaj, Gandhinagar, October 24 - November 5, 2018.

Invited Lectures/Seminars:

1. *Combinatorial properties of sparsely totient numbers*, 84th Annual Conference of the Indian Mathematical Society, Shri Mata Vaishno Devi University, Katra, Jammu & Kashmir, November, 2018.

Bidisha Roy

Research Summary:

In this year, I have studied some topics in combinatorial number theory and algebraic number theory.

In combinatorial number theory, one of the recent topic is the determination of *Zero-sum generalized Schur number* denoted by $S_{\mathfrak{z},2}(k;r)$. We could prove that this constant, $S_{\mathfrak{z},2}(k,r)$ is $kr-2r+1$ for all positive integers k and r with $k>r$ and $r \mid k$ which determines a open question asked by A. Robertson.

Another topic in combinatorial number thery is 'zero-sum theory'. In that topic, we have studied the Davenport constant with weight $\{\pm 1\}$ for some finite abelian groups of higher ranks and observed some related questions. Jointly with Sukumar Das Adhikari and Subha Sarkar, we proved that for an odd prime p, any sequence over $G=(\mathbb{Z}/p\mathbb{Z})^3$ of length $4p-3$ which contains at least five zero-elements, there is a $\{\pm 1\}$-weighted zero-sum subsequence of length p. We also show that for an odd prime p and for a positive even integer $k \geq 2$ which divides $p-1$, if θ is an element of order k of the multiplicative group $(\mathbb{Z}/p\mathbb{Z})^*$ and A is the subgroup of $(\mathbb{Z}/p\mathbb{Z})^*$ generated by θ, then any sequence over $(\mathbb{Z}/p\mathbb{Z})^{k+1}$ of length $4p+\frac{p-1}{k}-1$ contains an A-weighted zero-sum subsequence of length $3p$.

In algebraic number theory, one classical topic is to study the nature of quadratic residues and non-residues. Jointly with Jaitra Chattopadhyay, Subha Sarkar and R. Thangadurai, for any odd prime p, we study the number of quadratic residues and non-residues modulo p which are multiples of 2 or 3 or 4 and lying in the interval $[1,p-1]$, by applying the Dirichlet's class number formula for the imaginary quadratic field $\mathbb{Q}(\sqrt{-p})$. In similar direction, we have proved that for all primes p satisfying

$$p \equiv 1 \pmod{q}, \quad \log\log p > \frac{\log 6.83}{\frac{1}{2}-\epsilon} \text{ and } \frac{\phi(p-1)}{p-1} \leq \frac{1}{2}-\epsilon,$$

there exists a quadratic non-residue g which is not a primitive root modulo p such that $gcd\left(g, \frac{p-1}{q}\right)=1$, for $q \geq 1$ is any integer and $\epsilon \in [\frac{1}{11}, \frac{1}{2})$ is a given real number.

Another natural topic in algebraic number theory is to study fractionally dense sets. Jointly with Jaitra Chattopadhyay and Subha Sarkar, we proved that some subsets of the set of natural numbers $\mathbb{N}$ and any non-zero ideals of an order of imaginary quadratic fields are fractionally dense in $\mathbb{R}_{>0}$ and $\mathbb{C}$ respectively.

Publications:

1. Aaron Robertson, Bidisha Roy and Subha Sarkar,*The determination of 2-color zero-sum generalized Schur numbers.*Integers 18 (2018), Paper No. A96.

2. Bidisha Roy and Subha Sarkar, *Regularity of certain Diophantine equations,* Proc. Indian Acad. Sci. Math. Sci., 129 (2019), no. 2.

3. Jaitra Chattopadhyay, Bidisha Roy, Subha Sarkar and R. Thangadurai,*Quadratic nonresidues and nonprimitive roots satisfying a coprimality condition,* Bull. Aust. Math. Soc. 99 (2019), no. 2, 177-183.

Preprints:

1. Jaitra Chattopadhyay, Bidisha Roy and Subha Sarkar, *On Fractionally Dense Sets,* Rocky Mountain Journal of Mathematics. (Accepted for Publication)
2. Jaitra Chattopadhyay, Bidisha Roy, Subha Sarkar and R. Thangadurai, *Distribution of residues modulo p using the Dirichlet's class number formula,* ICCGNFRT Proceeding (Accepted for publication.)
3. Sukumar Das Adhikari, Bidisha Roy and Subha Sarkar, *Weighted zero-sums for some finite abelian groups of higher ranks,* Combinatorial and additive number theory Proceeding (Accepted for publication.)

Conference/Workshops Attended:

1. *International Conference on Class Groups of Number Fields and Related Topics*, HRI, September, 2018.
2. *Workshop on Number Theory,* NISER, December, 2018.
3. *Workshop and conference on Diophantine approximation, Transcendense, Topological Dynamics and related topics in Number theory,* RKMVERI, January, 2019.
4. *International Conference on Number Theory,* IISER, Thiruvananthapuram, March, 2019.
5. Workshop on Group Cohomology, HRI, Allahabad, March, 2019.

Visits to other Institutes:

1. NISER, Bhubaneswar, India, December 2018.
2. RKMVERI, Kolkata, India, January 2019.
3. IISERTVM, Thiruvananthapuram, India, March 2019.

Invited Lectures/Seminars:

1. *On Quadratic non residue non primitive roots,* International Conference on Class Groups of Number Fields and Related Topics-2018, HRI Allahabad, 2018.
2. *On torsion groups of Mordell Curves,* at NISER, Bhubaneswar, December, 2018.
3. *On zero-sum subsequences in a finite abelian p-group,* at RKMVERI, Kolkata, January, 2019.
4. *On Quadratic non residue non primitive roots,* International Conference on Number Theory, IISERTVM, Thiruvananthapuram, March, 2019.

Other Activities:

1. Tutorial in Algebra, Summer Program in Mathematics, HRI, Allahabad, May, 2018.

Gopinath Sahoo

Research Summary:

The first half of this academic year was spent studying a bit of Commutative Algebra particularly the dimension theory of noetherian local rings, this study was helpful to learn varieties. Next, some amount of time was given to learn a few topics of Homological Algebra and Algebraic Geometry. In the second half of the year, I tried to understand a paper by N. Spaltenstein - which removes some boundedness conditions on chain complexes for the existence of derived functors. In the process of understanding the paper, I studied localization of categories, triangulated categories and derived categories.

Subha Sarkar

Research Summary:

In this academic year, I have studied Combinatorial Number Theory, mostly Ramsey Theory and weighted zero-sum problems. More precisely, we considered the study of the Davenport constant with weight $\{\pm 1\}$ for some finite abelian groups of higher ranks. For instance, we proved that for an odd prime p, any sequence over $G = (\mathbb{Z}/p\mathbb{Z})^3$ of length $4p-3$ which contains at least five zero-elements, has a $\{\pm 1\}$-weighted zero-sum subsequence of length p.

For any subset A of the set of all integers $\mathbb{Z}$ (respectively, the set of all natural numbers $\mathbb{N}$), we define $R(A)$ to be the set of all rational numbers $\frac{a}{a'}$ such that both a and a' lie in A and we call the subset $R(A)$ to be the *quotient set* of A. If $A \subset \mathbb{Z}$ (respectively, $\mathbb{N}$) and $R(A)$ is dense in $\mathbb{R}$ (respectively, $\mathbb{R}_{>0}$), then we say A is *fractionally dense* in $\mathbb{R}$ (respectively, $\mathbb{R}_{>0}$).

Recently, we studied the fractional denseness of some subsets of integers as well as of some non-zero ideals of an order of any imaginary quadratic field K. Our results generalizes a couple of results by Garcia et. al.

In 2010, Levin, Pomerance and Soundararajan proved that *for all prime numbers $p \geq 5$, there exists a primitive root g modulo p which satisfies the condition $gcd(g, p-1) = 1$.* More precisely, they prove the above statement to tackle the fixed point discrete log problem which states that *for a given primitive root g in $(\mathbb{Z}/p\mathbb{Z})^*$, there exists an integer $t \in [1, p-1]$ such that $g^t \equiv t \pmod{p}$.*

We dealt with the similar problem for quadratic non-residues which are not primitive roots in $(\mathbb{Z}/p\mathbb{Z})^*$. We abbreviate 'a quadratic non-residue which is not a primitive root' by QNRNP modulo p. More precisely, we prove the following result.

Let $q \geq 1$ be an integer and $\epsilon \in [\frac{1}{11}, \frac{1}{2})$. Let p be a prime satisfying

$$p \equiv 1 \pmod{q}, \quad \log\log p > \frac{\log 6.83}{\frac{1}{2} - \epsilon} \text{ and } \frac{\phi(p-1)}{p-1} \leq \frac{1}{2} - \epsilon.$$

Then there exists a QNRNP g satisfying $1 < g < p-1$ and $gcd\left(g, \frac{p-1}{q}\right) = 1$. In particular, when $q = 1$, there exists an integer g with $1 < g < p-1$ and $gcd(g, p-1) = 1$ such that g is a QNRNP modulo p.

Publications:

1. Aaron Robertson, Bidisha Roy and Subha Sarkar, *The determination of 2-color zero-sum generalized Schur numbers*, Integers **18**, A96, (2018)

2. Bidisha Roy and Subha Sarkar, *Regularity of certain Diophantine equation*, Proceedings of Indian Academy of Sciences **129 (2)**, art. 19, (2019)

3. Jaitra Chattopadhyay, Bidisha Roy, Subha Sarkar and R. Thangadurai, *Quadratic nonresidues and nonprimitive roots satisfying a coprimality condition*, Bull. Aust. Math. Soc **99 (2)**, 177-183, (2019)

4. Jaitra Chattopadhyay, Bidisha Roy and Subha Sarkar, *On fractionally dense sets*, Rockey Mountain Journal of Mathematics, Accepted for publication

5. Jaitra Chattopadhyay, Bidisha Roy, Subha Sarkar and R. Thangadurai, *Distribution of residues modulo p using the Dirichlet's class number formula*, ICCGNFRT-2017 Conference proceedings, Accepted for publication

Preprints:

1. Sukumar Das Adhikari, Bidisha Roy and Subha Sarkar, *Weighted zero-sums for some finite abelian groups of higher ranks* (in preparation)

2. Bidisha Roy, Subha Sarkar, *On determination of zero-sum l-generalized Schur numbers for some linear equations* (in preparation)

Conference/Workshops Attended:

1. *International Conference on Class Group of Number Fields and Related Topics*, India, October 2018.

2. *Workshop on Number Theory*, India, November 2018.

3. *Workshop on Topological Dynamics, Number Theory and related areas*, India, January 2019.

4. *International Conference on Number Theory*, India, March 2019.

5. *School on Group Cohomology*, India, March 2019.

Visits to other Institutes:

1. Ramakrishna Mission Vivekananda Educational and Research Institute, Belur, India, February 2019.

Invited Lectures/Seminars:

1. *Regularity of certain Diophantine equations*, Workshop on Number Theory, NISER Bhubaneswar, Bhubaneswar, December 2018.

2. *On fractionally dense sets*, Workshop on Topological Dynamics, Number Theory and related areas, RKMVERI Belur, Belur, January 2019.

Other Activities:

1. Tutor for Algebra course in SPIM, June, 2018.

Anup Kumar Singh

Research Summary:

(i) Ramanujan – Mordell type formulas associated to certain quad- -ratic forms (joint work with Dongxi Ye): In 1916, S. Ramanujan gave a general formula for the number of representations of a positive integer n by sum of $2k$ squares. He also gave a formula (without proof) in which he expressed the modular form $\theta(z)^{2k}$ using Eisenstein series and some modular functions. This formula was proved first by Mordell utilizing the theory of modular forms, and thus giving credits to Mordell as well, it is now called the Ramanujan – Mordell Theorem (resp. the Ramanujan – Mordell formula). Inspired by the beauty of the Ramanujan – Mordell formula, S. Cooper, B. Kane and Dongxi Ye, extended the Ramanujan – Mordell formula to the modular forms (theta functions) $(\theta(z)\theta(mz))^k$ associated to the $2k$-ary quadratic forms

$$x_1^2 + \cdots + x_k^2 + m\left(x_{k+1}^2 + \cdots + x_{2k}^2\right)$$

for $m \in \{3, 7, 11, 23\}$, and analogously obtained a beautiful unified *polynomial representation* (or called Ramanujan – Mordell type representation) for the cusp form component $C_k(z)$. In that sequel, Dongxi Ye, further extended the Ramanujan – Mordell formula to the cases $m \in \{2, 4\}$, and in the end, he indicates the essence of the existence of these beautiful Ramanujan – Mordell type formulas for $(\theta(z)\theta(mz))^k$ and how one can give an attempt to other cases. Based on those comments, we further explore this interesting topic. We aim to treat the uncharted cases, $m = 5$ and $m = 8$, whose associated quadratic forms are of discriminants 20^k and 32^k, respectively, and obtain their corresponding Ramanujan–Mordell type formulas.

(ii) Construction of Shimura and Shintani liftings of certain cusp forms of half-integral and integral weights (joint work with Manish Kumar Pandey and Balakrishnan Ramakrishnan): In 1985, W. Kohnen constructed explicit Shintani lifts from the space of cusp forms of weight $2k$ on $\Gamma_0(N)$, which are mapped into the plus space $S^+_{k+1/2}(\Gamma_0(4N))$, where N is an odd integer. This lifting is adjoint to the (modified) Shimura map defined by him with respect to the Petersson scalar product. Using this construction along with the theory of newforms on $S^+_{k+1/2}(\Gamma_0(4N))$ (where N is an odd square-free natural number) developed by W. Kohnen. He derived explicit Waldspurger theorem for the newforms belonging to the space $S^+_{k+1/2}(\Gamma_0(4N))$. Further in this work, he considered the ± 1 eigen subspaces corresponding to the Atkin-Lehner involution and showed that the intersection of this $\pm$ spaces with the corresponding newform spaces are isomorphic under the Shimura correspondence. A natural question is whether a similar result holds good in the case of intersecting this subspace with the oldforms. In this direction, S. Choi and C.H. Kim considered the case where N is an odd prime p and constructed similar Shimura and Shintani maps between subspaces of forms of half-integral and integral weights. The subspaces considered by Choi and Kim are nothing but $+1$ eigenspace under the Fricke involution. In this paper, we show that the method of Choi and Kim can be generalised to the case where N is an odd square-free natural number.

Publications:

Preprints:

1. Anup Kumar Singh and Dongxi Ye, *Ramanujan–Mordell type formulas associated to certain quadratic forms of discriminant* 20^k *and* 32^k*, 2018.*

2. Manish Kumar Pandey, B. Ramakrishnan and Anup Kumar Singh, *Shimura and Shintani liftings of certain cusp forms of half-integral and integral weights, 2019.*

Conference/Workshops Attended:

1. *ATMW L-Function (2018)*, IIT Bombay, India, June 2018.

2. *Building Bridges: 4th EU/US summer school and workshop on Automorphic forms and related topics,* Alfred Renyi Institute of Mathematics, Budapest, Hungary, July 2018.

3. *School on Modular Forms - Phase II*, Kerala School of Mathematics, Kozhikode, Kerala, India, October 2018.

4. *Workshop on Number Theory,* National Institute of Science Education and Research, Bhubaneshwer, India, November/December 2018.

5. *Conference on Number Theory*, Kerala School of Mathematics, Kozhikode, Kerala, India, December 2018.

Visits to other Institutes:

1. The Institute of Mathematical Sciences, Chennai, India, May - June 2018.

2. Kerala School of Mathematics, Kozhikode, Kerala, India, September - December 2018.

3. National Institute of Science Education and Research, Bhubaneshwar, India, February 2019.

Invited Lectures/Seminars:

1. *Representations of a positive integer by octonary quadratic forms*, Building Bridges: 4th EU/US summer school and workshop on Automorphic forms and related topics, Alfred Renyi Institute of Mathematics, Budapest, July 2018.

2. *RamanujanMordell type formulas associated to certain quadratic forms of discriminant* 20^k *and* 32^k, Conference on Number Theory, Kerala School of Mathematics, Kozhikode, Kerala, December 2018.

Other Activities:

1. Compiled annual academic report (HRI), June - July 2018.
2. Submitted Ph.D Thesis, March 2019.

Anoop Singh

Research Summary:

In the academic year 2018-19, I have been working on the relative connections. More specifically, I have been studying the problem of existence of relative connections in families of vector bundles on families of compact Riemann surface. In a joint work with Prof. Indranil Biswas, we have proved a sufficient condition for the existence of relative holomorphic connections in family of vector bundles over a complex analytic family. Also, we have proved that the relative Chern classes of a family of holomorphic vector bundle admitting a relative holomorphic connection vanish, if each of the fiber of the complex analytic family is compact and Kähler.

I have proved a result of similar nature, for the existence of relative algebraic connection in an algebraic vector bundle on a smooth flat family of schemes over an arbitrary field.

In another direction, I have been studying the Picard group and regular functions on the moduli space of loagrithmic connections in a holomorphic vector bundle over compact Riemann surface having residues at finitely many points.

Preprints:

1. I. Biswas, Anoop Singh, *On The Relative Connections,* arXiv:1902.10397 (Submitted)

Conference/Workshops Attended:

1. *THEMATIC MONTH: Complex Geometry,* Centre International de Rencontres Mathmatiques (CIRM) - Luminy, France. January 28- February 15, 2019.

2. *Conference on Algebraic Geometry and related areas,* The Institute of Mathematical Sciences (IMSc), Chennai, India. July 10-12, 2018.

Visits to other Institutes:

1. Tata Institute of Fundamental Research, Mumbai, India, September, 2018.

Invited Lectures/Seminars:

1. *Relative holomorphic connection*, Complex Geometry:a Modern Viewpoint, Centre International de Rencontres Mathmatiques(CIRM) - Luminy, Marseille, France, January 28- February 15, 2019 .

Other Activities:

1. Took tutorial classes for the course "Measure Theory" in AFS-II, at Central University of Rajasthan, Rajasthan, December 2018.

2. Took tutorial classes for the course “Analysis” in SPIM at HRI, Allahabad, May 2018.

Lalit Vaishya

Research Summary:

(joint work with **B.Ramakrishnan) On Triangular numbers, Forms of mixed types and their Representation numbers.**

(a) K. Ono, S. Robins and P.T. Wahl (Aequat.Math. 1995) considered the problem of determining formulas for the number of representations of a natural number n by a sum of k triangular numbers and derived many applications, including the one connecting these numbers with the number of representations of n as a sum of k odd square integers. They also obtained an application to the number of lattice points in the k-dimensional sphere.

In this work, we consider triangular numbers with positive integer coefficients. First we show that if the sum of these coefficients is a multiple of 8, then the associated generating function gives rise to a modular form of integral weight (when even number of triangular numbers are taken). We then use the theory of modular forms to get the representation number formulas corresponding to the triangular numbers with coefficients. We also obtain several applications concerning the triangular numbers with coefficients similar to the ones obtained in work of Ono-Robins-Wahl. In the second part of the work, we consider more general mixed forms (as done by Xia-Ma-Tian IJNT 2016) and derive modular properties for the corresponding generating functions associated to these mixed forms. Using our method we deduce all the 21 formulas proved in by Xia-Ma-Tian and show that our method of deriving the 21 formulas together with the (p, k) parametrization of the generating functions of the three mixed forms imply the (p, k) parametrization of the Eisenstein series $E_4(\tau)$ and its duplications. It is to be noted that the (p, k) parametrization of E_4 and its duplications were derived by a different method by K. S. Williams and his co-authors.

(b) Our method can be generalised to higher figurate numbers. This work is in progress.

Preprints:

1. B. Ramakrishnan and Lalit Vaishya, On Triangular numbers, Forms of mixed types and their Representation numbers, submitted for publication 2019.

Conference/Workshops Attended:

1. Workshop on modular forms- II (Oct 03-14, 2018), Kerala School of Mathematics(KSoM), Kozhikode, India.

2. Workshop on Number Theory (Nov 30 - Dec 06, 2018), NISER, Bhubaneswar, India.

3. Conference on Number Theory (Dec 10-14, 2018), Kerala School of Mathematics(KSoM) Kozhikode, India.

4. School on Introduction to Group Cohomology, (March 22 - 31, 2019), HRI, Prayagraj, India.

Visits to other Institutes:

1. The Institute of Mathematical Sciences, Chennai, India, May 24 - Jun 10, 2018.
2. NISER, Bhubaneswar, India, Jun 12 - Jul 06, 2018
3. KSoM, Kozhikode, India, Oct 02 - Dec 15, 2018.

Invited Lectures/Seminars:

1. Talk : Triangular number and their Representation numbers, Workshop on Modular Forms- II, KSoM, Kozhikode, India, Oct 03 - 14, 2018.

Umamaheswaran Arunachalam

Research Summary:

G. Hochschild developed the theory of relative homological algebra in his paper [3, 5] in 1950's. The main purpose of his paper is to concentrate certain homological functors, exactly analogous to the functors "Tor" and "Ext" of Cartan-Eilenberg [2], but applicable to a module theory that is relativized with respect to a given subring of the basic ring of operators. By using Hochild techniques [3, 4, 5], Byoung-song Chwe in his paper proved some homological isomorphisms over restricted Lie algebras. The main purpose of the results of my research on the coincidence of the several kinds of homological dimension with stable condition for a restricted Lie algebras and modules and vanishing of stable homology and cohomology detects modules of finite Gorenstein homological dimension over restricted universal enveloping algebras and restricted Lie algebras.

References:

1. Maurice Auslander and Mark Bridger, *Stable Module Theory*, Memoirs of the American Mathematical Society, No. 94, AMS, Providence, R. I., 1969.

2. H. Cartan and S. Eilenberg, *Homological Algebra*, Princeton, NJ: Princeton Univ. Press. 1956.

3. G. Hochschild, *Cohomology of restricted Lie algebras*, Amer. J. Math 76 (1954), 555-580.

4. G. Hochschild, *Representations of restricted Lie algebra of characteristic p*, Proc. Amer. Math. Soc. 5 (1954), 603-605.

5. G. Hochschild, *Relative homological algebra*, Trans. Amer. Math. Soc. 50 (1941), 15-25.

Publications:

1. Biju, Udhayakumar, Umamaheswaran Arunachalam, M. Parimala, *The dimension of Gorenstein $\mathcal{X}_Y$-flat modules with respect to a Semidualizing module*, Advanced studies in contemporary Mathematics, **28(4)**, 669 - 679, (2018).

Preprints:

1. Ashish Gupta and Umamaheswaran Arunachalam, *Gelfand–krillov dimensions of simple modules over twisted group algebras $k \star A$*,
arxiv.org/pdf/1812.02629

2. Umamaheswaran Arunachalam, *Coresolutions and dimensions of right orthogonal class of pure projective modules*,
https://arxiv.org/abs/1605.03704

Conference/Workshops Organized:

1. *Advanced Instructional School on Lie algebra*, Harish-Chandra Research Institute, Prayagraj, India, December 2018.

Conference/Workshops Attended:

1. *International School on Cluster algebras*, ICTS, Bangalore, India, December, 2018

Visit to other Institutes:

1. Universitat de Paris Diderot, Paris, France, September 2019,

Invited Lectures/Seminars:

1. *Stable homology of modules with restricted Lie algebras*, Two weeks of Silting, University of Stuttgart, Germany, August 2019.

Academic recognition/Awards:

- IMU-Abel Grant for Abel Visiting Scholar Program from the Abel board, 2019,

Kalyan Banerjee

Research Summary:

In the last academic year my research was centered around the area of algebraic geometry and number theory. I was studying the algebraic cycles on abelian varities on one hand and on the other hand understanding the relation between cycles and arithmetic. To be precise I (along with Azizul Hoque and Prof. Kalyan Chakraborty) was investigating the relations between Chow groups and class groups, Tate-Shafarevich groups and Selmer groups. In the first project I was trying find the injectivity of a certain homomorphism at the level of Chow groups of abelian varities. While the second project was involved to prove the weak Mordell-Weil theorem for Chow groups of abelian varities defined over number fields and its consequences.

Another project that I am working on is studying algebraic cycles on cubic hypersurfaces in P5 and its relation to the rationality/ irrationality of the cubic. In precise terms we are trying to find obstructions to rationality of a cubic interms of one-cycles on the cubic.

Preprints:

1. Kalyan Banerjee, *Torsion-ness of the Gysin kernel and irrationality of cubic in dimension four*, (In preparation).
2. Kalyan Banerjee, Kalyan Chakraborty, Azizul Hque *Tate-Shafarevich group and Selmer group constructions for Chow group of an abelian variety.* (In preparation)
3. Kalyan Banerjee, Azizul Hoque *From Picard group of hyperelliptic surfaces to class groups of families of quadratic fields,*

   https://arxiv.org/abs/1903.04210
4. Kalyan Banerjee *Theta divisors of abelian varieties and push-forward homomorphism at the level of Chow groups,*

   https://arxiv.org/abs/1609.03636

Conference/Workshops Attended:

1. *Complex algebraic geometry at ICTS Bangalore*, India, October 2018.
2. *ICTS Ramanujan Lecture series by Claire Voisin*, India, October 2018.

Visits to other Institutes:

1. ICTS Bangalore, Indian, October 2018.
2. ISI Bangalore, India October 2018.
3. TIFR Mumbai, India, October 2018.
4. Chennai Mathematical Institute, India, January 2019.

Invited Lectures/Seminars:

1. *Algebraic cycles and the rationality problem*, CMI Mathematics Seminar, Chennai Mathematical Institute, Chennai, India, January 2019.

2. *Four Lectures in the school "Group Cohomology"* , at HRI, India, March 2019.

Other Activities:

1. Running advanced seminar on Selmer Groups and Tate-Shafarevich groups at HRI, January- May, 2019

Snigdha Bharati Choudhury

Research Summary:

One of the interesting observations made by Bárány, Shlosman and Szücs in proving the topological Radon's Theorem is: There exists a continuous map $g : S^n \to \partial\triangle^{n+1}$ having the disjoint support property, that is, for each pair of antipodal points a, $-a$ of S^n, $\text{supp } g(a) \cap \text{supp } g(-a) = \emptyset$. Since S^n and $\partial\triangle^{n+1}$ are homeomorphic, it is natural to ask whether or not there is a homeomorphism $h : S^n \to \partial\triangle^{n+1}$ with disjoint support property. Let K_N be any triangulation of S^2 having N faces, $N \geq 4$. We have proved that for $N < 8$, there exists a continuous map $f : S^2 \to |K_N|$ having disjoint support property and there is no homeomorphism from S^2 to $|K_N|$ having disjoint support property, and for each $N \geq 8$, S^2 has at least two non-isomorphic triangulations L_N and K_N where the first one admits a continuous map $f : S^2 \to |L_N|$ with disjoint support property and no homeomorphism with disjoint support property and K_N admits a homeomorphism $h : S^2 \to |K_N|$ with disjoint support property.

Preprints:

1. Snigdha Bharati Choudhury and Satya Deo, *Strong independence and the dimension of a Tverberg set* (communicated).
2. Snigdha Bharati Choudhury and Satya Deo, *Continuous maps with disjoint support property* (communicated).

Conference/Workshops Attended:

1. *Einstein Workshop on Geometric and Topological Combinatorics*, Germany, October, 2018.
2. *Einstein Workshop on Algebraic Combinatorics*, Germany, November, 2018.
3. *School on Group Cohomology*, India, March, 2019.

Azizul Hoque

Research Summary:

The divisibility properties of the class numbers of number fields are very important for understanding the structure of the class groups of number fields. We consider the family of imaginary quadratic fields, $K_{x,y,n,\mu} = \mathbb{Q}(\sqrt{x^2 - \mu y^n})$, where $x, \mu \geq 1$ and $y, n \geq 2$ are integers. Assume that $n \geq 3$ is an odd integer. For each odd prime $q \neq n$, let M_q be the set of all odd primes p distinct from q, n satisfying $q^2 < p^n$ and n does not divide the class number of $K_{q,p,n,1}$. In [*Divisibility of the class numbers of imaginary quadratic fields*, J. Number Theory **185** (2018), 339–348], we proved that $|M_q| < \infty$. The following question arises from this work: Is $M_q \neq \phi$ for infinitely many q? The work on this question is in progress. In a work jointly with Kalyan Chakraborty, we prove for distinct odd primes p and q that class group of $K_{p,q,n,2}$ has an element of order n provided $3q^{n/3} \neq p + 2$ whenever $3 \mid n$. This family of quadratic fields gives a counter example of the following conjecture by H. Wada [*A table of ideal class groups of imaginary quadratic fields*, Proc. Japan Acad. **46** (1970), 401–403]:

All the class groups of imaginary quadratic fields are either cyclic or of the type $\mathbb{Z}_{h_1} \times \mathbb{Z}_{h_2} \times \mathbb{Z}_{2^{r_1}} \times \mathbb{Z}_{2^{r_2}} \times \cdots \times \mathbb{Z}_{2^{r_t}}$.

Finding real quadratic fields with class number one is a classical and interesting problem. D. Byeon and H. K. Kim obtained some necessary and sufficient conditions for the class number of real quadratic fields of certain Richaud-Degert type to be one (resp. two). In a work jointly with Kalyan Chakraborty and Mohit Mishra, we obtain analogous conditions for the class numbers of certain Richaud-Degert type fields to be three. We also consider the same problem for class number two which were not considered earlier. For a positive integer n, let $\mathcal{N}$ be the number of distinct odd prime divisors of n. In another work jointly with Kalyan Chakraborty and Mohit Mishra, we proved that $h(n^2 + 1) \to \infty$ as $\mathcal{N} \to \infty$, where $h(n^2 + 1)$ denotes the class number of $\mathbb{Q}(\sqrt{n^2 + 1})$. We then applied this result to classify all those class groups of $\mathbb{Q}(\sqrt{n^2 + 1})$ which are of order 4.

We consider the Diophatine equation $x^2 + d^m = \lambda y^n$, where d and λ are fixed positive integers. J. H. E. Cohn determined all the solutions of this equation for $m = \lambda = 1$ and for some values of $d \leq 100$. Earlier, we considered this equation when $m = \lambda = 1$, $d \equiv 1, 2 \pmod 4$ and n is odd. For these values, we proved that it has no solution if $na^{n-1} \equiv \pm 1 \pmod d$ and $\gcd(n, h(-d)) = 1$, where $h(-d)$ denotes the class number of $\mathbb{Q}(\sqrt{-d})$ and a is any odd integer. Applying this result, we derived some criteria on x for which $n \mid h(-d)$. In a work jointly with S. Bhatter and R. Sharma, we completely solve this equation in non-negative integers x, y, m and n when $\lambda = 4$ and $D = 19$. In another work jointly with K. Chakraborty and R. Sharma, we slightly modify the previous arguments and determine all the solutions (x, y, m, n) of the above equation in non-negative integers when $\lambda = 4$ and $h(-d) = 1$.

In 1986, D. Zagier [*Hyperbolic manifolds and special values of Dedekind zeta-functions*, Invent. Math. **83** (1986), 285–301] gave a famous formula for $\zeta_K(2)$ attached to an imaginary quadratic number field K. His method is completely geometric, where it involves the interpretation of $\zeta_K(2)$ as the volume of a hyperbolic manifold. Since it is the only $\zeta_K(2)$ which can be interpreted geometrically, this method fails to get a formula for $\zeta_K(2m)$ as well as for $\zeta_K(2m+1)$ for all natural numbers m. Thus he asked

the following question:
Whether there is a formula for $\zeta_K(4)$, $\zeta_K(6)$, etc. attached to an arbitrary real (resp. imaginary) quadratic number field K?
He remarked that the answer to this question is possible by the method of analytic number theory. In a joint work with Soumyarup Banerjee and Kalyan Chakraborty, we find two expressions for $\zeta_K(m)$ attached to an arbitrary real (resp. imaginary) quadratic number field K for any integer $m \geq 2$. In order to derive these expressions, we obtain an interesting formula for the product of two Dedekind zeta functions. This product formula is a number theoretic analog of Wilton's formula.

Let S be a certain affine algebraic surface over $\mathbb{Q}$ such that it admits a regular map to $\mathbb{A}^2(\mathbb{Q})$. We consider the following question:
Let $\mathfrak{L}$ be a non-trivial line bundle in the relative Picard group $Pic^0(S/\mathbb{A}^2)$. Is it possible to some find points $P \in \mathbb{A}^2(\mathbb{Q})$ for which the pull back of $\mathfrak{L}$ at P is a non-trivial ideal class of the number field $\mathbb{Q}(S_P)$?
This a special case of a question raised by A. Agboola and G. Pappas [*Line bundles, rational points and ideal classes*, Math. Res. Lett. **7** (2000), no. 5-6, 709–717]. J. Gillibert and A. Levin [*Pulling back torsion line bundles to ideal classes*, Math. Res. Lett. **19** (2012), no. 6, 1171–1184.] affirmatively answered the question raised by A. Agboola and G. Pappas in the case of torsion line bundles on a hyperelliptic curve. In a work jointly with Kalyan Banerjee, we prove that any non-trivial torsion line bundle in the relative Picard group $\mathrm{Pic}^0(S/\mathbb{A}^2)$ can be pulled back to ideal classes of quadratic fields whose order can be made sufficiently large. This gives an affirmative answer to the above question in case of quadratic fields. We also prove by constructing an element of odd order $n \geq 3$ in the class group of certain imaginary quadratic fields that the Picard group of S_P has a subgroup isomorphic to $\mathbb{Z}/n\mathbb{Z}$.

Publications:

1. Kalyan Chakraborty and Azizul Hoque, *Pell-type equations and class number of the maximal real subfield of a cyclotomic field*, The Ramanujan Journal **46**, no. 3, 727–742, (2018). arXiv: 1710.09760.

2. Kalyan Chakraborty, Azizul Hoque and Richa Sharma, *Divisibility of class numbers of quadratic fields: Qualitative aspects*, Advances in Mathematical inequalities and Application, 247–264, Trends in Mathematics, Birkhäuser/Springer, Singapore, (2018).

3. Sanjay Batter, Azizul Hoque and Richa Sharma, *On the solutions of a Lebesgue-Nagell type equation*, Acta Mathematica Hungarica **158**, no. 1, 17–26, (2019).
   arXiv: 1810.04512v3.

4. Kalyan Chakraborty, Azizul Hoque and Mohit Mishra, *A note on certain real quadratic fields with class number upto three*, Kyushu Journal of Mathematics, (2019) (to appear). arXiv: 1812.02488v3.

5. Md. Helal Ahmed, Azizul Hoque and Jagmohan Tanti, *Complete solution to Cyclotomy of order $2\ell^2$ with prime ℓ*, The Ramanujan Journal, (2019) (to appear). arXiv: 1807.07708v2.

6. Kalyan Chakraborty, Azizul Hoque and Prem Prakash Pandey, *Class groups of number fields and related topics*, Conference proceedings (edited), 180 pages (approx.), Springer, Singapore, (2019) (in press).

Preprints:

1. Kalyan Banerjee and Azizul Hoque, *From Picard group of hyperelliptic surfaces to class groups of families of quadratic fields*, Under review. arxiv: 1903.04210.

2. Azizul Hoque, *Rank zero quadratic twists of* $y^2 = x^3 + 2$, Under review. arXiv: 1904.02073.

3. Kalyan Chakraborty, Azizul Hoque and Mohit Mishra, *A classification of order* 4 *class groups of* $\mathbb{Q}(\sqrt{n^2+1})$, Under review. arxiv:1902.05250.

4. Soumyarup Banerjee, Azizul Hoque and Kalyan Chakraborty, *An analogue of Wilton's formula and values of Dedekind zeta functions*, Under review. arXiv:1611.08693v4.

5. Kalyan Chakraborty, Azizul Hoque and Richa Sharma, *Complete solutions of certain Lebesgue-Ramanujan-Nagell equations*, Under review. arxiv:1812.11874.

6. Kalyan Chakraborty and Azizul Hoque, *Exponents of class groups of certain imaginary quadratic fields*, Under review. arXiv:1801.00392.

7. Kalyan Chakraborty, Azizul Hoque, Shigeru Kanemitsu and Antanas Laurinčikas, *Complex powers of L-functions and integers without small prime factors*, Under review.

8. Azizul Hoque, *3-part of class group of a quadratic field, 3-Selmer group and Tate-Shafarevich group*, (in preparation).

9. Kalyan Banerjee, Kalyan Chakraborty and Azizul Hoque, *Tate-Shafarevich group and Selmer group constructions for Chow group of an abelian variety*, (in preparation).

Conference/Workshops Attended:

1. *Number Theory and its connections with Random Matrices and Extreme Values*, Hong Kong, April, 2018.

2. *14-th International Conference in Number Theory and Smarandache Problems*, China, April, 2018.

3. *AIS Algebraic Number Theory*, India, May, 2018.

4. *11-th International Conference on Mathematics and Mathematics Education for Developing Countries*, Laos, November, 2018.

5. *International Conference on Special Functions & Applications (ICSFA-2018)*, India, November, 2018.

Visits to other Institutes:

1. The University of Hong Kong, Hong Kong, April, 2018.
2. Northwest University, Xi'an, China, April, 2018.
3. Wienan Normal University, Wienan, China, April, 2018.
4. Shaanxi Normal University, Xi'an, China, April, 2018.
5. IIT Guwahati, Guwahati, India, May, 2018.
6. Gauhati University, Guwahati, India, August, 2018.
7. Mahidol University, Bangkok, Thailand, November, 2018.
8. The National University of Laos, Vientiane, Laos, November, 2018.

Invited Lectures/Seminars:

1. *Pell-type equations and class groups of cyclotomic fields*, Colloquium, Shaanxi Normal University, Xia'an, China, April, 2018.
2. *Exponents and class groups of quadratic fields*, 14-th International Conference in Number Theory and Smarandache problems, Northwest University, Yangling, China, April, 2018.
3. *Pell-type equations and class numbers of cyclotomic fields*, Colloquium, Northwest University, Xi'an, China, April, 2018.
4. *Closed form expressions for Dedekind zeta values*, International Conference on Special Functions & Applications (ICSFA-2018), Amal Jyothi College of Engineering, Kerala, November, 2018.
5. *Real quadratic fields with class numbers 1, 2 and 3*, Colloquium, Mahidol University, Bangkok, Thailand, November, 2018.
6. *Real quadratic fields with small class number*, 11-th International Conference on Mathematics and Mathematics Education for Developing Countries, The National University of Laos, Vientiane, Laos, November, 2018.

Other Activities:

1. Organized International Conference on Class Groups of Number Fields and Related Topics-2018 with Prof. Kalyan Chakraborty and Dr. Prem Prakash Pandey, October 08–11, 2018.
2. Tutor in AIS Algebraic Number Theory, IIT Guwahati, May, 2018.

Abhishek Juyal

Research Summary:

In a joint work with Mithun Kumar Das, we obtain a trigonometric identity for $\sec^m(2x)\cot^{2n}(x)$ in terms of integers linear combination of powers of $\sec 2x$ and $\cot x$. We have given two application of it. As the first application we have given a partial answer of a question raised A. Straub about the irrationality of the series

$$\sum_{n=1}^{\infty}\frac{\cot(\pi n\tau_1)\cdots\cot(\pi n\tau_k)}{n^s},$$

where $\tau_1,\ldots\tau_k$ are quadratic (or algebraic) irrationality. As another application of the trigonometric identity, we have derived some special values of Zagier's higher dimensional Dedekind sums. Next, for Dirichlet characters χ modulo an odd integer q, a positive integer c co-prime to q and any positive integers m, n, we have shown that the mean values

$$M(q,c,m,n)=\frac{2}{\phi(q)}\sum_{\chi \pmod q}\chi(c)L(m,\chi)L(n,\overline{\chi})$$

can be evaluate in terms of higher dimensional Dedekind sums. Using special values of Zagier's higher dimensional Dedekind sums we obtained some formulas of mean values $M(q,c,m,n)$. These formulas are generalize results of H. Liu (J. Number Theory 147 [2015], 172-183).

Preprints:

1. Abhishek Juyal, Mithun Kumar Das, *Trigonometric sums, higher dimensional Dedekind sums and twisted mean value of Dirichlet L-series* (submitted).

Conference/Workshops Attended:

1. "School on Introduction to Group Cohomology", held at Harish-Chandra Research Institute, Allahabad, March 23-31, 2019.

Chudamani Pranesachar Anil Kumar

Research Summary:

Number Theory and Geometry- On the Surjectivity of Certain Maps: We associate a generalized projective space $\mathbb{PF}_{\mathcal{I}}^{k,(m_0,m_1,\ldots,m_k)}$ to an ideal $\mathcal{I}$ in a commutative ring $\mathcal{R}$ with unity where $k, m_i \in \mathbb{N}, 0 \leq i \leq k$. In the first context we prove the surjectivity (in fact bijectivity) of chinese remainder reduction map associated to the generalized projective space of an ideal with a given factorization into mutually co-maximal ideals, each of which is contained in finitely many maximal ideals, using the key concept of choice multiplier hypothesis which is satisfied. In the second context, we prove surjectivity of the map from k-dimensional special linear group to the product of generalized projective spaces of k-mutually co-maximal ideals associating the k-rows or k-columns under certain conditions either on the ring or on the generalized projective spaces. We extend this result to symplectic groups. In fact we prove the surjectivity of the map from $(2k \times 2k)$-order symplectic group over a commutative ring with unity to the product of generalized projective spaces of $2k$-mutually co-maximal ideals associating the $2k$-rows or $2k$-columns again under certain conditions either on the ring or on the generalized projective spaces. The surjectivity in the second context uses a result of strong approximation type. We prove this in a very general setting for both special linear groups and symplectic groups in the case of commutative ring with unity quotiented by an ideal which satisfies unital set condition.

Combinatorics-Hyperplane Arrangements: In the case of hyperplane arrangements over ordered fields, we associate invariants such as normal system, concurrency arrangement, and its sign function to completely classify them up to a certain type of isomorphism. Normal systems under convex positive bijections in this case give rise to coarse invariants. They classify hyperplane arrangements modulo translation of any hyperplane. As a consequence in dimension two, any line arrangement of a certain cardinality can be represented by some line arrangement of the same cardinality which has a given set of distinct slopes. The normal systems associated to hyperplane arrangements give rise to antipodal point arrangements on spheres. These are further combinatorially classified up to isomorphism by associating a finite set of cycle invariants. For a fixed normal system which is concurrency free (a generic condition), the combinatorics of the concurrency arrangement, in particular the characteristic polynomial of the concurrency arrangement is used to enumerate the number of isomorphisms classes of hyperplane arrangements with the given normal system under isomorphisms which are trivial on subscripts.

Line arrangements in the plane have been studied extensively in the literature in various contexts. However a combinatorial characterization of triangles in a line arrangement in the euclidean plane has not been done before. For certain types of line arrangements we characterize the triangles present combinatorially and mention some consequences. This characterization requires a combinatorial nomenclature for line arrangements. This is done for two types of line arrangements, those which have global cyclicity and those which are of infinity type. We also prove a nice theorem of characterizing a line at infinity using the nomenclature of an infinity type arrangement.

Combinatorics-Point Arrangements in the Plane: For a positive integer $n \geq 3$, the sides and diagonals of a convex n-gon divide the interior of the convex n-gon into

finitely (polynomial in n) many regions bounded by them. We associate to every region a unique n-cycle in the symmetric group S_n of a certain type (defined as two standard consecutive cycle) by studying point arrangements in the plane. Then we find that there are more (exponential in n) number of such cycles leading to the conclusion that not every region labelled by a cycle appears in every convex n-gon. In fact most of them do not occur in any given single convex n -gon. We characterize combinatorially those cycles (defined as definite cycles) whose corresponding regions occur in every convex n-gon and those cycles (defined as indefinite cycles) whose corresponding regions do not occur in every convex n-gon.

Publications:

1. C.P. Anil Kumar, *On the surjectivity of certain maps*, Journal of Ramanujan Mathematical Society **Vol. 33, No. 4**, 335-378, (2018)

2. C.P. Anil Kumar, *On the gaps in multiplicatively closed sets generated by atmost two elements*, Proceedings Mathematical Sciences: Indian Academic of Sciences **Vol. 129:42**, 42(1)-42(15), (2019)

Preprints:

1. C.P. Anil Kumar, *On the Factorization of Two Adjacent Numbers in Multiplicatively Closed Sets Generated by Two Elements*, arXiv:1806.03344 Recently Submitted to a Journal

2. C.P. Anil Kumar, *On the Surjectivity of Certain Maps II: For Generalized Projective Spaces*, arXiv:1810.03474 Recently Submitted to a Journal

3. C.P. Anil Kumar, *On the Surjectivity of Certain Maps III: For Symplectic Groups Over Rings and Generalized Projective Spaces*, arXiv:1902.09311

4. C.P. Anil Kumar, *Normal Representations of Hyperplane Arrangements over an Ordered Field and Convex Positive Bijections*, arXiv:1711.07030 Recently Submitted to a Journal

5. C.P. Anil Kumar, *Antipodal Point Arrangements on Spheres, Classification of Normal Systems and Hyperplane Arrangements over Ordered Fields*, arXiv:1801.09575 Recently Submitted to a Journal

6. C.P. Anil Kumar, *On the Regions Formed by the Diagonals of a Convex Polygon*, arXiv:1904.04065

7. C.P. Anil Kumar, *On the Triangles in Certain Types of Line Arrangements*, (in preparation)

Conference/Workshops Attended:

1. *School on 'Group Cohomology'*, HRI Prayagraj, INDIA, March 2019.

2. *International Conference on 'Algebra, Combinatorics and Representation Theory'*, IISER Trivandrum, INDIA, December 2018.

Invited Lectures/Seminars:

1. *Normal Representation of Hyperplane Arrangements and Convex Positive Bijections*, International Conference on 'Algebra, Combinatorics and Representation Theory', IISER Trivandrum, Trivandrum, INDIA, December 2018.

2. *Hyperplane Arrangements Over Ordered Fields*, Post Doctoral Fellow Seminars, Harish-Chandra Research Institute, Prayagraj, INDIA, March 2019.

Jai Laxmi

Research Summary:

In 2012, Ananthnarayan, Avramov and Moore give a new construction of Gorenstein rings from two Gorenstein local rings, called their connected sum. Given a Gorenstein ring, one would like to know whether it decomposes as a connected sum and if so, what are its components. In a joint work with H. Ananthnarayan, E. Celikbas and Z. Yang, we answer these questions in the Artinian case and investigate conditions on the ring which force it to be indecomposable as a connected sum. We further give a characterization for Gorenstein Artin local rings to be decomposable as connected sums, and as a consequence, obtain results about its Poincare series and minimal number of generators of its defining ideal. Finally, we show that the indecomposable components appearing in the connected sum decomposition are unique up to isomorphism.

Publications:

1. H.Ananthnarayan, Ela Celikbas, Jai Laxmi, Zheng Yang, *Decomposing Gorenstein Rings as Connected Sums,* Journal of Algebra, **vol.-527**, 241-263, (2019).

Preprints:

1. Ela Celikbas, Jai Laxmi, Jerzy Weyman,Witold Kraśkiewicz, *The family of perfect ideals of codimension 3, of type 2 with 5 generators,* arxiv.org/pdf/1812.09736.pdf.

2. H. Ananthnarayan, and Jai Laxmi, *Idealizations and connected sums,* (in preparation).

Academic recognition/Awards:

- Fulbright-Nehru Postdoctoral Fellowship, 2019.

Ebtsam Hassan Taha

Research Summary:

I joined HRI as a post-doctoral fellow on 28th January, 2019. This being my first position immediately after my doctoral dissertation with specialization in Finsler geometry, I and Dr. Hemangi Shah, with specialization in differential geometry, have been putting our efforts to generalize some results of a notable work by (Akhil Ranjan and Hemangi Shah, Busemann functions in a harmonic manifold, Geom. Dedicata 101 (2003), 167-183) from Riemannian to Finsler geometry. In fact, Finsler manifolds are rich and contain 33 special spaces for example, Riemannian, Berwald, Rander and Landsberg manifolds. Dr. Shah has been working on harmonic and asymptotic harmonic manifolds, in setting of Riemannian geometry, for quite few years. So, we set a goal to investigate harmonic and asymptotic harmonic manifold in Finslerian setting. Now, regarding originality, let it be noted that theories and applications of either of these two manifolds are substantially mature in setting of Riemannian geometry but neither of them have been yet studied in Finslerian setting. In order to define and study such spaces, we shall naturally use Finsler Laplacain, but non uniqueness of it, contrary to Riemannian case (Laplace-Beltrami operator) and for certain reason we have chosen Shens Laplacian. We studied such spaces using Busemann function without any restriction on Finsler distance function or the flag curvature. To do so, we used the hypothesis that Shens Laplacain of Busemann function is a real constant. Under above set of assumptions, we proved: smoothness of Busemann function and we established that harmonic spaces having minimal horospheres have the bi-asymptotic property. Moreover, we are studying some special cases like Berwald space with same set of assumption as we had in our first result and to this date we have some interesting results in this direction as well.

Shubhankar Podder

Research Summary:

Completely hyperexpansive operators have been extensively studied by several authors since its introduction in 1993. We investigate the reflexivity of completely hyperexpansions and their Cauchy dual operators. In particular, we show that any cyclic completely hyperexpansive operator is reflexive. As an application, we deduce that any cyclic 2-isometry is reflexive. This does not hold in general for cyclic m-isometries, $m > 2$. We also discuss some instances in which finitely multicyclic completely hyperexpansive operators are reflexive. Further, we show that the Cauchy dual of 2-hyperexpansions are reflexive. Among various applications, we prove the reflexivity of the so-called Bergman-type operators. Also, we deduce the fact that the Cauchy dual of an m-isometry is reflexive for $m = 1, 2$; but the result is not true in general for $m > 2$. However, in case of a expansive m-isometry its Cauchy dual is always reflexive. Moreover, we establish the reflexivity of certain power bounded left-invertible operators and study some cases where left-invertible operators and their Cauchy duals are reflexive.

Publications:

1. Sameer Chaven, Shubhankar Podder and Shailesh Trivedi, *Commutants and Reflexivity of Multiplication tuples on Vector-valued Reproducing Kernel Hilbert Spaces,* Journal of Mathematical Analysis and Applications **466**, 1337-1358, (2018).

Preprints:

1. Shubhankar Podder and Deepak Kumar Pradhan, *The reflexivity of hyperexpansions and their Cauchy dual operators,* submitted.

Conference/Workshops Attended:

1. *6th Summer Workshop on Operator Theory (SWOT)*, Poland, July 2018.
2. *Operator Theory & Operator Algebras (OTOA-2018)*, India, December 2018.

Visits to other Institutes:

1. IIT Kanpur, India, August 13 - August 31, 2018.

Soham Swadhin Pradhan

Research Summary:

My research work in this period focused mainly on *matrix representations of finite solvable groups over arbitrary fields*.

For a finite group G, generated by n elements $x_1, \ldots, x_n$, say, to know an F-representation (ρ, V), we need to know only $\rho(x_i)$'s. If V is finite dimensional, for the matrix representation of ρ, we choose a basis of V, and w.r.t. that basis we need to find matrices for $\rho(x_i)$'s. If F is a field of characteristic either 0 or prime to $|G|$ and (ρ, V) is an irreducible F-representation of G, then V lies as a minimal left-sided ideal in the semi-simple group ring $F[G]$. So, for the matrix representation of ρ, we find a basis of V, as elements of $F[G]$, and w.r.t. that basis we find the matrices for $\rho(x_i)$'s.

For a finite solvable group G of order $N = p_1 p_2 \ldots p_n$, where p_i's are primes, there exists a subnormal series: $\langle e \rangle = G_o < G_1 < \cdots < G_n = G$ such that G_i/G_{i-1} is isomorphic to a cyclic group of order p_i, $i = 1, 2, \ldots, n$. Associated with this series, there exists a system of generators consisting n elements $x_1, x_2, \ldots, x_n$ (say), such that $G_i = \langle x_1, x_2, \ldots, x_i \rangle$, $i = 1, 2, \ldots, n$, which is called a "long system of generators". In terms of this system of generators, we give simple expressions for the primitive central idempotents of $\mathbb{C}[G]$ and present an algorithm for constructing the irreducible matrix representations of G over $\mathbb{C}$. We also exhibit an algorithmic construction of primitive central idempotents, in the semi-simple group algebra of G over a field F of characteristic either 0 or prime to $|G|$.

The investigation of finite groups, which possess a faithful irreducible representation was initiated by Burnside. In 1954, Gaschütz characterized such groups in terms of structure of certain normal subgroups. Within some specific class of groups, an elementary characterization has been given by various mathematicians In 1993, H. S. Sim proved that, all the faithful irreducible representations of a finite metacyclic group, over a field of positive characteristic (if exists), have the same degree. We generalize this result for (1) finite metabelian groups, over fields of positive characteristic coprime to the order of groups, and (2) finite groups, having a cyclic quotient by an abelian normal subgroup, over number fields.

Preprints:

1. Ravi S. Kulkarni and Soham Swadhin Pradhan, *An Extension of Berman's Theorem*, (in preparation).

2. Rahul Dattatraya Kitture and Soham Swadhin Pradhan, *Degrees of Faithful Irreducible Representations of Metabelian Groups*, (submitted for publication).

Conference/Workshops Attended:

1. *Algebras, Combinatorics, and Representation Theory*, India, December, 2018.

2. *Introduction to Group Cohomology*, India, March, 2019.

Visits to other Institutes:

1. Bhaskaracharya Pratishthana, Pune, India, March, 2019.

Rajesh Kumar Singh

Research Summary:

In 1971, Charles Fefferman proved that the spherical partial Fourier integrals, $S_R f$, of a function f in $L_p(\mathbb{R}^n)$, $1 \leq p \leq \infty$, $n \geq 2$, defined by $(S_R f)(x) = \int_{|\xi| \leq R} e^{2\pi i x \cdot \xi} \hat{f}(\xi) d\xi$, $R > 0$, $x \in \mathbb{R}^n$, where $\hat{}$ denotes the Fourier transform, do not converge in the norm to the function, unless $p = 2$. After that, the study of other summation methods, such us Ceśaro or Bochner-Riesz sums, became the object of very active research in Harmonic Analysis. Those are examples of oscillatory integrals.

The Bochner-Riesz multiplier operator T_δ, whose L_p-boundedness is equivalent to the corresponding norm convergence of the Bochner-Riesz sums, is defined for $\delta > 0$, by $\widehat{T_\delta f}(\xi) := (1 - |\xi|^2)_+^\delta \hat{f}(\xi)$, $f \in L_2(\mathbb{R}^n) \cap L_p(\mathbb{R}^n)$, where $x_+ := \max(x, 0)$ denotes the positive part of x.

After almost forty seven years, the problem of their boundedness is still open except in the dimensions one and two.

We consider a variant of the Bochner-Riesz multiplier operator:

$$\widehat{T_\alpha f}(x, z) := \phi(z) \left(1 - \frac{|x|^a}{z}\right)_+^\alpha \hat{f}(x, z),$$

$(x, z) \in \mathbb{R}^n \times \mathbb{R}$, where $\phi \in C_c^\infty(1, 2)$, $n \geq 2$ and $a \geq 1$. We are interested in the problem of the boundedness of T_α on $L_p(\mathbb{R}^{n+1})$.

We are studying the case $a = 2$, that is when the singularity of the above multiplier is along the paraboloid, $\{|y|^2 = t\}$. It suffices to study the multiplier $m_\alpha(y, t) := e^{-t}\, t_+^\alpha \left(1 - \frac{|y|^2}{t}\right)_+^\alpha$, $(y, t) \in \mathbb{R}^n \times \mathbb{R}$. The corresponding multiplier operator T_α is a convolution operator given by $T_\alpha f = K_\alpha * f$ where the kernel K_α is given by $K_\alpha(x, z) = \check{m}_\alpha(x, z) = C \frac{e^{\frac{|x|^2}{1+z^2}}}{(1+iz)^{\alpha+1+n/2}}\ e^{-i\frac{|x|^2 z}{1+z^2}}$. Using de Leew's theorem, T_α to be bounded on $L_p(\mathbb{R}^{n+1})$, that is $\|T_\alpha f\|_{L_p(\mathbb{R}^{n+1})} \leq C \|f\|_{L_p(\mathbb{R}^{n+1})}$ one must have $\left|\frac{1}{p} - \frac{1}{2}\right| \leq \frac{2\alpha+1}{2n}$.

In the case $\alpha \leq \frac{n}{2}$ (other case being trivial), we singled out a region E, as small as possible, in $\mathbb{R}^{n+1}$ on which the kernel K_α is non-integrable but integrable on the complement of E. The kernel K_α is integrable in the complement of the region $E = \left\{(x, z) \in \mathbb{R}^n \times \mathbb{R} : (1 + z^2)^{\beta_1} \leq |x|^2 \leq \beta_2 (e + z^2) \log(e + z^2)\right\}$, where $\beta_1 < \frac{1}{2} + \frac{\alpha}{n}$ and $\beta_2 > \max\left(\frac{1}{2}\left(\frac{n}{2} - \alpha\right), \frac{1}{e}\right)$.

So, it is enough to consider K_α supported on E. Let $K^\alpha = K_\alpha \chi_E$. Now, our strategy will be to decompose the kernel (hence the operator) $K^\alpha = \sum_j K_j$, where $K_j(x, z) = K^\alpha(x, z)\phi_j(z)$, using partition of unity in z-variable. If T_j be the convolution with the kernel K_j, the we look for the estimates of the form $\|T_j f\|_{L_p(\mathbb{R}^{n+1})} \leq C_j \|f\|_{L_p(\mathbb{R}^{n+1})}$ with $C = \sum_j C_j < \infty$. We also decompose the general function $f \in L_p(\mathbb{R}^{n+1})$ as $f = \sum_l f_l$, where support of f_l is the cube $Q_l = Q_0 + l$, where Q_0 is the unit cube centered at origin and $l \in \mathbb{Z}^{n+1}$. Now using the translation invariance of the operator T_α, we need to show that $\|T_j f\|_{L_p(\tilde{E}_j)} \leq C_j \|f\|_{L_p(Q_0)}$ where $\tilde{E}_j = E_j + Q_0$. Because then, we will be having $\|Tf\|_{L_p(\mathbb{R}^{n+1})} \leq \left(\sum_j \lambda_j^{1/p} C_j\right) \|f\|_{L_p(\mathbb{R}^{n+1})}$, where $\lambda_j = \#\{l' : supp\, T_j f_l \cap supp\, T_j f_{l'} \neq \emptyset\}$ for any given l.

Publications:

1. Ron Kerman, Rama Rawat and Rajesh K. Singh, *Dilation-commuting operators on power-weighted Orlicz classes*, Math. Inequal. Appl. 22, pp. 463-486, (2019)

2. Ron Kerman, Rama Rawat and Rajesh K. Singh, *A sharp form of the Marcinkiewicz Interpolation Theorem for Orlicz spaces*, recommended for publication to Studia Math.

Subramani Muthukrishnan

Research Summary:

Let K be an algebraic number field, $\mathcal{O}_K$ be its ring of integers. We shall say that K is Euclidean or K admits a Euclidean algorithm, if there exists a function $\phi : \mathcal{O}_K \to \mathbf{N} \cup \{0\}$ with the property that for all $a, b \in \mathcal{O}_K, b \neq 0$ there exists $q, r \in \mathcal{O}_K$ such that $a = bq + r$ and $\phi(r) < \phi(b)$. If ϕ is the norm-function, then we say K is norm-Euclidean. The determination of number fields which are Euclidean is an interesting topic of research in algebraic number theory. Recently, the following theorem is proved. Let $K = \mathbf{Q}(\sqrt{m}, \sqrt{n})$ be an imaginary biquadratic field of class number 1. Then K is Euclidean. The concept of *'admissible'* primes plays a fundamental role in determining Euclidean number fields. It is conjectured that every number field of rank r contains an *admissible* set of primes with $r + 1$ primes. I studied this problem for real quadratic field, proved that there exists infinitely many real quadratic fields each contains an *admissible* set of prime ideals with exactly two elements. This is a joint work with K. Srinivas, IMSc.

Euclidean ideal was introduced by H.W. Lenstra and proved that if an ideal C is Euclidean then the class group Cl_k is cyclic and $Cl_k = \langle C \rangle$. The converse is also true but under the assumption of generalized Riemann hypothesis (GRH). We proved the following theorems without assuming GRH. More precisely, (i) Let $K_1 = \mathbf{Q}(\sqrt{q}, \sqrt{kr})$, where $q \equiv 3 \pmod 4$ and $k, r \equiv 1 \pmod 4$ are prime numbers. Suppose that $h_{K_1} = 2$. Then K_1 has an Euclidean ideal class. (ii) Let p, q be two prime numbers with $p, q \equiv 1 \pmod 4$. Then the biquadratic field $K_2 = \mathbf{Q}(\sqrt{2}, \sqrt{pq})$ with $h_{K_2} = 2$ has an Euclidean ideal class. This is a joint work with Jaitra Chattopadhyay, HRI.

Let k be an algebraic number field. Contruct, by induction, the following increasing sequence of number fields

$$k = k_0 \subset k_1 \subset \cdots k_i \subset k_{i+1} \cdots$$

where k_{i+1} is the Hilbert class field of k_i. Let $l(k)$ be the length of this sequence. If $l(k) = \infty$, then we say that k has an infinite class field tower. Golod and Shafarevich proved the existence of number fields with infinite class field tower. I am interested to find number fields with infinite class field tower ramifying at few rational primes. This work is in progress.

Publications:

1. Jaitra Chattopadhyay, M. Subramani, *Biquadratic fields having a non-principal Euclidean ideal class,* Journal of number theory, **To appear**

2. K. Srinivas, M. Subramani, *Survey on recent progress on Euclidean number fields and non-Wieferich primes,* ICCGNFRT-2017 Conference Proceeding, **To appear**

Preprints:

1. K. Srinivas, M. Subramani, *Complete classification of Euclidean imaginary multiquadratic fields,* communicated

2. K. Srinivas, M. Subramani, *Admissible primes in a family of Chowla fields,* in preparation

Conference/Workshops Attended:

1. *The fourth mini symposium of the Roman Number theory association*, Italy, April 2018.
2. *ICCGNFRT-2018, Conference*, HRI, India, October, 2018
3. *Workshop on Number Theory*, NISER, Bhubaneswar, India, November, 2018
4. *Conference on Number Theory*, KSOM, Kerala, India, December, 2018
5. *School on Group Cohomology*, HRI, Prayagraj, India, March, 2019

Visits to other Institutes:

1. Institute of Mathematical Sciences, Chennai, India, 19-Dec to 16-Jan, 2018

Invited Lectures/Seminars:

1. *Euclidean ideal class*, Workshop on Number theory, NISER, Bhubaneswar, November - 2018.
2. *Introduction to Cohomology via category theory*, Workshop on Group Cohomology, HRI, Prayagraj, Mar-2018.

Academic Report - Physics

Anirban Basu

Research Summary:

My research has focussed on understanding the structure of multiloop amplitudes in superstring theory. In order to do so, it is very useful to analyze the structure of modular invariant integrands of the various string amplitudes. I have studied the field theory limit of some such two loop amplitudes, as well as obtained an eigenvalue equation on moduli space that certain modular graph functions satisfy at genus two.

I considered the contributions to certain terms in the derivative expansion of the two loop four graviton amplitude in maximal supergravity that arise in the field theory limit of genus two modular graph functions that result from the derivative expansion of the four graviton amplitude in toroidally compactified type II string theory, using the worldline formalism of the first quantized superparticle.

I obtained a second order differential equation on moduli space satisfied by certain modular graph functions at genus two, each of which has two links. This eigenvalue equation is obtained by analyzing the variations of these graphs under the variation of the Beltrami differentials. This equation involves seven distinct graphs, three of which appear in the integrand of the $D^8\mathcal{R}^4$ term in the low momentum expansion of the four graviton amplitude at genus two in type II string theory.

Publications:

1. Anirban Basu, *Supergravity limit of genus two modular graph functions in the worldline formalism,* Phys.Lett. **B782**, 570, (2018)

2. Anirban Basu, *Eigenvalue equation for genus two modular graphs,* JHEP **1902**, 046, (2019)

Conference/Workshops Attended:

1. *Indian Strings Meeting 2018*, IISER Thiruvananthapuram, December 2018

2. *Mini Conference on Recent Topics in String Theory and Cosmology*, NISER Bhubaneswar, March 2019

Invited Lectures/Seminars:

1. *Eigenvalue equation for genus two modular graphs*, Indian Strings Meeting 2018, IISER Thiruvananthapuram, December 2019

2. *Eigenvalue equation for genus two modular graphs*, Mini Conference on Recent Topics in String Theory and Cosmology, NISER Bhubaneswar, March 2019

Other Activities:

1. Taught the Quantum Field Theory-I course, HRI Aug-Dec 2018.

2. Was on the postdoctoral selection committee in the department of Physics, IIT Ropar, June, 2018.

3. Attended the meeting of the Board of Studies, (Integrated M.Sc.) HBNI at NISER Bhubaneswar, Match 2019.

Sandhya Choubey

Research Summary:

My research work in the last academic year has focused mainly in the area of neutrino physics and dark matter physics. I give below a brief summary of my research done.

Dark Matter- Models: We have worked in building models beyond the Standard Model of particle physics that explain dark matter along with neutrino masses and mixing. We published three papers in the last year. In JHEP **1808**, 062 (2018) we proposed a model where Standard Model (SM) gauge group is extended with a gauged $U(1)_{B-L}$ as well as gauged $U(1)_{l_\mu - L_\tau}$. This model generates neutrino masses by the inverse seesaw mechanism, provides a viable dark matter candidate and explains the muon (g-2) anomaly. While $U(1)_{l_\mu - L_\tau}$ is anomaly free, the anomaly introduced by $U(1)_{B-L}$ is cancelled between the six SM singlet fermions introduced for the inverse seesaw mechanism and four additional chiral fermions introduced in this model. After spontaneous symmetry breaking the four chiral fermionic degrees of freedom combine to give two Dirac states. The lightest Dirac fermion becomes stable and hence the dark matter candidate. The $U(1)_{l_\mu - L_\tau}$ gauge symmetry provides a flavour structure to the inverse seesaw framework, successfully explaining the observed neutrino masses and mixings. We studied the model parameters in the light of neutrino oscillation data and found correlation between them. Moreover, the muon (g-2) anomaly can be explained by the additional contribution arising from $U(1)_{L_\mu - L_\tau}$ gauge boson. In JHEP **1905**, 193 (2019) we explained three beyond standard model (BSM) phenomena, namely neutrino masses, the baryon asymmetry of the Universe and dark matter, within a single model and in each explanation the right handed (RH) neutrinos play the prime role. The baryon asymmetry of the Universe can arise from thermal leptogenesis from the decay of lightest RH neutrino. At the same time, the decay of the RH neutrino can produce the Dark Matter (DM) as an asymmetric Dark Matter component. The source of CP violation in the two sectors is exactly the same, related to the complex couplings of the neutrinos. In another paper due to appear in JHEP, we proposed and studied a two-component dark matter model in which the dark matter is produced by the so-called FIMP mechanism. We considered the $U(1)_{B-L}$ extension of the standard model gauge group and an additional Z_2 symmetry to stabilise the dark matter.

Dark Matter- Indirect Detection: In JHEP **1905**, 039 (2019) we studied the prospects of detecting muon events at the upcoming Iron CALorimeter (ICAL) detector to be built at the proposed India-based Neutrino Observatory (INO) facility due to neutrinos arising out of annihilation of Weakly Interactive Massive Particles (WIMP) in the centre of the earth. The atmospheric neutrinos coming from the direction of earth core presents an irreducible background. We presented 90 % C.L. exclusion sensitivity limits on the WIMP-nucleon Spin Independent (SI) interaction cross-section. The expected sensitivity limits calculated for ICAL for the WIMP annihilation in the earth are more stringent than the limits obtained by any other indirect detection experiment.

Neutrino Oscillations In JHEP **1808**, 141 (2018) we probed for evidence of invisible neutrino decay in the latest NOvA and T2K data. It was shown that both NOvA and T2K data sets are better fitted when one allows for invisible neutrino decay. We considered a scenario where only the third neutrino mass eigenstate is unstable and decays into invisible components. We obtained the best-fit value of the neutrino life-

time from the analysis of T2K, NOvA and the combined data sets. In arXiv:1811.08684 [hep-ph] we probed a new degeneracy in the sterile neutrino sector at long-baseline neutrino experiments in the so-called 3+1 scenario. We showed that the degeneracy exists in the appearance channel only while the disappearance channel does not have this degeneracy. In arXiv:1812.02608 [hep-ph] we studied in depth the physics reach of the Protvino to ORCA (P2O) experiment. This is an experimental proposal where a neutrino beam from the Protvino accelerator complex located in Russia will be sent to the detector facility called 'Oscillation Research with Cosmics in the Abyss' (ORCA) in the Mediterranean sea. The distance neutrinos will travel will be 2588 km and the aim of the experiment is to study neutrino oscillation parameters. In this paper, we carried out an optimization study to extract the best possible physics sensitivity of the P2O experiment. In particular, we studied the effect of antineutrino run, the role of background as well as the impact of controlling the systematic uncertainties vis-a-vis the statistics.

Neutrinoless Double Beta Decay: In Phys. Rev. D **99**, no. 9, 095038 (2019) we studied the implications of the Dark-LMA solution to the solar neutrino problem for neutrino-less double beta decay ($0\nu\beta\beta$). We show that while the predictions for the effective mass governing $0\nu\beta\beta$ remains unchanged for the inverted mass scheme, that for normal ordering becomes higher for the Dark-LMA parameter space and moves into the "desert region" between the two. This sets a new goal for sensitvity reach for the next generation experiments if no signal is found for the inverted ordering by the future search programmes.

Neutrinos in Cosmology: In JCAP **1809**, no. 09, 017 (2018) we presented the bounds on the sum of three active neutrinos in various cosmological models. In arXiv:1807.10294 [astro-ph.CO] we explored the thermal light sterile neutrino situation from cosmological perspective in the $\Lambda CDM + r_{0.05} + N_{eff} + m_s^{eff}$ model using combinations of latest data sets available.

Publications:

1. K. N. Vishnudath, Sandhya Choubey and Srubabati Goswami, *A New Sensitivity Goal for Neutrino-less Double Beta Decay Experiments,* Phys. Rev. D **99**, no. 9, 095038 (2019)

2. Anirban Biswas, Sandhya Choubey, Laura Covi and Sarif Khan, *Common origin of baryon asymmetry, dark matter and neutrino mass,* JHEP **1905**, 193 (2019)

3. Shouvik Roy Choudhury and Sandhya Choubey, *Updated Bounds on Sum of Neutrino Masses in Various Cosmological Scenarios,* JCAP **1809**, no. 09, 017 (2018)

4. Deepak Tiwari, Sandhya Choubey and Anushree Ghosh, *Prospects of indirect searches for dark matter annihilations in the earth with ICAL@INO,* JHEP **1905**, 039 (2019)

5. Sandhya Choubey, Debajyoti Dutta and Dipyaman Pramanik, *Invisible neutrino decay in the light of NOvA and T2K data,* JHEP **1808**, 141 (2018)

6. Anirban Biswas, Sandhya Choubey and Sarif Khan, *Inverse seesaw and dark matter in a gauged B-L extension with flavour symmetry,* JHEP **1808**, 062 (2018)

7. Waleed Abdallah, Sandhya Choubey and Sarif Khan, *FIMP dark matter candidate(s) in a $B - L$ model with inverse seesaw mechanism,* To appear in JHEP

Preprints:

1. Sandhya Choubey, Monojit Ghosh and Dipyaman Pramanik, *On the Optimization of Protvino to ORCA (P2O) Experiment,* arXiv:1812.02608 [hep-ph]

2. Sandhya Choubey, Debajyoti Dutta and Dipyaman Pramanik, *Exploring a New Degeneracy in the Sterile Neutrino Sector at Long-Baseline Experiments,* arXiv:1811.08684 [hep-ph]

3. Shouvik Roy Choudhury and Sandhya Choubey, *Constraining light sterile neutrino mass with the BICEP2/Keck Array 2014 B-mode polarization data,* arXiv:1807.10294 [astro-ph.CO]

4. B. Abi *et al.* [DUNE Collaboration], *The DUNE Far Detector Interim Design Report, Volume 3: Dual-Phase Module,* arXiv:1807.10340 [physics.ins-det].

5. B. Abi *et al.* [DUNE Collaboration], *The DUNE Far Detector Interim Design Report, Volume 2: Single-Phase Module,* arXiv:1807.10327 [physics.ins-det].

6. B. Abi *et al.* [DUNE Collaboration], *The DUNE Far Detector Interim Design Report Volume 1: Physics, Technology and Strategies,* arXiv:1807.10334 [physics.ins-det].

Conference/Workshops Attended:

1. *Invisibles 2018*, Germany, September 2018.

2. *IMHEP*, India, January 2019.

Visits to other Institutes:

1. KTH, Stockholm, Sweden, May-June 2018,

Invited Lectures/Seminars:

1. *Discussion leader*, NSI in Neutrino Oscillations, ICTP, IITB, Mumbai, December 2018.

2. *Invited talk*, Dark Matter in Lmu-Ltau extensions of the Standard Model, IMHEP, IOP, Bhubaneswar, January, 2019.

Other Activities:

1. Taught Mathematical Methods II course, January-May, 2018.

2. Taught Mathematical Methods II course, August-December, 2018.

3. Chairperson of Internal Complaints Committee / Women's Grievances' Cell

4. Member of Cluster Committee.

5. Member of Academic Infrastructure Facilities Committee.

6. Member of International's Organising Committee of *XVII International Workshop on Neutrino Telescopes*, March 18-22, 2019, Venice, Italy.

Tapas Kumar Das

Research Summary:

I have been working on relativistic stellar structure, the dynamics of fractal medium in strong gravity space time, cosmological models in F(R,T) gravity, analogue gravity phenomena, and on the Penrose-Carter formalism of acoustic geometry for accretion in the Kerr metric and related emergent wormholes connecting the coresponding multiverse.

Publications:

1. Md. Arif Shaikh & Tapas K Das, *Linear perturbations of low angular momentum accretion flow in the Kerr metric and the corresponding emergent gravity phenomena,* Physical Review D **Volume 98, Issue 12**, id.123022, (2019)

2. Md. Arif Shaikh, Susovan Maity, Sankhasubhra Nag, & Tapas K Das, *Effective sound speed in relativistic accretion discs around Schwarzschild black holes,* New Astronomy **Volume 69**, 48, (2019)

3. Sofiqul Islam, Satadal Datta, & Tapas K Das, *A Parametric model to study the mass radius relationship of stars,* Pramana Indian Journal of Physics **Volume 92, Issue 3, article id. 43**, 15 pp, (2019)

4. Safiqul Islam, Pavan Kumar, G. S. Khadekar, & Tapas K Das, *(2+1) dimensional cosmological models in F(R,T) gravity with $\Lambda(R,T)$,* IOP conference proceedings at 'The First Sharjah International Conference on Particle Physics, Astrophysics and Cosmology (FISICPAC), 2018, held at University of Sharjah, UAE, during November 11 – 13, 2018 (2018)

Preprints:

1. Susovan Maity, Md. Arif Shaikh, & Tapas K Das, *Effective sound speed in relativistic accretion discs around rotating black holes,* arXiv:1811.04975 [astro-ph.HE]

Visits to other Institutes:

1. Physics & Applied Mathematics Unit (PAMU), Indian Statistical Institute (ISI), Kolkata, India, for one year (April 2018 to April 2019) as a sabbatical visitor.

2. Visited S N Bose National Centre of Basic Sciences, St. Xavier's College, Sarojini Naidu College, Calcutta University and other academic institutions in Kolkata for academic works during my stay at PAMU, ISI as a sabbatical visitor (visiting scientist).

Other Activities:

1. Served as (Ph.D.) thesis examiner (A thesis on aspects of general relativity and quantum gravity, submitted in Calcutta University).

2. Served as external referee for promotion of faculty members at USA universities.
3. During my stay at PAMU ISI, supervised the following project students:

    (a) Pathikrith Banerjee from University of Pittsburgh USA.
    (b) Manabputra from NISER, India.

AseshKrishna Datta

Research Summary:

In a collaboration with physicists from another Institute we explored the consequences of some characteristic features of nonholomorphic soft supersymmetry (SUSY) breaking terms in the popular setup of the Minimal SUSY Standard Model (MSSM). It is shown that such a SUSY scenario, known in the literature as the NonHolomorphic SUSY Standard Model (NHSSM), could remain 'natural' (i.e., not fine-tuned) even in the presence of a rather heavy higgsino-like LSP. However, it turns out that distinguishing such a scenario from the MSSM is unlikely to be an easy task, in particular at the Large Hadron Collider (LHC). In a first study of such a scenario at colliders (LHC), we explore a possible way that focuses on the bottom squark phenomenology. This exploits the usual $\tan\beta$-dependence (enhancement) of the bottom Yukawa coupling but reinforced/altered in the presence of non-vanishing nonholomorphic soft trilinear parameter A'_b. For a given set of masses of the sbottom(s) and the light electroweakinos (LSP, lighter chargino etc.) which are known from experiments, the difference between the two scenarios could manifest itself via event rate in the $2b$-jets + $\not{E}_T$ final state, which could be characteristically different from its MSSM expectation. Impact on the phenomenology of the stop top squark at the LHC is also touched upon. This work is now published in the *Journal of High Energy Physics (JHEP)*.

In the same collaboration we are continuing to explore further the implications of such an enhanced bottom Yukawa coupling in the associated productions of the bottom and sbottom pairs along with various Higgs bosons of the scenario. It is hoped that the analysis would help constrain the NHSSM parameter space rather efficiently from the current and upcoming experimental analyses from the LHC and other relevant non-accelerator experiments.

In a different collaboration with a postdoctoral fellow at HRI and a physicist from another Institute, we have been studying for sometime the implications of a singlino-like dark matter in a popular SUSY scenario like the Next-to-Minimal SUSY Standard Model (NMSSM). It appears that in a much theoretically motivated setup having an enhanced 'naturalness' (i.e., with a smaller higgsino mass parameter $\mu_{\rm eff}$) and in the presence of relatively light singlet scalars (which could have, till now, escaped searches at the LHC), very characteristic regions in the parameter space with sub-100 GeV masses for the DM candidate exist that exploit the light singlet scalar funnels to comply with the experimentally observed DM relic density. However, crucially enough, simultaneous compatibility with the results from the DM direct detection experiments and from various relevant searches at the LHC compel one to allow for an optimal tempering of the singlino-like DM with nontrivial admixtures of higgsinos and the gauginos. The study is nearing a completion and will be circulated soon.

The study is likely to open up a general field of "well-tempered" neutralinos as DM candidates in the NMSSM akin to earlier studies in the MSSM. Its prospects are being assessed closely before undertaking a detailed study. An HRI graduate student is working on a project with me in this area.

In yet another study, along with a postdoctoral fellow at HRI and a physicist from an Institute abroad, we are studying the plausibility and the implications of a fat Z'-boson of a simple and well-known and extension of the MSSM called the BLSSM. The

scenario is much motivated from the view point of non-vanishing neutrino masses. This has an added symmetry group $U(1)_{(B-L)}$ over and above the SM gauge group whose breaking is related to SUSY breaking in general and both occur at around the TeV scale thus making them testable at the LHC. Our present study is also motivated by the lack of a detailed understanding of 'fat' resonances and their implications for a collider like the LHC.

Publications:

1. Utpal Chattopadhyay, AseshKrishna Datta, Samadrita Mukherjee, Abhaya Kumar Swain, *Sbottoms as probes to MSSM with nonholomorphic soft interactions*, JHEP **1810**, 202, (2018).

Conference/Workshops Attended:

1. *Is SUSY still the best bunker to hide in, in light ofexperimental data?*, CHEP, IISc.,India, May, 2018.
2. *International Meeting on High Energy Physics (IMHEP)*, IOP, India, January, 2019.
3. *Recent Issues in Nuclear and Particle Physics (RINP2)*, Visva-Bharati, India, February, 2019.

Visits to other Institutes:

1. Visited the School of Physical Sciences, Indian Association for the Cultivation of Science, Kolkata, India several times during the period.

Invited Lectures/Seminars:

None

Academic recognition/Awards:

- Promoted to the position of Professor 'H', July, 2018.

Other Activities:

1. One student working with me towards his Ph.D. thesis successfully defended the same in July, 2018.
2. Served as the external examiner in the viva-voce examination for the promotion of a Ph.D. student at the Department of Physics, University of Delhi, October, 2018.
3. Served as a member of the organising committee of the International Meeting on High Energy Physics (IMHEP) held at Visva-Bharati, Santiniketan, India, February, 2019.

Aditi Sen De

Research Summary:

During 2018-19, we have studied several topics on quantum information science which include nonclassicality in quantum states, different aspects in quantum communication, quantum random walks, dynamics of quantum correlations in many-body physics, detection of quantum correlation in photonic systems.

Nonclassicality of temporal correlations pertaining to non-commutative sequential measurements is defined through the violation of macrorealistic inequalities, known as Leggett-Garg inequalities (LGI). In reality, every physical process is performed within the realm of limited resources. To fulfil such requirement, we established a connection between the thermodynamics, via energy considerations, and macrorealism, by employing LGI we call it as canonical LGI. Specifically, we asked the following question: For a given amount of energy available in the system, how much violation of LGI can be obtained by choosing suitable measurement strategies and dynamics? To this end, we found that although LGI is independent of the initial state, the maximal violation of LGI for a given energy cost depends upon the initial state in noiseless as well as in noisy scenarios.

In one of our work, we investigated the consequence on the violation of local realism based on pseduospin operators when photons are added or subtracted in a single mode or in both the modes of the two-mode squeezed states of light in presence of noise. In the event of a faulty twin-beam generator, we obtained a lower-than-expected squeezing in the state. In such a case, or in imperfect photon addition (subtraction), or under local noise, we found that the violation of local realism by the noise-affected two-mode squeezed states always decreases. Interestingly however, we noticed that photon addition (subtraction) can in general help to conquer the ill-effects of noise by enhancing the violation of local realism or by transforming non-violating states to violating ones, thereby acting as an activating agent.

Quantum many body systems can undergo phase transition due to a variation in the system parameters at temperatures very close to absolute zero entirely driven by quantum fluctuations. Recent studies have shown that along with those in the equilibrium scenarios, quantum systems can also change their characteristics drastically by developing non-analyticities with time during their time evolution, such a phenomenon was named as dynamical quantum phase transition (DQPT), and is observed during the transient regime of evolution. DQPTs have been studied in one-dimensional quantum spin models like XY and XXZ models under different types of quenches and several counter-intuitive results have been reported regarding the relation between the equilibrium quantum phase transition and DQPT. In our recent work, we considered a uniform and alternating transverse field XY spin chain (ATXY) in presence of an additional antisymmetric interaction, the Dzyaloshinskii-Moriya (DM) interaction. In equilibrium, the model displays several exotic phases which are not present in the XY spin chain, thereby, raising the possibility of having counter-intuitive observations in DQPTs in the generalized models. Unlike the Ising model, the analysis of Loschmidt echo, analytically, yields non-uniformly spaced transition times in this model. Comparative study between the equilibrium and the dynamical quantum phase transitions in this case reveals that there are quenches where one occurs without the other, and the regimes where they co-exist. However, such transitions happen

only when quenching is performed across at least a single gapless or critical line. Contrary to equilibrium phase transitions, bipartite entanglement measures do not turn out to be useful for the detection while multipartite entanglement emerges as a good identifier of this transition when the quench is done from a disordered phase of this model.

Publications:

1. Saptarshi Roy, Titas Chanda, Tamoghna Das, Debasis Sadhukhan, Aditi Sen(De), and Ujjwal Sen, *Phase boundaries in an alternating-field quantum XY model with Dzyaloshinskii-Moriya interaction: Sustainable entanglement in dynamics,* Phys. Rev. B **99**, 064422 (2019)

2. Sreetama Das, Avijit Misra, Amit Kumar Pal, Aditi Sen De, Ujjwal Sen, *Necessarily transient quantum refrigerator,* Europhys. Lett. **125**, 20007 (2019)

3. Anindita Bera, Shiladitya Mal, Aditi Sen(De), and Ujjwal Sen, *Witnessing bipartite entanglement sequentially by multiple observers,* Phys. Rev. A **98**, 062304 (2018)

4. Saptarshi Roy, Titas Chanda, Tamoghna Das, Aditi Sen(De), and Ujjwal Sen, *Response in the violation of the Bell inequality to imperfect photon addition and subtraction in noisy squeezed states of light,* Phys. Rev. A **98**, 052131 (2018)

5. Sreetama Das, Sudipto Singha Roy, Himadri Shekhar Dhar, Debraj Rakshit, Aditi Sen(De), and Ujjwal Sen, *Adiabatic freezing of entanglement with insertion of defects in a one-dimensional Hubbard model,* Phys. Rev. B **98**, 125125 (2018)

6. Asutosh Kumar, Indranil Chakrabarty, Arun Kumar Pati, Aditi Sen De, Ujjwal Sen, *Quantum no-go theorems in causality respecting systems in presence of closed timelike curves: Tweaking the Deutsch condition,* Europhys. Lett. **122(1)**, 10007 (2018)

7. Titas Chanda, Tamoghna Das, Shiladitya Mal, Aditi Sen(De), and Ujjwal Sen, *Canonical Leggett-Garg inequality: Nonclassicality of temporal quantum correlations under energy constraint,* Phys. Rev. A **98**, 022138 (2018)

8. Saptarshi Roy, Tamoghna Das, Asutosh Kumar, Aditi Sen(De), and Ujjwal Sen, *Activation of nonmonogamous multipartite quantum states,* Phys. Rev. A **98**, 012310 (2018)

9. Titas Chanda, Tamoghna Das, Debasis Sadhukhan, Amit Kumar Pal, Aditi Sen(De), and Ujjwal Sen, *Scale-invariant freezing of entanglement,* Phys. Rev. A **97**, 062324 (2018)

10. Kavan Modi, Arun Kumar Pati, Aditi Sen(De), and Ujjwal Sen, *Masking Quantum Information is Impossible,* Phys. Rev. Lett. **120**, 230501 (2018)

11. Sudipto Singha Roy, Himadri Shekhar Dhar, Debraj Rakshit, Aditi Sen(De), and Ujjwal Sen, *Response to defects in multipartite and bipartite entanglement of isotropic quantum spin networks,* Phys. Rev. A **97**, 052325 (2018)

Preprints:

1. C. S. Sudheer Kumar, Anup Biswas, Aditi Sen(De), Ujjwal Sen, *Frequentist-approach inspired theory of quantum random phenomena predicts signaling*, arXiv:1903.12096.

2. Chirag Srivastava, Anindita Bera, Aditi Sen(De), Ujjwal Sen, *One-shot conclusive multiport quantum dense coding capacities*, arXiv:1903.11709.

3. Sreetama Das, Asutosh Kumar, Aditi Sen(De), Ujjwal Sen, *Quantum Process Randomness*, arXiv:1903.03564.

4. Jayanth Jayakumar, Sreetama Das, Aditi Sen(De), Ujjwal Sen, *Interference-induced localization in quantum random walk on clean cyclic graph*, arXiv:1812.05158.

5. Stav Haldar, Saptarshi Roy, Titas Chanda, Aditi Sen(De), Ujjwal Sen, *Multipartite entanglement at dynamical quantum phase transitions with non-uniformly spaced criticalities*, arXiv:1811.12796.

6. Soorya Rethinasamy, Saptarshi Roy, Titas Chanda, Aditi Sen(De), Ujjwal Sen, *Universality in Distribution of Monogamy Scores for Random Multiqubit Pure States*, arXiv:1811.09201.

7. Sudipto Singha Roy, Himadri Shekhar Dhar, Aditi Sen(De), Ujjwal Sen, *Tensor-network approach to compute genuine multisite entanglement in infinite quantum spin chains*, arXiv:1807.04033.

8. Saubhik Sarkar, Aditi Sen (De), Ujjwal Sen, *Disorder-induced Effects in Noisy Dynamics of Bose-Hubbard and Fermi-Hubbard Quantum Glasses*, arXiv:1804.09621.

Conference/Workshops Attended:

1. *Quantum Frontiers and Fundamentals: Experimental Studies and Theoretical Ramifications*, India, May 2018.

2. *Annual award Ceremony of Jagadis Bose National Science Talent Search*, India, December 2018.

3. *ONE-DAY NATIONAL SEMINAR on MATHEMATICS AND APPLICATIONS*, India, January 2019.

4. *National Symposium on "Recent Trends in Applied Mathematics 2019 (RTAM19)"*, India, March 2019.

Visits to other Institutes:

1. Visited the group of Prof. Sourin Das, Indian Institute of Science Education and Research, Kolkata, December 2018.

2. Visited the group of Prof. Pankaj Agarwal, Institute of Physics, Bhubaneswar, December 2018.

3. Visited Department of Mathematics, Bethune College, Kolkata, January 2019.

Invited Lectures/Seminars:

1. *Monogamy of quantum correlations*, Quantum Frontiers and Fundamentals: Experimental Studies and Theoretical Ramifications, Raman Research Institute, Bengaluru, April 2018.

2. *Communication in a quantum world*, Colloquium, University of Calcutta, Kolkata, December 2018.

3. *Quantum Technologies*, Annual award Ceremony of Jagadis Bose National Science Talent Search , Presidency University, Kolkata, December 2018.

4. *Quantum Technologies*, ONE-DAY NATIONAL SEMINAR on MATHEMATICS AND APPLICATIONS, Department of Mathematics, Bethune College, Kolkata,January 2019.

5. *Monogamy for Random Multiqubit Pure States*, National Symposium on "Recent Trends in Applied Mathematics 2019 (RTAM19), Department of Applied Mathematics, University of Calcutta, Kolkata, March 2019.

Academic recognition/Awards:

- Awarded Shanti Swarup Bhatnagar Prize for Science and Technology from Council of Scientific and Industrial Research, in the category of physical sciences, 2018.

Other Activities:

1. Member of international program committee of 26th International conference on atomic physics, ICAP 2018, Barcelona, July 2018.

2. Organizer of quantum information processing and applications, Dec 2018.

3. Member of national organizing committee of School on Quantum measurement and Topological Quantum Computation and Asia Pacific Conference and Workshop on Quantum Information Science, Kolkata, Dec 2018.

4. Taught a one-semester course on "Quantum information and computation during Aug-Dec 2018.

5. Guiding the theses of Saptarshi Roy of HRI.

6. Guided projects of the following HRI graduate students:

   Stav Haldar, "Dynamical quantum phase transition (Aug 2018 -Mar 2019)

   Ratul Banerjee, " Localizable entnaglement" (Jan- May 2019)

   Srijon Ghosh, "Quantum batteries" (Jan-May 2019)

7. Guided project works of Master students under VSP program at HRI and Academies.

8. Serving as the convenor of the Housing Committee, and member of the physics graduate committee, Guest House / Pantry / Student Mess committee, Women Grievence Cell committee at HRI.

9. Serving as referees in national and international journals.
10. Serving as members of the PhD committees of several PhD students at HRI.

Raj Gandhi

Research Summary:

My work over the past year has focussed on long baseline physics, dark matter and the effort to understand an unexpalined but statistically highly significant excess in the low energy data of the MiniBoone experiment. My student Samiran Roy and I are working on new physics explanations of this anomaly, which can connect the standard model to the dark sector. This is an inherently difficult problem, and progress has been slow, but we have been slowly and steadily moving forward.

Preprints:

1. B. Abi *et al.* [DUNE Collaboration], [physics.ins-det]. Authors and co-authors name, *"The DUNE Far Detector Interim Design Report, Volume 3: Dual-Phase Module,"*, arXiv:1807.10340
2. B. Abi *et al.* [DUNE Collaboration], *"The DUNE Far Detector Interim Design Report, Volume 2: Single-Phase Module,"* arXiv:1807.10327
3. B. Abi *et al.* [DUNE Collaboration], *"The DUNE Far Detector Interim Design Report, Volume 1: Physics, Technology and Strategies,"* arXiv:1807.10334

Conference/Workshops Attended:

1. *DUNE Collaboration meeting*, Fermilab, USA, June 2018
2. *DAE HEP Symposium*, IIT Chennai, December 2018.
3. *IITB ICTP WOrkshop*, IIT Mumbai, December 2018.

Visits to other Institutes:

1. Fermilab, Chicago, Aug -Sep 2018

Invited Lectures/Seminars:

1. *Recent Directions in Neutrino Theory*, Plenary Talk, DAE HEP Symposium, IIT Chennai, December 2018.
2. *Future Atmospheric Detectors*, Plenary Talk, IIT-Mumbai ICTP Workshop, IIT Mumbai, December 2018

Academic recognition/Awards:

- Fermilab Neutrino Physics Center Fellow, 2018

Other Activities:

1. Member, International Advisory Committee, NEUTRINO 2020 Conference .
2. Member, International Advisory Committee, XVth Rencontres du Vietnam 2019 Conference.
3. Member, DUNE International Collaboration, 2014-present.
4. Member, DUNE International Collaboration Institutional Board, 2014- present.
5. Currently supervising one Ph.D student.

Dileep Prabhakar Jatkar

Research Summary:

I worked with Sujay Ashok and Madhusudhan Raman on relation between the Chazy hierarchy and generalised Ramanujan identities. We showed that there exists a generalisation of the Halphen system associated with the generalised Chazy equation. We also show that the generalised Halphen system is related to a Borcherds-Kac-Moody algebra.

I worked with Ritabrata Bhattacharya and Arnab Kundu on SYK model with complex fermions. We studied higher point correlation functions in this model. By taking triple short time limit of the six point functions we obtained expressions for three point functions of the fermion bilinears. These results may help distinguish possible holographic dual theories.

With Ritabrata Bhattacharya and Nilakash Sorokhaibam, I studied non-equilibrium dynamics in SYK models using quantum quench. We consider models with two, four, and higher fermion interactions (q=2, 4, and higher) and use two different types of quench protocol, step and bump quenches. We observe that in q=2 theory the two-point functions do not thermalize. We find thermalization in q=4 and higher theories without long time averaging. We also calculate two different exponents of which one is equal to the coupling and the other is proportional to the final temperature. This result is more robust than thermalization obtained from long time averaging as proposed by the eigenstate thermalization hypothesis(ETH), and is more akin to mixing than ergodicity.

I worked with K. Kolekar and K. Narayan on the ghost-spin chains and entanglement of multi-component spin states. We show that this system has O(N) or Sp(N) symmetry. We study entanglement pattern and find that positive norm correlated ghost-spin states in two copies of ghost-spin ensembles, where we entangle identical ghost-spins from each copy, has positive entanglement entropy.

Publications:

1. Dileep P. Jatkar, Kedar S. Kolekar, K. Narayan, *N-level ghost-spins and entanglement* , Phys.Rev. D99 (2019) no.10, 106003.

Preprints:

1. Sujay K. Ashok, Dileep P. Jatkar, Madhusudhan Raman, *Aspects of Hecke Symmetry II: Anomalies, Curves, and Chazy Equations,* eprint arXiv:1810.07919

2. Ritabrata Bhattacharya, Dileep P. Jatkar, Arnab Kundu, *Chaotic Correlation Functions with Complex Fermions*, eprint arXiv:1810.13217

3. Ritabrata Bhattacharya, Dileep P. Jatkar, Nilakash Sorokhaibam, *Quantum Quenches and Thermalization in SYK models*, eprint arXiv:1811.06006

Conference/Workshops Attended:

1. *Strings 2018*, Japan, June 2018,
2. *Geometry, Physics and Representation Theory*, India, July 2018,
3. *ISM*, India, December 2018.

Visits to other Institutes:

1. OIST, Japan, June 2018.
2. ICTS, Bengaluru, India, July 2018,
3. IACS, Kolkata, India, October 2018,
4. IACS, Kolkata, India, January 2019,
5. IISER, Pune, India, Nov-Dec. 2018,
6. IISER, Pune, India, March 2019,
7. NISER, Bhubaneswar, India, March 2019.

Invited Lectures/Seminars:

1. *AdS/CFT Correspondence*, Workshop at IACS, IACS, Kolkata, October 2018.
2. A Course on Conformal Bootstrap, IACS, Kolkata, January 2019.
3. Free field realisation of BMS_3 algebra, IISER, Pune, March 2019.
4. *Generalised Chazy Equations*, NISER String Meeting, NISER, Bhubaneswar, March 2019.

Other Activities:

1. Chair, SERB-THEP School committee, since August 2017.
2. Dean Academic, HRI, since March 2018.

Anshuman Maharana

Research Summary:

The primary goal was to connect flux compactifications (in string theory) to to cosmology and particle physics. In the last two decades, observations of the cosmic microwave background (CMB) have revealed many interesting features. The inflationary paradigm provides a theoretical framework to explain the observed patterns in the CMB. A generic feature of string models is scalar fields which interact with gravitational strength. We have studied the implications of such fields on inflationary predictions and the interplay of this with dark matter abundances. Observations have shown that at the present epoch the rate of the expansion of the universe is increasing. The simplest theoretical models which can account for this acceleration are ones in which the geometry of the universe at late times is that of de Sitter space. We have explored constructions of de Sitter space in string theory and studied their phenomenology. We have also studied models of quintessence (in which the acceleration arises as a result of a slowly rolling scalar field), and examined the challenges associated with these models in light of bounds on fifth forces.

On the particle physics side we have analysed various scenarios for supersymmetric breaking in flux compactifications.

Publications:

1. B. S. Acharya, A. Maharana and F. Muia, *Hidden Sectors in String Theory: Kinetic Mixings, Fifth Forces and Quintessence*, *JHEP* **1903** *(2019) 048;*

2. M. Cicoli, S. De Alwis, A. Maharana, F. Muia and F. Quevedo,

   De Sitter vs Quintessence in String Theory, *Fortsch. Phys.* **2018** *1800079*

3. R. Allahverdi, K. Dutta and A. Maharana, *Constraining Non-thermal Dark Matter by CMB*, *JCAP* **1810** *(2018) no.10, 038*

4. A. Maharana and I. Zavala, *Postinflationary scalar tensor cosmology and inflationary parameters*, *Phys. Rev. D* **97** *(2018) no.12, 123518, arXiv:1712.07071*

5. S. Bhattacharya, K. Dutta, M. R. Gangopadhyay and A. Maharana, *Confronting Kahler moduli inflation with CMB data*, *Phys. Rev. D* **97** *(2018) no.12, 123533*

Conference/Workshops Attended:

1. 30^{th} *Meeting of the Indian Association of General Relativity and Gravitation*, India, January 2019

2. *Conference on Recent Developments in Cosmology*, India, April 2018

Visits to other Institutes:

1. ICTP, Trieste, Italy, June-July 2018

Invited Lectures/Seminars:

1. *Moduli and Cosmlogy*, Conference on Recent Developments in Cosmology, BHU, Varanasi, April 2018.

2. *String Cosmology*, 30^{th} Meeting of the Indian Association of General Relativity and Gravitation, Hyderabad, January 2019.

Other Activities:

1. Instructor for Statistical Mechanics, January 2019 - May 2019

2. Member of Endowment, Outreach and Public Interface committees

Pinaki Majumdar

Research Summary: (Technical)

We have invested significantly in developing the Langevin equation approach to finite temperature real time dynamics of correlated electron systems. It not only reproduces the thermal physics and transition scales that the earlier Monte Carlo approach did but also captures large amplitude dynamical fluctuations that earlier methods could not access.

We have used the method to address phonon dynamics in the strong coupling Holstein model and have made significant progress in addressing spin dynamics in the repulsive Hubbard model and the role of thermal fluctuations in the bias driven metallisation of a Mott insulator.

Research Summary: (Non-Technical)

We now have a method that captures both the thermodynamics and the real time dynamics of interacting electron systems. This can address lattice vibrations or magnetic fluctuations across phase transitions, and their effect on electronic properties. It provides insight on hitherto inaccessible physics, and also addresses real material properties.

Publications:

1. Dheeraj Kumar Singh, Alireza Akbari and Pinaki Majumdar, *Quasi-one-dimensional nanoscale modulation as sign of nematicity in iron pnictides and chalcogenides.* Phys Rev B 98, 180506(R) (2018).

2. Dheeraj Kumar Singh and Pinaki Majumdar, *Drude weight anisotropy in the doped iron pnictides: The primary role of orbital weight redistribution along the reconstructed Fermi surfaces.* Phys Rev B 98, 195130 (2018).

3. Sauri Bhattacharyya, Sankha Subhra Bakshi, Samrat Kadge and Pinaki Majumdar, *Langevin approach to lattice dynamics in a charge-ordered polaronic system.* Phys Rev B 99, 165150 (2019).

4. Arijit Dutta, Abhishek Joshi, K. Sengupta and Pinaki Majumdar, *Thermal transitions of the modulated superfluid for spin-orbit coupled correlated bosons in an optical lattice.* Phys Rev B 99, 195126 (2019).

Preprints:

1. Sauri Bhattacharyya, Saurabh Pradhan and Pinaki Majumdar *Modeling dynamical phonon fluctuations across the magnetically driven polaron crossover in the manganites.* arXiv: 1806.06577.

2. Madhuparna Karmakar and Pinaki Majumdar, *Thermally induced gaplessness and Fermi arcs in a "s-wave" magnetic superconductor.* arXiv: 1808.02012.

3. Abhishek Joshi and Pinaki Majumdar, *The impact of speckle disorder on a superfluid Fermi system* arXiv: 1810.03582.

Biswarup Mukhopadhyaya

Research Summary:

The possibility of observing radio synchrotron signals arising from dark matter annihilation in dwarf spheroidal galaxies was investigated in the context of the Square Kilometer Array (SKA) radio telescope. The most striking conclusion reached was that one can in this way see the signals of multi-TeV weakly interacting dark matter particles in about 100 hours of observation at the SKA, thus indicating a manifold enhancement of indirect search reach, as compared to searches at the Large Hadron Collider (LHC) as well as direct dark matter search experiments.
(Arpan Kar, Sourav Mitra, Tirthankar Roy Choudhury, Biswarup Mukhopadhyaya)

Supersymmetric (SUSY) scenarios with right-sneutrino dark matter were investigated. The methods of reconstruction of heavier, non-strongly interacting particles in such cases were consolidated, including the freeze-in constraints on dark matter.
(Shankha Banerjee, Genevieve Belanger, Avirup Ghosh, Biswarup Mukhopadhyaya)

The sneutrino dark matter scenarios undergo fresh twists if $\Delta L = 2$ masses for neutrinos as well as their scalar partners exist. The additional constraints on such spectra, from considerations of terrestrial phenomenology as well as cosmology, were obtained.
(Avirup Ghosh, Tanmoy Mondal, Biswarup Mukhopadhyaya)

The constraints on extended Higgs sectors arising from a detailed analysis of LHC data were obtained in a novel approach, including effective operators to parametrise additional loop contributions to rare Higgs decays. The connection between model-independent analyses of such scenarios with those bases on specific models was established.
(Atri Dey, jayita Lahiri, Biswarup Mukhopadhyaya)

Investigations were carried out on the possibility that while the 125 -GeV scalar cannot serve as a dark matter portal, the additional neutral scalar(s) in an extended electroweak symmetry breaking sector can play such a role. The detectability of such extended Higgs portals at the LHC was established, using conventional cut-based analysis as well as thpse based on gradient boosting and neural network techniques.
(Atri Dey, Jayita Lahiri, Biswarup Mukhopadhyaya)

The LHC signals of a SUSY spectrum with Higgsino-like low-lying neutralinos and with a gravitino dark matter was calculated in detail, including all phenomenological constraints. The methodology and usefulness of distinguishing longitudinal Z-bosons from transverse ones in this connection were brought to the fore.
(Juhi Dutta, Biswarup Mukhopadhyaya, Santosh Kumar Rai)

Scenarios with more than one Higgs triplet help in understanding certain neutrino mass generation mechanisms. Some hitherto unexplored signals of such scenarios at the LHC were pointed out
(Dilip Kumar Ghosh, Nivedita Ghosh, Biswarup Mukhopadhyaya)

A type-X two-Higgs doublet theory containing a very light (30-60 GeV) pseudoscalar is not only phenomenologically viable but also can explain the observed value of the muon anomalous magnetic moment. Following up on our earlier, pioneering work on

the mass reconstruction of such a pseudoscalar, methods of reconstructing the masses of heavier scalars in the spectrum were established.
(Eung Jin Chun, Siddharth Dwivedi, Tanmoy Mondal, Biswarup Mukhopadhyaya, Santosh Kumar Rai)

Publications:

1. Arpan Kar, Sourav Mitra, Biswarup Mukhopadhyaya, Tirthankar Roy Choudhury, *Can Square Kilometre Array phase 1 go much beyond the LHC in supersymmetry search?,* Phys. Rev. (Rapid Communications) **D99**, 021302, (2019)

2. Atri Dey, Jayita Lahiri, Biswarup Mukhopadhyaya, *Extended scalar sectors, effective operators and observed data,* JHEP **1811**, 127, (2018)

3. Dilip Kumar Ghosh, Nivedita Ghosh, Biswarup Mukhopadhyaya, *Distinctive Collider Signals for a Two Higgs Triplet Model,* Phys. Rev. **D99**, 015036, (2019)

4. Eung Jin Chun, Siddharth Dwivedi, Tanmoy Mondal, Biswarup Mukhopadhyaya, Santosh Kumar Rai, *Reconstructing heavy Higgs boson masses in a type X two-Higgs-doublet model with a light pseudoscalar particle,* Phys. Rev. **D98**, 075008, (2018)

5. Avirup Ghosh, Tanmoy Mondal, Biswarup Mukhopadhyaya, *Right sneutrino with $\Delta L = 2$ masses as nonthermal dark matter,* Phys. Rev. **D99**, 035018, (2019)

6. Shankha Banerjee, Genevieve Belanger, Avirup Ghosh, Biswarup Mukhopadhyaya, *Long-lived stau, sneutrino dark matter and right-slepton spectrum,* JHEP **1809**, 143, (2018)

Preprints:

1. Arpan Kar, Sourav Mitra, Biswarup Mukhopadhyaya, Tirthankar Roy Choudhury, *Heavy dark matter particle annihilation in dwarf spheroidal galaxies: radio signals at the SKA telescope,* arXiv:1905.11426 [hep-ph]

2. Atri Dey, Jayita Lahiri, Biswarup Mukhopadhyaya, *LHC signals of a heavy doublet Higgs as dark matter portal: cut-based approach and improvement with gradient boosting and neural networks,* arXiv:1905.02242 [hep-ph]

3. Juhi Dutta, Biswarup Mukhopadhyaya, Santosh Kumar Rai, *Identifying Higgsino-like neutralino with a keV-scale dark matter,* arXiv:1904.08906 [hep-ph]

Conference/Workshops Attended:

1. *Recent Issues in Nuclear and Particle Physics*, Visva-Bharati, Santiniketan, Febuary, 2019

2. *Symposium on Frontier Problems in Physics*, Indian Institute of Technology, Gandhinagar, November, 2018

3. *National Conference on Frontiers of Modern Physics,* Adamus University, West Bengal, August, 2018

Visits to other Institutes:

1. Technical University, Munich, Germany, April-May, 2018.
2. University of Gottingen, Germany, May, 2018.
3. Indian Association for the Cultivation of Science, Kolkata, June-July, 2018.
4. Indian Institute of Science, Gandhinagar, November, 2018.
5. Physical Research Laboratory, Ahmedabad, November, 2018.
6. Uppsala University, Sweden, December, 2019.
7. Indian Institute of Science Education and Research, Kolkata, March, 2019.

Invited Lectures/Seminars:

1. *Some dark matter scenarios beyond the beaten track* , High Energy Physics Seminar, Technical University, Munich, Germany, April, 2018.
2. *From Answers to questions in fundamental physics: the example of the Higgs boson*, Theoretical Physics Colloquium, University of Gottingen, Germany, May, 2018.
3. *There are more things in heaven and earth*, Stephen Hawking Memorial Lecture, Adamus University, West Bengal, August, 2018.
4. *Scince and Sanskrit: looking ahead*, , Sanskrit College University, Kolkata, August, 2018.
5. *There are more things in heaven and earth*, Physics Colloquium, Banaras Hindu University, Varanasi, September, 2018.
6. *There are more things in heaven and earth*, Symposium on Frontier Problems in Physics, Indian Institute of Technology, Gandhinagar, November, 2018.
7. *Looking for dark matter: usual and unusual ways*, Recent Issues in Nuclear and Particle Physics, Visva-Bharati, Santiniketan, November, 2018.

Academic recognition/Awards:

- Fellow, Indian Academy of Science, 2018.
- Visiting Scientist Award, Excellence Cluster Universe, Munich, Germany, 2018.

Other Activities:

1. Taught a course on Quatntum Mechanics 1 at Harish-Chandra Research institute.
2. Delivered two outreach lectures for high school and undergraduate students, at Harish-Chandra Research institute.
3. Continued to serve as Co-ordinator, Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute.

4. Served on: Guest House and Pantry Committee (convener), Endowment Committee, Physics Graduate Committee, Harish-Chandra Research institute. Also served as Nodal Officer, Homi Bhabha National Institute.

Satchidananda Naik

Research Summary:

Consistent formulation of Covariant Fermionic String Field theory and Supermoduli Space:
A consistent formulation of covariant string field theory is not only essential but also desirable.Just to show the non-linear gauge invarinace of the Yang-Mills theory to all orders is quite involved and to show the consistency of the quantization one requires the A_∞ structure. The Open Bosonic String field theory of Witten is just like Chern-Simon's gauge theory action and consistent quantization has already A_∞ structure. Introduction of fermionic variables for covariant formulation is via Neveue-Schwarz(NS) string which brings in Picture Changing operation. The Picture Changing operator plagues many nice things by bringing singularites. Berkovits formulated a beautiful theory in the large Hilbert space where this NS fomulation as a Wess-Zumino- Witten model. However this lacks A_∞ structure but later on it was shown that this can be achieved in a particular gauge choice. The introduction of Ramond variable makes life further difficult. Recently there are very many approaches to formualte this theory consistently but still a consistent theory in closed form is lacking which we are trying to do so.

Conference/Workshops Attended:

1. *International Strings Meeting 2018*, IISER Thiruvanta Puram, India, December, 2018.

Invited Lectures/Seminars:

1. *A series of Lectures given on Large N gauge theories*, BHU, Varanasi,.

Courses given:

1. *Quantum mechanics III* , from August-December 2018.

Other activities

1. Supervising a Student for his Thesis.
2. Supervising several students for their reading special projects.
3. (Worked in several academic and non-academic Committees)

Tribhuvan Prasad Pareek

Research Summary:

I have been working on coupled spin and charge transport over years. Spin transport is rather nontrivial as there is no continuity equation for spin currenst in presence of spin-orbit interaction. Moreover the spin-orbit interaction in condensed matter system essential a non-perturbative effect and to deal with it a new theoretical methods is required. Along these lines we have develop a non-perturbatice density matrix approach to study spin orbit interecation effects. Beside this we have developed a unified quaternionic description of coupled spin and charge transport. Where it has been shown that coupled charge and spin can be combined to define a quaternionic currents and it can be used to define unitarity condition for spin and charge currents at equal footing.

Publications:

1. Unified quaternionic description of charge and spin transport and intrinsic nonlinearity of spin currents. IJMPB, Vol 32, 26, 2018

Other Activities:

1. Taught a course on classical mechanics. Member of graduate comm. and transport comm.

Arun Kumar Pati

Research Summary: (Technical)

Potent Value and Potent Operator: We introduce a novel concept which we call as potent value of system observable for pre- and post-selected quantum states. This describes, in general, how a quantum system affects the state of the apparatus during the time between two strong measurements corresponding to pre- and post-selections. The potent value can be realized for any interaction strength and for arbitrary coupling between the system and the apparatus observables. Most importantly, potent values generalize and unify the notion of the weak values and modular values of observables in quantum theory. Furthermore, we define a potent operator which describes the action of one system on the another and show that superposition of time-evolutions and time-translation machines are potent operators. These concepts may find useful applications in quantum information processing and can lead to technological benefits.

Impossibility of Cloning of Quantum Coherence: It is well known that it is impossible to clone an arbitrary quantum state. However, this inability does not lead directly to no-cloning of quantum coherence. Here, we show that it is impossible to clone the coherence of an arbitrary quantum state which is a stronger statement than the 'no-cloning of quantum state'. In particular, with ancillary system as machine state, we show that it is impossible to clone the coherence of states whose coherence is greater than the coherence of the known states on which the transformations are defined. Also, we characterize the class of states for which coherence cloning will be possible for a given choice of machine. Furthermore, we find the maximum range of states whose coherence can be cloned perfectly. The impossibility proof also holds when we do not include machine states.

Stronger classes of sum uncertainty and reverse uncertainy relations: Uncertainty relations are old, yet potentially rewarding to explore. By introducing a quantity called the uncertainty matrix, we provide a link between purity and observable incompatibility, and derive several stronger uncertainty relations in both forward and reverse directions for arbitrary quantum states, i.e., mixed as well as pure, and arbitrary incompatible quantum observables, none of which suffer from the problem of triviality. Besides the tightness, the interpretations of terms in these uncertainty relations may be of independent inter- est. We provide the possible generalization of stronger uncertainty relations to sum of variances of more than two observables. We also demonstrate applications of techniques used here to, firstly, obtain a simple reverse quantum speed limit for quantum states undergoing Markovian dynamical evolution, and secondly, to provide a lower bound for fidelity between two quantum states

Measuring average of non-Hermitian operator : Quantum theory allows direct measurement of the average of a non-Hermitian operator using the weak value of the positive semidefinite part of the non-Hermitian operator. Here, we experimentally demonstrate the measurement of weak value and average of non-Hermitian operators by a novel interferometric technique. Our scheme is unique as we can directly obtain the weak value from the interference visibility and the phase shift in a Mach Zehnder interferometer without using any weak measurement or post selection. Both the experiments discussed here were performed with laser sources, but the results would

be the same with average statistics of single photon experiments. Thus, the present experiment opens up the novel possibility of measuring weak value and the average value of non-Hermitian operator without weak interaction and post-selection, which can have several technological applications

Superposition of causal order as a metrological resource for quantum thermometry: We propose a novel approach to qubit thermometry using a quantum switch, that introduces an indefinite causal order in the probe-bath interaction, to significantly enhance the thermometric precision. The resulting qubit probe shows improved precision in both low and high temperature regimes when compared to optimal qubit probes studied previously. It even performs better than a Harmonic oscillator probe, in spite of having only two energy levels rather than an infinite number of energy levels as that in a harmonic oscillator. We thereby show unambiguously that quantum resources such as the quantum switch can significantly improve equilibrium thermometry. We also derive a new form of thermodynamic uncertainty relation that is tighter and depends on the energy gap of the probe. The present work may pave the way for using indefinite causal order as a metrological resource.

Quantifying the particle aspect of quantum systems : The possibility of a quantum system to exhibit properties that are akin to both the classically held notions of being a particle and a wave, is one of the most intriguing aspects of the quantum description of nature. These aspects have been instrumental in understanding paradigmatic natural phenomena as well as to provide nonclassical applications. A conceptual foundation for the wave nature of a quantum state has recently been presented, through the notion of quantum coherence. We introduce here a parallel notion for the particle nature of a quantum state of an arbitrary physical situation. We provide hints towards a resource theory of particleness.

Quantum precision thermometry with weak measurement : As the minituarization of electronic devices, which are sensitive to temperature, grows apace, sensing of temperature with ever smaller probes is more important than ever. Genuinely quantum mechanical schemes of thermometry are thus expected to be crucial to future technological progress. We propose a new method to measure the temperature of a bath using the weak measurement scheme with a finite dimensional probe. The precision offered by the present scheme not only shows similar qualitative features as the usual Quantum Fisher Information based thermometric protocols, but also allows for flexibility over setting the optimal thermometric window through judicious choice of post selection measurements.

Superposition of causal order enables perfect quantum teleportation : We show that the fidelity of the standard quantum teleportation protocol, which utilizes an impure resource state, applied successively, can be significantly improved, when used in conjunction with a quantum switch. In particular, we find that for two such teleportation channels conjugated with the superposition of causal order, teleportation fidelity beyond the classical threshold is achieved for significantly larger noise than would be possible conventionally. One can even make the effective teleportation channel perfectly faithful for very large noise. We also discuss the generalization of our scheme for more than two pathways, and define a figure of merit in that context

Teleporting Grin of a Quantum Chesire Cat without cat : Quantum Chesire Cat is a counterintuitive phenomenon that provides a new window into the nature of the quantum systems in relation to multiple degrees of freedom associated with a single

physical entity. Under suitable pre and postselections, a photon (the cat) can be decoupled from its circular polarization (its grin). In this paper, we explore whether the grin without the cat can be teleported to a distant location. This will be a totally disembodied teleportation protocol. Based on the original Quantum Chesire Cat setup, we design a protocol where the circular polarization is successfully teleported between two spatially separated parties even when the photon is not physically present with them. The process raises questions in our understanding about properties of quantum system. In particular it shows that question like "whose polarization is it" can prove to be vacuous in such scenario.

Quantum Coherence, Coherent Information and Information Gain in Quantum Measurement: A measurement is deemed successful, if one can maximize the information gain by the measurement apparatus. Here, we ask if quantum coherence of the system imposes a limitation on the information gain during quantum measurement. First, we argue that the information gain in a quantum measurement is nothing but the coherent information or the distinct quantum information that one can send from the system to apparatus. We prove that the maximum information gain from a pure state, using a mixed apparatus is upper bounded by the initial coherence of the system. Further, we illustrate the measurement scenario in the presence of environment. We argue that the information gain is upper bounded by the entropy exchange between the system and the apparatus. Also, to maximize the information gain, both the initial coherence of the apparatus, and the final entanglement between the system and apparatus should be maximum. Moreover, we find that for a fixed amount of coherence in the final apparatus state the more robust apparatus is, the more will be the information gain.

Publications:

1. G. Nirala, S. N. Sahoo, A. K. Pati, U. Sinha, *Measuring average of non-Hermitian operator with weak value in a Mach-Zehnder interferometer*, Phys. Rev. A 99, 022111 (2019).

2. Sk Sazim, S. Adhikari, A. K. Pati, and P. Agrawal, *Mutual Uncertainty, Conditional Uncertainty, and Strong Subadditivity*, Phys. Rev. A 98, 032123 (2018).

3. G. Sharma, C. Mukhopadhyay, Sk Sazim, A. K. Pati, *Quantum Uncertainty Relation Based on the Mean Deviation*, Phys. Rev. A 98, 032106 (2018).

4. G. Sharma, A. K. Pati, *Tradeoff Relation for Coherence and Disturbance*,Phys. Rev. A 97, 062308 (2018).

5. K. Modi, A. K. Pati, A. Sen De, U. Sen, *Masking Quantum Information is Impossible*, Phys. Rev. Lett. 120, 230501 (2018).

6. C. Datta, Sk Sazim, A. K. Pati, P. Agrawal, *Coherence of quantum channels*, Annals of Physics, 397, 243-258 (2018).

7. C. Mukhopadhyay, A. Misra, S. Bhattacharya, A. K. Pati, *Quantum speed limit constraints on a nanoscale autonomous refrigerator*,Physical Review E 97, 062116 (2018).

8. *C. Mukhopadhyay, Sk Sazim, A. K. Pati, Coherence makes quantum systems magical*, J. Phys. A: Math. Theor. 51, 414006 (2018).

9. S. Bhattacharya, S. Banerjee, A. K. Pati, *Evolution of coherence and non-classicality under global environmental interaction*, Quantum Inf Process 17, 236 (2018).

10. Asutosh Kumar, I. Chakrabarty, A. K. Pati, A. Sen De, U. Sen, *Quantum no-go theorems in causality respecting systems in presence of closed time- like curves: Tweaking the Deutsch condition,* Euro Phys. Lett. 122, 10007 (2018).

Preprints:

1. G. Sharma, Sk Sazim, A. K. Pati, *Quantum Coherence, Coherent Information and Information Gain in Quantum Mea- surement*, arXiv:1903.09622.

2. D. Das, A. K. Pati, *Teleporting Grin of a Quantum Chesire Cat without cat*, arXiv:1903.04152.

3. C. Mukhopadhyay, A. K. Pati, *Superposition of causal order enables perfect quantum teleportation with very noisy singlets* , arXiv:1901.07626.

4. A. K. Pati, C. Mukhopadhyay, S. Chakraborty, S. Ghosh, *Quantum precision thermometry with weak measurement* arXiv:1901.07415.

5. C. Mukhopadhyay, M. K. Gupta, A. K. Pati, *Superposition of causal order as a metrological resource for quantum thermometry* arXiv:1812.07508

6. C. Mukhopadhyay, A. K. Pati, *Stronger Classes of Sum Uncertainty and Reverse Uncertainy Relations*, arXiv:1806.11347 (2018).

7. D. Patel, S. Patro, C. Vanarasa, I. Chakrabarty, A. K. Pati, *Impossibility of Cloning of Quantum Coherence*, arXiv:1806.05706 (2018)

8. A. K. Pati, *Potent Value and Potent Operator with Pre- and Post-selected Quantum Systems,* arXiv:1805.10202 (2018).

Visits to other Institutes:

1. Visited Prof. S. Ghosh at IMSc, Chennai from January 3- Feb 3, 2019.

2. Visited Prof. U Sinha at RRI, Bangalore from Feb 10-25, 2019.

3. Visited Dr I. Chakrabarti at IIIT, Hyderabad from 26 th April- 8 th May 2018.

Invited Lectures/Seminars:

1. Invited speaker for Workshop on Quantum Information and Quantum Foundations in Chania, Crete, Greece during July 8-12, as part of the larger "7th International Conference on New Frontiers in Physics".

2. Invited speaker in Quantum Frontiers and Fundamentals 2018 held at Raman Research Institute, Bangalore during 30th April to 04th May 2018.

3. Invited speaker for IEEE Chapter on Quantum Computing at Microsoft Garage, Hyderabad on January 19, 2019.

4. Invited speaker in International Symposium titled Celebrating the Physics of Anthony Leggett in honour of Prof. Anthony Leggett on his 80th Birthday at Raman Research Institute, Bangalore during 3 4 February 2019.

5. Invited speaker in Conference on Quantum Information and Many-Body Theory during March 01-03, 2019 held at IIT, BHU, Varanasi.

Academic Highlights:

- J C Bose Fellowship for 2019 from the Department of Science and Technology.
- Impossible to mask quantum information was featured in physics of APS site and was highlighted in phy.org.
- Quantum information revolution —-is India ready? An interview with K. S. Jayaraman of Nature India, published on May 28, 2018.

Other Activities:

1. Guided several visiting students in the area of Quantum Information.

2. Evaluated Ph.D. thesis from University of Calcutta.

3. 4 Ph.D. students are working in the area of Quantum Information.

Santosh Kumar Rai

Research Summary: (Technical)

My research has been mainly focussed on studying models beyond the Standard Model (SM) of particle physics and analysing their collider signals at the Large Hadron Collider (LHC). During last year I have proposed models with specifics on fermion mass generation in extended gauge symmetries and in particular existence of vector-like fermions. The role of vector-like fermions in collider signals as well as flavour physics was also studied in a model dependent way. I have also studied extended scalar sectors and studied their collider signatures. In addition, I have continued my work on supersymmetric scenarios with left-right symmetry as well as compressed mass spectrum and studied their LHC phenomenology.

In studying a popular extension of the scalar sector of the SM by an additional scalar doublet, we analyzed the prospects of reconstructing the mass of a heavy charged Higgs boson in the context of a Type-X two-Higgs doublet model where a light pseudoscalar A in the mass range 4060 GeV is phenomenologically allowed, and is in fact favoured if one wants to explain the muon anomalous magnetic moment. The associated production of charged Higgs with the pseudoscalar A and subsequent decay of the charged Higgs into a W and A, is found to be our relevant channel. The branching ratio for $H^+ \to W^+A$ with $M_{H^+} \sim 200$ GeV, is close to 50%. The hadronic decay of the W boson, coupled with the leptonic decays of A into a tau and muon pair, help in identifying the charged Higgs. The neutral heavy Higgs, being degenerate with the charged Higgs for most of the allowed parameter space of the model, also contributes to similar final states. Thus both of these particles are reconstructed within a band of about 10 GeV.

In another model which extends the scalar sector of SM by a triplet, generation of neutrino mass forms the motivation and the model predicts a doubly-charged scalar in the process. We studied the discovery prospect of this doubly-charged component of the $SU(2)_L$ triplet scalar at the future $e^- p$ collider FCC-eh, proposed to operate with an electron beam energy of 60 GeV and a proton beam energy of 50 TeV. We consider the associated production of the doubly-charged Higgs boson along with leptons and jet(s), and its subsequent prompt decay to same-sign lepton pair. We present our analysis for two different final states, $3\ell+ \geq 1j$ and an inclusive $\geq 2\ell+ \geq 1j$ channel. Considering its decay to electrons only, we found that the doubly-charged Higgs with mass around a TeV could be observed at 3σ confidence level with $(200) fb^{-1}$ of integrated luminosity, while masses up to 2 TeV could be probed within a few years of data accumulation. The reach is significantly improved if it is triggered in the $\mu\mu$ mode. We also highlight the sensitivity of FCC-eh to the Yukawa coupling responsible for production of the doubly-charged Higgs boson as a function of its mass in both the ee and $\mu\mu$ channels.

In continuation of an earlier work of ours on a non-abelian extension to the SM where we considered a leptophobic model with vector-like fermions, we studied signals for vector-like quarks in a 221 model characterized by the gauge group $SU(2)_L \times SU(2)_2 \times U(1)_X$, where the $SU(2)_2$ is leptophobic in nature. We discuss about the pattern of mixing between SM quarks and vector-like quarks and how we prevent tree level flavour-changing interactions in the model. The model also predicts tauphilic

scalars decaying mostly to tau leptons. We studied a typical signal of the model in the form of pair production of top-type vector-like quarks which decays to the tauphilic scalars and a third generation quark. We analyze the resulting final state signal for the 13 TeV and 14 TeV LHC, containing $\geq 3j\,(1b)+ \geq 2\tau+ \geq 1\ell$ and discuss the discovery prospects of such vector-like quarks with non-standard decay modes.

In a study involving a left-right symmetry extension of the minimal supersymmetric standard model (MSSM), we performed a comprehensive dark matter analysis that included constraints from dark matter direct and indirect detection experiments. We focused on dark matter candidates which, while satisfying all constraints, are different from those of the MSSM. We considered in our analysis all possible co-annihilation channels relevant for setups in which several states are light and nearly degenerate, and devise a set of representative benchmark points, requiring co-annihilations, which satisfy all restrictions. We then studied their consequent LHC signals, which exhibit promising new multileptonic signatures involving W_R, that if observed, would provide a strong support for left-right supersymmetry.

In other relevant works, we studied the phenomenology of an universal seesaw mechanism for the generation of masses of all the SM quarks and leptons and also looked at flavour physics signals and studied the phenomenological consequences of introducing a new fourth generation Z_2 odd vector-like lepton doublet along with a SM singlet scalar and an $SU(2)_L$ singlet scalar leptoquark carrying electromagnetic charge of +2/3, both odd under a Z_2.

Research Summary: (Non-Technical)

My current area of research encompasses the study of phenomena involving elementary particles and its interactions. During last year my research has mainly focused on studying models with exotic vector-like quarks, neutrino mass models, scalar sectors and new dark matter candidates, while studying their implications at hadron and lepton-hadron colliders at CERN. I worked on the above beyond standard model physics scenario signals and proposed new models and analyzed ways of discovering their signals experimentally.

Publications:

1. A. Chatterjee, M. Frank, B. Fuks, K. Huitu, S. Mondal, Santosh Kumar Rai and H. Waltari, *Multileptonic signals of co-annihilating left-right supersymmetric dark matter,* Phys. Rev. D **99**, no. 3, 035017 (2019).

2. E. J. Chun, S. Dwivedi, T. Mondal, B. Mukhopadhyaya and Santosh Kumar Rai, *Reconstructing heavy Higgs boson masses in a type X two-Higgs-doublet model with a light pseudoscalar particle,* Phys. Rev. D **98**, no. 7, 075008 (2018).

3. A. Patra and Santosh Kumar Rai, *Lepton-specific universal seesaw model with left-right symmetry,* Phys. Rev. D **98**, no. 1, 015033 (2018) .

Preprints:

1. P. S. B. Dev, S. Khan, M. Mitra and Santosh Kumar Rai, *Doubly-charged Higgs Boson at Future Electron-Proton Collider,* [arXiv:1903.01431 [hep-ph]].

2. K. Das, T. Mondal and Santosh Kumar Rai, *Non-standard signatures of vector-like quarks in a leptophobic 221 model,* [arXiv:1807.08160 [hep-ph]].

3. L. Dhargyal and Santosh Kumar Rai, *Implications of a vector-like lepton doublet and scalar Leptoquark on $R(D^{(*)})$,* [arXiv:1806.01178 [hep-ph]].

Conference/Workshops Attended:

1. *Invitation to Particle Cosmology* : Manipal Academy of Higher Education (MAHE), Manipal, Karnataka, India, December 2018.

2. *IMHEP 2019:* Institute of Physics (IOP), Bhubaneswar, India, January, 2019.

Visits to other Institutes:

1. Institute of Physics (IOP), Bhubaneswar, India, July 2018.

2. Indian Institutes of Science Education and Research (IISER) Pune, India, August 2018.

3. Manipal Academy of Higher Education (MAHE), Manipal, December, 2018.

4. Institute of Physics (IOP), Bhubaneswar, India, January 2019.

Invited Lectures/Seminars:

1. *Some non-standard signals of vector-like quarks at LHC:* IMHEP 2019, Institute of Physics (IOP), Bhubaneswar, January 2019.

2. *Introduction to Standard Model:* Invitation to Particle Cosmology; Manipal Academy of Higher Education (MAHE), Manipal, December 4-6, 2018.

3. *Search for light Higgsinos at LHC with a right-sneutrino LSP:* Indian Institutes of Science Education and Research (IISER) Pune, August 2, 2018.

4. *Search for light Higgsinos at LHC with a right-sneutrino LSP:* Institute of Physics (IOP), Bhubaneswar, July 30, 2018.

Other Activities:

1. Taught M.Sc. course at HRI titled *Electrodynamics*, Jan-April, 2018 and Aug-Dec, 2018.

2. Supervising Ph.d. of Mr. Kasinath Das (defended in Jan, 2019) and Ms. Juhi Dutta.

3. Member, Local Works Committee 2018, HPC Cluster, 2018.

4. Member, Organising Committee, Invitation to Particle Cosmology; Manipal Academy of Higher Education (MAHE), Manipal, December 2018.

5. Academic Co-ordinator, Working Group on Neutrinos at Colliders, IMHEP 2019, Institute of Physics (IOP), Bhubaneswar, January 2019.

Sumathi Rao

Research Summary: (Technical)

During the period, April 2018-March 2019, we continued our work on topological phases of matter.

We are studying spin-mode switching at the edges in the $\nu = 4$ quantum Hall effect, which appears to have many new features beyond the case of $\nu = 3$ edge states. Besides multiple mode switchings, we also note that there are some parameter regimes, where the transitions appear to be first order. We are also investigating possible neutral modes that arise in the $\nu = 3$ case, when the spin of the modes switch in a second order transition, using an effective theory approach. We are also looking at possible further extensions of this work to graphene systems.

We are studying the physics of the one dimensional Luttinger liquids formed at a junction where light of two different polarisations impinge normally on bilayer graphene. We find that the Luttinger liquid parameters can be tuned by the polarisation and amplitude of the light shining on it, and we study transport signals sensitive to the light.

We are continuing our earlier work on Weyl semimetals. More specifically, we are now studying how the anomaly term induces charges on monopoles (end-points of vortices which can be physically realised) and converts them into dyons. We are also trying to understand the difference between consistent and covariant anomalies, in the context of lattice models, both for gauge as well as gravitational anomalies.

We are studying the physics of introducing a vortex in a topological superconductor (p wave superconductor), and we find that similar to s-wave superconductors, here also, there is a change in the change in the periodicity of the persistent current when the value of the superconducting gap changes from small to large. We are also working on weak pairing higher order topological superconductors. Higher order implies that these are d-dimensional topologically non-trivial insulators or superconductors with $d - 2$ dimensional boundary states - corners in 2 dimensions and hinges in 3 dimensions.

We worked on quantum charge pumping through Majorana bound states in an Aharanov-Bohm ring geometry following our earlier work on transport in this geometry. We showed that the Fourier transform of the pumped charge with respect to the flux shows distinct differences between a Majorana bound state and an Andreev bound state and can be thought of as a diagnostic for Majorana bound states. We are currently working on a lattice model to confirm the same and also understand differences between adiabatic pumping and pumping at higher frequencies.

We are also working on obtaining the critical exponents for topological phase transitions in Floquet topological phases, using a formalism called curvature renormalisation group formalism. We have obtained the critical exponents and phase diagrams for an inversion symmetric model and an inversion symmetry broken model in one dimension and are working on extending the formalism to higher dimensions.

Research Summary: (Non-Technical)

We have continued to work on new phases of matter classified by topology, rather than the older paradigm of broken symmetries. In particular, we have looked at new

phenomena that happens at the physical edge of topological samples when electron-electron interactions are included and also at edges formed by shining light of different polarisations on samples. We have worked on new topological materials that have been recently discovered including Weyl semi-metals and higher order topological insulators and superconductors where the boundary states are formed in two dimensions lower than the dimension in which the material exists. We are trying to study formalisms using curvature functions and renormalisation group approaches with the aim of going beyond band theory and including electron-electron interactions in these materials. Finally, we are also working on non-abelian excitations like Majorana modes and parafermions, with the long-term aim of using these excitations in topological quantum computation.

Publications:

1. Priyanka Mohan and Sumathi Rao, *Interplay of Floquet Lifshitz transitions and topological transitions in bilayer Dirac materials*,cond-mat/1805.04125, Phys. Rev.**B98**, 165406(2018).

2. Dibya Kanti Mukherjee, Sumathi Rao and Sourin Das, *Fabry-Perot interferometry in Weyl semi-metals*, cond-mat/1710.06873, Journal of Condensed matter physics, **31**, 045302 (2019).

3. Krashna Mohan Tripathi, Sumathi Rao and Sourin Das, *Quantum charge pumping through Majorana bound states*, Phys. Rev.**B99**, 085435 (2019).

Conference/Workshops Attended:

1. Edge reconstruction:Transport and quantum phase transitions, PCS IBS, Daejeon, June 25-29, 2018

2. National conference on quantum condensed matter, IISER Mohali, 25-27 July 2018

3. New Trends in Field Theories, Banaras Hindu University, Varanasi Nov 25-30, 2018

4. Topological aspects of quantum matter, TIFR, Mumbai, December 17-20, 2018

5. Asia Pacific Conference and Workshop on quantum information Science, IISER Kolkata, Dec 20-23, 2018

6. March meeting of the American Physical Society, Boston Convention Centre, Boston, U.S.A., March 4-8 2019

7. Recent topics in string theory and cosmology, NISER, Bhubaneswar, March 28-31, 2019

Visits to other Institutes:

1. Visit to ICTP, Trieste, Italy, May 19-June 10, 2018
2. Visit to Presidency University, Kolkata, October 10, 2018
3. Visit to University of Kentucky, Lexington, U.S. A., Feb 28-March 3, 2019

Invited Lectures/Seminars:

1. Majorana bound states in an Aharanov-Bohm geometry, PCS IBS Daejeon, Korea, June 25, 2018
2. Spin mode switching in the integer quantum Hall effect, IISER, Mohali, July 25, 2018
3. Topological phases of quantum matter, Presidency University, Kolkata, October 10, 2018
4. Spin mode switching in the integer quantum Hall effect, BHU Varanasi, November 27 2018
5. Spin mode switching in the integer quantum Hall effect, TIFR, Mumbai, Dec 18, 2018
6. Majorana modes and their identification, University of Kentucky, Lexington, U.S.A, Feb 25, 2019
7. Majorana modes and their identification, IPA-DAE C. V. Raman Lecture, BHU, Varanasi, March 27, 2019
8. Topological phases of quantum matter, NISER, Bhubaneswar, 31 March 2019

Academic recognition/Awards:

1. Selected as senior associate of the ICTP, Trieste, Italy.

Other Activities:

1. Divisional Associate Editor, Physical Review Letters
2. Member, Academic council, MNNIT (Motilal Nehru National Institute of Technology), Allahabad
3. Convenor, Endowment committee
4. Member, Housing allotment committee, Women's grievance cell/Internal Complaints committee, HRI
5. Taught Condensed matter physics, HRI, Aug - Dec 2018

6. Worked with several visiting students and wrote a report on topological phases of matter with an Indian Academy of Science visiting student Raghav Chaturvedi, July 2018

Ashoke Sen:

Research Summary:

My work during April 2018 - March 2019 has been on different aspects of string theory and classical and quantum theory of gravity.

1. Together with Alok Laddha, I showed that in four space-time dimensions, soft theorem gets a logarithmic correction at the subleading order. This has the effect of producing a tail in the gravitational wave radiation that falls off as inverse power of the retarded time at late time. The original analysis was done in the context of decay where a massive object decays to a massive object and some light objects. In collaboration with Biswajit Sahoo, I generalized this to the most general scattering process.

2. With Roji Pius I showed how our previous proof of the Cutkosky rules in string theory can be used to show explicitly the unitarity of a box diagram in quantum field theory. In particular the contribution from unphysical singularities like anomalous threshold drops out in the final formula.

3. With Corinne de Lacroix and Harold Erbin I examined analyticity properties of superstring loop amplitudes and showed that they are the same as in local quantum field theories.

4. I showed how string field theory can be used to regulate the usual world-sheet ultraviolet divergences that arise in the computation of tree amplitudes of string theory.

5. I analyzed Hamiltonian formulation of theories of chiral (2n+1)-forms in (4n+2) dimensions, using the action that I had proposed earlier. Duality symmetries that are not manifest in the action, becomes manifest in the Hamiltonian formalism.

Publications:

1. A. Laddha and A. Sen, *Logarithmic Terms in the Soft Expansion in Four Dimensions*, JHEP **1810**, 056 (2018) doi:10.1007/JHEP10(2018)056.

2. R. Pius and A. Sen, *Unitarity of the Box Diagram*, JHEP **1811**, 094 (2018).

3. B. Sahoo and A. Sen, *Classical and Quantum Results on Logarithmic Terms in the Soft Theorem in Four Dimensions*, JHEP **1902**, 086 (2019).

4. C. De Lacroix, H. Erbin and A. Sen, *Analyticity and Crossing Symmetry of Superstring Loop Amplitudes*, JHEP **1905**, 139 (2019).

Preprints:

1. A. Laddha and A. Sen, *Observational Signature of the Logarithmic Terms in the Soft Graviton Theorem*, arXiv:1806.01872 [hep-th].

2. A. Sen, *String Field Theory as World-sheet UV Regulator*, arXiv:1902.00263 [hep-th].

3. A. Sen, *Self-dual forms: Action, Hamiltonian and Compactification,* arXiv:1903.12196 [hep-th].

Conferences/Workshop Attended

1. 50 years of the Veneziano model, GGI, Florence, May 2018
2. Solvay workshop on Infrared Physics, Brussels, May 2018
3. Cargese Summer School in High Energy Physics and Astrophysics, June 2018
4. Amplitudes 2018, SLAC, Stanford, June 2018
5. Strings 2018, Okinawa, Japan, June 2018
6. New Frontiers in String Theory, YITP, Kyoto, July 2018
7. New Trends in Field Theories, BHU, November 2018
8. String and M-Theory: The New Geometry of the 21st Century, Singapore, December 2018
9. Indian strings meeting, IISER Trivandrum, December 2018

Other Activities

1. General Relativity, August-October, 2018
2. Cosmology, January-April, 2019

Prasenjit Sen

Research Summary:

We studied evolution of the structure and electronic properties of α-MnO_2 under pressure. At $\sim$ 66 GPa, it transforms to δ-MnO_2, which is a layered material. Removal of pressure does not transform the structure back to α-MnO_2. So far, δ-MnO_2 has been produced only through thermal decomposition of $KMnO_4$. Our results suggest a possible physical way of producing δ-MnO_2. Currently we are studying properties of α-MnO_2 as cathode in Li-air batteries.

We have studied structural, electronic and magnetic properties of clusters with the general composition Co_4A_2; A is one of C, Si, Ge, N, P and As. We have also calculated their magnetic anisotropy energies (MAE). This is motivated by the strategic requirement of designing permanent magnets without the rare earth elements. We discovered a strong positive, nearly linear correlation between the ratio of the sum of the spin moments on all the atoms and the HOMO-LUMO gaps, and the MAEs of these clusters. This observation can be exploited in design of new nano-scale hard magnets.

Publications:

1. K. Alam, N. Seriani and P. Sen, *α-MnO_2 under pressure: Possible route to δ-MnO_2*, Mat. Res. Exp. **6**, 076108, (2019)

2. S. Bhattacharyya, P. Sen, S. Mukund, S. Yarlagadda, D. Bandyopadhyay, S. G. Nakhate, *Ionization energies and structures of small lanthanum oxide clusters $(La_2O_3)_n.LaO$ $(n = 1 - 3)$*, Eur. Phys. J D **accepted**, (2019)

Preprints:

1. A. Sen and P. Sen, *Designing rare earth free permanent magnets: Insights from small Co clusters.*

Conference/Workshops Attended:

1. *International Symposium on Advanced Functional Materials (ISAFM-2018)*, India, July, 2018.

2. *National Conference on Electronic Structure (NCES-2018)*, India, December, 2018.

1. *Computational design of novel materials: Magnetic semiconductors, spin-gapless materials and more*, International Symposium on Advanced Functional Materials (ISAFM-2018), IISER Thiruvananthapuram, Thiruvananthapuram, July, 2018.

2. *Designing permanent magnets without rare earths: Insights from atomic clusters*, National Conference on Electronic Structure (NCES- 2018), SRM University, Chennai, December 2018.

Other Activities:

1. Member of Editorial Board, Physica Scripta.
2. External member of Expert Committee to set up computational facilities at IISER-Mohali.
3. Taught Mathematical Methods 1 during August-December, 2018.
4. Reviewed papers for journals.
5. Convener Cluster Committee, member Colloquium Committee, Physics Graduate Committee, Internal Complaints Committee.

Ujjwal Sen

Research Summary: (Technical)

In the last academic year, we have worked in several areas in quantum information and computation, including fundamentals as well as applications of the subject. In particular, we have provided a general resource theory by quantifying the particle aspect of general quantum systems. This is complementary to the recently formulated theory of quantum coherence that quantifies the wave aspect of quantum systems. We have also argued that the usual method to optimize a quantum process by using the fidelity is incomplete, and introduce a new measure called quantum process randomness to, at least partly, handle the incompleteness. In another work, we have considered disorder-induced effects on bipartite entanglement in noisy dynamics of Bose-Hubbard and Fermi-Hubbard quantum glasses.

In our argument for incompleteness of quantum process optimization, we conceptualize and propose a measure of "randomness" in the measurement result at the output of that quantum process, and inquire whether an optimization of the quantum process based on that measure, can reach the point where the process operates with maximum fidelity. We consider approximate quantum cloning and teleportation processes, and find, in particular, that the optimal approximate state-dependent quantum cloning machine obtained by maximizing the fidelity is different from that obtained by minimizing the randomness.

The possibility of a quantum system to exhibit properties that are akin to both the classically held notions of being a particle and a wave, is one of the most intriguing aspects of the quantum description of nature. These aspects have been instrumental in understanding paradigmatic natural phenomena as well as to provide nonclassical applications. A conceptual foundation for the wave nature of a quantum state has recently been presented, through the notion of quantum coherence. In our work on the resource theory of quantum particleness, we introduce a parallel notion for the particle nature of a quantum state of an arbitrary physical situation. We provide hints towards a resource theory of particleness, give a quantification of the same, and indicate a complementarity of the particleness with quantum coherence for arbitrary quantum states.

In our work on quantum glasses, we address the effects of quenched disorder averaging in the time-evolution of systems of ultracold atoms in optical lattices in the presence of noise, imposed by of an environment. For bosonic systems governed by the Bose-Hubbard Hamiltonian, we quantify the response of disorder in Hamiltonian parameters in terms of physical observables, including bipartite entanglement in the ground state and report the existence of disorder-induced enhancement in weakly interacting cases. For systems of two-species fermions described by the Fermi-Hubbard Hamiltonian, we find similar results. In both cases, our dynamical calculations show no appreciable change in the effects of disorder from that of the initial state of the evolution. We explain our findings in terms the statistics of the disorder in the parameters and the behaviour of the observables with the parameters.

In another work, we consider a quantum particle (walker) on a line who coherently chooses to jump to the left or right depending on the result of toss of a quantum coin. The lengths of the jumps are considered to be independent and identically distributed

quenched Poisson random variables. We find that the spread of the walker is significantly inhibited, whereby it resides in the near-origin region, with respect to the case when there is no disorder. The scaling exponent of the quenched-averaged dispersion of the walker is sub-ballistic but super-diffusive. We also show that the features are universal to a class of sub- and super-Poissonian distributed quenched randomized jumps. In a related work, we quantitatively differentiate between the spreads of discrete-time quantum and classical random walks on a cyclic graph. Due to the closed nature of any cyclic graph, there is additional "collision"- like interference in the quantum random walk along with the usual interference in any such walk on any graph, closed or otherwise. We find that the quantum walker remains localized in comparison to the classical one, even in the absence of disorder, a phenomenon that is potentially attributable to the additional interference in the quantum case. This is to be contrasted with the situation on open graphs, where the quantum walker, being effectively denied the collision-like interference, garners a much higher spread than its classical counterpart. We use Shannon entropy of the position probability distribution to quantify spread of the walker in both quantum and classical cases. We find that for a given number of vertices on a cyclic graph, the entropy with respect to number of steps for the quantum walker saturates, on average, to a value lower than that for the corresponding classical one. We also analyze variations of the entropies with respect to system size, and look at the corresponding asymptotic growth rates.

In another work, we introduce a probabilistic version of the one-shot quantum dense coding protocol in both two- and multiport scenarios, and refer to it as conclusive quantum dense coding. Specifically, we analyze the corresponding capacities of two-qubit, two-qutrit, and three-qubit shared states. We identify cases where Pauli and generalized Pauli operators are not sufficient as encoders to attain the optimal one-shot conclusive quantum dense coding capacities. We find that there is a rich connection between the capacities, and the bipartite and multipartite entanglements of the shared state.

Different ensembles of the same density matrix are indistinguishable within the modern Kolmogorov probability measure theory of quantum random phenomena. In a further work, we find that changing the framework from the Kolmogorov one to a frequentist-inspired theory of quantum random phenomena – a la von Mises – would lift the indistinguishability, and potentially cost us the no-signaling principle (i.e., leads to superluminal communication). We believe that this adds to the recent works on the search for a suitable representation of the state of a quantum system. While erstwhile arguments for potential modifications in the representation of the quantum state were restricted to possible variations in the formalism of the quantum theory, we indicate a possible fallout of altering the underlying theory of random processes.

Further works include those on tensor-network approach to compute genuine multisite entanglement in infinite quantum spin chains, witnessing entanglement sequentially, canonical Leggett-Garg inequality, response in violation of Bell inequality to imperfect photon addition and subtraction in noisy squeezed states of light, partial coherence and quantum correlation with fidelity and affinity distances, universality in distribution of monogamy scores for random multiqubit pure states, multipartite entanglement at dynamical quantum phase transitions with non-uniformly spaced criticalities, etc.

Research Summary: (Non-Technical)

Quantum information and computation is an area of research that has an interface with several other sciences, including quantum condensed matter, ultra-cold gases, quantum optics, information theory, cryptography, etc. It promises to provide quantum technologies for various tasks that are otherwise hard to perform. The members of the quantum information and computation (QIC) group at HRI works on a broad range of topics in these areas, and some of the topics covered in the previous academic year are quantum Chesire cat, quantum batteries, quantum uncertainty relations, quantum thermodynamics, quantum thermometry, monogamy of entanglement, quantum resource theories, quantum particleness, quantum channels, wave-particle duality, quantum dense coding, quantum master equations, non-Markovianity, disordered quantum many-body systems, genuine multisite entanglement, etc.

The quantum information and computation group at HRI consists of three faculty members, 14 PhD students, five postdoctoral fellows, and one adjunct professor. The group has research contacts with several other groups, both theoretical and experimental, in different institutes in India and abroad (mainly in Europe, Singapore, Canada, and the US). The group encourages students, and junior and senior scientists as visitors for short research stays from all over India and abroad, as part of their general humanpower development program. Members of the group have presented invited lectures in different institutes in India and abroad to disperse the research performed by the group, as well as to forge new collaborations. The group has produced several research papers in the last academic year. The group takes part of the India-wide umbrella organization of DST called QUEST. It had recently organised a DST meeting that chalked out the possible directions that the country should take in experimental and theoretical quantum computation, quantum cryptography, and beyond.

Publications:

1. Soorya Rethinasamy, Saptarshi Roy, Titas Chanda, Aditi Sen De, Ujjwal Sen, *Universality in Distribution of Monogamy Scores for Random Multiqubit Pure States*, Phys. Rev. A **99**, 042302 (2019).

2. Chunhe Xiong, Asutosh Kumar, Minyi Huang, Sreetama Das, Ujjwal Sen, Junde Wu, *Partial coherence and quantum correlation with fidelity and affinity distances*, Phys. Rev. A **99**, 032305 (2019).

3. Sudipto Singha Roy, Himadri Shekhar Dhar, Aditi Sen De, Ujjwal Sen, *Tensor-network approach to compute genuine multisite entanglement in infinite quantum spin chains*, Phys. Rev. A **99**, 062305 (2019).

4. Saptarshi Roy, Titas Chanda, Tamoghna Das, Aditi Sen De, Ujjwal Sen, *Response in violation of Bell inequality to imperfect photon addition and subtraction in noisy squeezed states of light*, Phys. Rev. A **98**, 052131 (2018).

5. Sreetama Das, Shiladitya Mal, Aditi Sen De, Ujjwal Sen *Inhibition of spreading in quantum random walks due to quenched Poisson-distributed disorder*, Phys. Rev. A **99**, 042329 (2019).

6. Anindita Bera, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Witnessing entanglement sequentially: Maximally entangled states are not special*, Phys. Rev. A **98**, 062304 (2018).

7. Titas Chanda, Tamoghna Das, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Canonical Leggett-Garg Inequality: Nonclassicality of temporal quantum correlations under energy constraint*, Phys. Rev. A **98**, 022138 (2018).

8. Sudipto Singha Roy, Himadri Shekhar Dhar, Aditi Sen De, Ujjwal Sen, *Fibonacci sequence and its generalizations in doped quantum spin ladders*, Journal of Magnetism and Magnetic Materials **478**, 100 (2019).

9. Anindita Bera, Utkarsh Mishra, Sudipto Singha Roy, Anindya Biswas, Aditi Sen De, Ujjwal Sen, *Benford analysis of quantum critical phenomena: First digit provides high finite-size scaling exponent while first two and further are not much better*, Phys. Lett. A **382**, 1639 (2018).

10. Saptarshi Roy, Titas Chanda, Tamoghna Das, Debasis Sadhukhan, Aditi Sen De, Ujjwal Sen, *Phase boundaries in alternating field quantum XY model with Dzyaloshinskii-Moriya interaction: Sustainable entanglement in dynamics*, Phys. Rev. B **99**, 064422 (2019).

11. Sreetama Das, Sudipto Singha Roy, Himadri Shekhar Dhar, Debraj Rakshit, Aditi Sen De, Ujjwal Sen, *Adiabatic freezing of entanglement with insertion of defects in a one-dimensional Hubbard model*, Phys. Rev. B **98**, 125125 (2018).

12. Natasha Awasthi, Samyadeb Bhattacharya, Aditi Sen De, Ujjwal Sen, *Universal quantum uncertainty relations between non-ergodicity and loss of information*, Phys. Rev. A **97**, 032103 (2018).

13. Saptarshi Roy, Titas Chanda, Tamoghna Das, Aditi Sen De, Ujjwal Sen, *Deterministic Quantum Dense Coding Networks*, Phys. Lett. A **382**, 1709 (2018).

14. Anindita Bera, Debmalya Das, Aditi Sen De, Ujjwal Sen, *Universal quantum uncertainty relations: Minimum-uncertainty wave packet depends on measure of spread*, Phys. Lett. A **383**, 1850 (2019).

15. Titas Chanda, Tamoghna Das, Debasis Sadhukhan, Amit Kumar Pal, Aditi Sen De, Ujjwal Sen, *Emergence of entanglement with temperature and time in factorization-surface states*, Phys. Rev. A **97**, 012316 (2018).

16. Mahasweta Pandit, Sreetama Das, Sudipto Singha Roy, Himadri Shekhar Dhar, Ujjwal Sen, *Effects of cavity-cavity interaction on the entanglement dynamics of a generalized double Jaynes-Cummings model*, J. Phys. B: At. Mol. Opt. Phys. **51**, 045501 (2018).

17. Titas Chanda, Tamoghna Das, Debasis Sadhukhan, Amit Kumar Pal, Aditi Sen De, Ujjwal Sen, *Scale-invariant freezing of entanglement*, Phys. Rev. A **97**, 062324 (2018).

18. Saptarshi Roy, Tamoghna Das, Asutosh Kumar, Aditi Sen De, Ujjwal Sen, *Activation of Nonmonogamous Multipartite Quantum States*, Phys. Rev. A **98**, 012310 (2018).

19. Kavan Modi, Arun Kumar Pati, Aditi Sen De, Ujjwal Sen, *Masking quantum information is impossible*, Phys. Rev. Lett. **120**, 230501 (2018).

20. Sudipto Singha Roy, Himadri Shekhar Dhar, Debraj Rakshit, Aditi Sen De, Ujjwal Sen, *Response to defects in multi- and bipartite entanglement of isotropic quantum spin networks*, Phys. Rev. A **97**, 052325 (2018).

21. Sreetama Das, Avijit Misra, Amit Kumar Pal, Aditi Sen De, Ujjwal Sen, *Necessarily transient quantum refrigerator*, EPL **125**, 20007 (2019).

22. Asutosh Kumar, Indranil Chakrabarty, Arun Kumar Pati, Aditi Sen De, Ujjwal Sen, *Quantum no-go theorems in causality respecting systems in presence of closed timelike curves: Tweaking the Deutsch condition*, EPL **122**, 10007 (2018).

Preprints:

1. C. S. Sudheer Kumar, Anup Biswas, Aditi Sen De, Ujjwal Sen, *Frequentist-approach inspired theory of quantum random phenomena predicts signaling,* arXiv:1903.12096.

2. Chirag Srivastava, Anindita Bera, Aditi Sen De, Ujjwal Sen, *One-shot conclusive multiport quantum dense coding capacities,* arXiv:1903.11709 .

3. Sreetama Das, Asutosh Kumar, Aditi Sen De, Ujjwal Sen, *Quantum Process Randomness,* arXiv:1903.03564.

4. Sreetama Das, Indranil Chakrabarty, Arun Kumar Pati, Aditi Sen, Ujjwal Sen, *Quantifying the particle aspect of quantum systems,* arXiv:1812.08656.

5. Jayanth Jayakumar, Sreetama Das, Aditi Sen De, Ujjwal Sen, *Interference-induced localization in quantum random walk on clean cyclic graph,* arXiv:1812.05158.

6. Stav Haldar, Saptarshi Roy, Titas Chanda, Aditi Sen De, Ujjwal Sen, *Multipartite entanglement at dynamical quantum phase transitions with non-uniformly spaced criticalities,* arXiv:1811.12796.

7. Saubhik Sarkar, Aditi Sen, Ujjwal Sen, *Disorder-induced Effects in Noisy Dynamics of Bose-Hubbard and Fermi-Hubbard Quantum Glasses,* arXiv:1804.09621.

Conference/Workshops Attended:

1. *Asia Pacific Conference and Workshop on Quantum Information Science at IISER Kolkata*, India, December 2019.

2. *Conference on Quantum Information and Many-Body Theory at IIT BHU, Varanasi*, India, March 2019.

Visits to other Institutes:

1. Tata Institute of Fundamental Research, Mumbai, India, April 2018.

2. Indian Institute of Technology - Banaras Hindu University, Varanasi, India, August 2018.

3. Institute of Physics, Bhubaneswar, India, December 2018.

Invited Lectures/Seminars:

1. *Quantum uncertainty relations: further landscapes*, Invited talk, Indian Institute of Technology - Banaras Hindu University, Varanasi, India, March 2019.

Other Activities:

1. Taught part of a one-semester course on "Quantum Information and Computation" during Jan-May 2019.
2. Taught a one-semester course on "Quantum Mechanics II" during Jan-May 2018.
3. Taught a one-semester course on "Quantum Mechanics II" during Jan-May 2019.
4. Guiding the theses of Sreetama Das and Chirag Srivastava of HRI.
5. Co-guide of the thesis of Anindita Bera, Calcutta University, Kolkata.
6. Serving as the convenor of Computer Committee, and member of Cluster Computing Committee at HRI.
7. Serving as referees in national and international journals.
8. Serving as members of the PhD committees of several students.
9. Serving as member of International Advisory Board of Journal of Physics B.
10. Serving as one of the (founding) editors of Quantum journal.
11. Guiding/guided projects and numerical projects of several students.
12. Guided MSc project of Subhalakshmi Bhatt, IISER Pune.
13. Guided MSc project of Sreyash Garg, NIT Surat.
14. Guiding/guided project works of several students [including Anagha KV, Khyati Jain [BITS Pilani], Ipsita Bar [IIT Chennai], Asmitha M [IIT BHU], Jayant Jayakumar [IIT Roorkee], Shivam Kesarwani].

Pratishruti Saha

Research Summary:

Project 1 - B-sector anomalies - the top connection : Measurements of B-meson decays have revealed several departures from the Standard Model. In contrast, measurements of top-quark processes seem to adhere strictly to the Standard Model. This presents a conundrum given that the left-handed bottom and top quarks belong to the same SU(2) doublet. Several models have been proposed in the literature to explain the B-sector anomalies. We confront some such models with top-sector observables to examine whether they can be tested by such measurements.

Project 2 - Diquarks in single top production : In the paper "B-sector anomalies - the top connection" mentioned above, we studied a generic Z' model. The Z' is a spin-1 particle and hence represents a vector interaction. Next we turn to scalar interactions. We posit that physics beyond the Standard Model manifests through spin-0 particles that also have baryon-number-violating couplings (i.e. diquarks). In the first of a series of projects, we examine the impact of such particles on single top production at the Large Hadron Collider.

Publications:

1. Pratishruti Saha, Ken Kiers and Alejandro Szynkman, *Single-top production and rare top interactions,* Phys. Rev. D **98**, 035003, (2018)

Preprints:

1. David London, Pratishruti Saha and Ryoutaro Watanabe, *B-sector anomalies - the top connection,* To appear in the Proceedings of the 16th Conference on Flavor Physics & CP Violation (FPCP 2018)

Conference/Workshops Attended:

1. *The 16th Conference on Flavor Physics and CP Violation (FPCP 2018)*, India, July, 2018

2. *International Meeting on High Energy Physics (IMHEP)*, India, January, 2019.

Visits to other Institutes:

1. Centre for Theoretical Physics, Jamia Millia Islamia, New Delhi, India, December-January, 2018.

Invited Lectures/Seminars:

1. *Tutorial sessions for the "Statistical Methods in High Energy Physics" course (6 sessions, 1.25 hrs each)*, SERB Preparatory School on Theoretical High Energy Physics, University of Hyderabad, Hyderabad, India, August-September 2018.

2. *Tutorial sessions for the "Standard Model and Collider Physics" course (2 sessions, 1.5 hrs each)*, SERB Preparatory School on Experimental High Energy Physics, Tata Institute of Fundamental Research, Mumbai, India, January, 2019.

Faruk Abdulla

Research Summary:

I am working on topological phases and transitions between them in condensed matter system. In the last two decade, the study of topological system has been the main stream of research in condensed matter physics. The intriguing features and the robustness of their properties against perturbation make topological insulator and topological superconductor attractive. Non-trivial topological responses of some system can have potential application. To exploit these features, we need the system to be in non-trivial topological phase. We expect topological phase transitions by tuning the driving parameters in the system. We look at the different symmetry class of the system and then identify the existence of non-trivial topology in the system. Topological phase transitions necessarily involves band inversion or closing of the bulk energy gap. This gap closing occurs if we tune the driving parameter(M) of the system. We use a scaling procedure to extract the topology involved in the system. We take a function say F(k,M) (defined in the momentum space), whose integration gives the topological number. A systematic renormalization procedure(a scaling scheme) is applied to the function F(k,M) to obtain the RG equations in the parameter space. This method introduces a set of critical exponents and the notion of universality in topological phase transitions. So far we looked at some 1D models, but our goal is to apply this method in interacting system.

Conference/Workshops Attended:

1. *Edge Dynamics in Topological phases*, ICTS Bangalore, India, June 2019.

Other Activities:

1. Teaching Assistant, CMP 2 Course, January-May 2019.

Khorsed Alam

Research Summary:

During the academic year 2018-2019, I have completed the study on the structural and electronic properties of α-MnO_2 subjected to pressure using first principles electronic structure calculations. α-MnO_2 is found to transform to the δ-MnO_2 polymorph at 66 GPa of hydrostatic pressure. This comes as an interesting addition to the list of proposed transition from non-layered to layered structures at high pressure. Unlike MnO, MnO_2 does not undergo a magnetic collapse at least up to this pressure. This pristine δ-MnO_2, though not having intercalated K^+ ions or H_2O molecules, unlike δ-MnO_2 synthesized by chemical means or by thermal treatment of $KMnO_4$, is found to be dynamically stable.

In an ongoing project, I am studying the catalytic properties of α-MnO_2 at the cathode in lithium air battery. Dependence of free energies of the intermediates during discharge and recharge process with the applied bias are studied to find the overpotential using DFT calculations.

Publications:

1. Khorsed Alam, Nicola Seriani and Prasenjit Sen, *α-MnO_2 under pressure: Possible route to δ-MnO_2,* Materials Research Express **6,7**, 076108, (2019)

Conference/Workshops Attended:

1. *International Symposium of Advanced Functional Materials*, IISER TVM, Kerala, India, July, 2018.
2. *Modelling and Simulations of Materials for Energy and the Environment*, JNCASR, Bengaluru, India, December, 2018.

Invited Lectures/Seminars:

1. *High Pressure Transition From α-MnO_2 to Layered MnO_2*, ISAFM, IISER TVM, Kerala, India, July, 2018.

Other Activities:

1. I presented a poster on the project "α-MnO_2 under pressure: Possible route to δ-MnO_2" in a conference at JNCASR, Bengaluru, India in December, 2018.
2. Earlier, I presented a poster on the same project at the symposium "ISAFM", IISER TVM, Kerala in July, 2018.

Sankha Subhra Bakshi

Research Summary:

During the last academic year, I have been working towards developing a method based on the Langevin equation to study the collective modes in strongly correlated systems. We used a Langevin approach to treat the finite temperature dynamics of displacement variables in the half-filled spinless Holstein model. Exploiting the smallness of adiabatic parameter we simplified the memory effects and estimated the displacement costs from an instantaneous electronic Hamiltonian. In addition, we used a phenomenological damping rate and kept the noise as uncorrelated white noise. This Langevin scheme generates equilibrium thermodynamic properties that are consistent with Monte Carlo results. It additionally yields the dynamical structure factor which shows nontrivial behavior across different temperature regimes.

We have also applied this method to Holstein-double exchange model as an attempt to study the effects of spins on the collective modes of phonons which are interacting via electrons as an attempt to explain the 2d Manganites.

Moreover, I have also tried to develop a method based on the Langevin equation to study the many-body localization of phonons as an effect of mass impurity in the Holstein model

Publications:

1. Sauri Bhattacharyya, Sankha Subhra Bakshi, Samrat Kadge, and Pinaki Majumdar, *Langevin approach to lattice dynamics in a charge-ordered polaronic system,* Phys. Rev. B, 165150 **99** (2019)

Conference/Workshops Attended:

1. *Summer school on Statistical Physics at SNBNCBS*, India, June 2018

Other Activities:

1. Organizing Member of "Talent Search Exam" conducted by HRI, December, 2018.

Nirnoy Basak

Research Summary:

My work is in the field of topological materials mostly for topological insulators and Weyl semimetals. We propose to study the electromagnetic responses involving Dyons in three-dimensional cubic lattice of topological insulators and Weyl semimetals. This work partly involves numerical calculation of density of states in order to find out the extra half integer charge accumulated in a cubic lattice of topological insulators due to placing of a magnetic monopole at the centre of the lattice. We plan to implement this technique again to generalize this result for Weyl semimetals. Later we also plan to derive the result analytically by integrating the total electric charge density with the help of modified Maxwells electromagnetic equations. Another part of my work involves investigating the possibility of intrinsic superconductivity for Weyl semimetals in slab geometry. By intrinsic superconductivity we mean the superconductivity that arises from electron- phonon coupling for a solid. We did something similar for the case of doped Graphene which has two dimensional honeycomb lattice structure. We wrote the deformation potential for this case and wrote it in second quantized language. This potential involves electron operators in a quadratic structure and phonon operators in linear form. We then wrote the corresponding action and in order to remove the time derivative we wrote the electronic and phonon fields in terms of Matsubara summations. The time integral was performed and we are left with a summation over Matsubara frequencies. Now this part can be evaluated by the standard method of Matsubara summation. We then write the whole partition function involving integrals over fermionic and bosonic fields. Now as the interaction part is linear in bosonic fields we can easily integrate out the bosonic fields by Hubbard-Stratonovich transformation. We are the left with the electronic kinetic part and the effective density-density interaction for electrons. If the sign of this part is opposite to that of the kinetic part then we may have the possibility of superconductivity and the Cooper-pair formation is plausible in this system. The rest of the process involves solving self-consistent equations that comes out of the Mean-field theory. From here we found the gap equation for doped Graphene at zero temperature and at finite temperature and investigated the possibility of different orders which can arise for the case of Graphene. Our plan on the Weyl semimetal slab geometry takes the similar path. For this case we have to solve Weyl semimetal Hamiltonian for slab geometry and find the corresponding wavefunctions. At the same time we have to solve the phonon equations in this geometry also. Then we have to find the effective action and do the mean-field theory to get the gap equation.

Visits to other Institutes:

1. Indian Institute of Technology, Kanpur, India, February, 2019

Ritabrata Bhattacharya

Research Summary:

In the Academic Year 2018-2019 I have been working on different issues related to the SYK model. My current work is related to quantum quench in SYK. In a recent paper by Sachdev et al.(PHYSICAL REVIEW B 96, 205123 (2017)) showed the effect on the spectral function and the post quench thermalization of some particular quench protocols. Since the works require numerical techniques which we carry out in Mathematica same as the authors of the above mentioned paper. Also in another work we want to calculate the six point function of the complex SYK(with complex fermions) in the deep IR as done previously for SYK(with Majorana fermions) by Gross and Rosenhaus. Also I am currently working on a problem related to the analytic properties of the off shell Green's functions in Superstring Field Theory.

Publications:

1. arXiv:1709.07613, *JHEP 2017*

Conference/Workshops Attended:

1. *SERC school, India, January, 2017*
2. *National Strings Meet, India, December 2017*
3. *Kavli Asian Winter School, India, January 2018*
4. *AdS/CFT @ 20, India, May 2018*
5. *ST4, India, July 2018*
6. *Indian Strings Meet, India, December 2018*
7. *Spring School on Superstring and related topics, Italy, March-April 2019*

Visits to other Institutes:

1. Saha Institute of Nuclear Physics, Kolkata, India, April, 2017.

Invited Lectures/Seminars:

1. Gave talk based on publication in the *National Strings Meet(NSM 2017)*
2. Gave talk based on ongoing work in the *Indian Strings Meet(ISM 2017)*

Sauri Bhattacharyya

Research Summary:

We have developed a Langevin equation based scheme to study equilibrium statics and dynamics of correlated systems. A concrete application of the method was done in case of the thermal order-disorder transition in the half-filled Holstein (electron-phonon) problem. An extension of this model, which contains additional spin degrees of freedom, is currently under investigation. The implications found regarding phonons in the present case should have direct consequences for manganites. We are also studying magnetism in the repulsive Hubbard problem on mildly frustrated lattices.

Publications:

1. Sauri Bhattacharyya, Sankha Subhra Bakshi, Samrat Kadge, and Pinaki Majumdar, *Langevin approach to lattice dynamics in a charge-ordered polaronic system,* Phys. Rev. B **99**, 165150, (2019)

Conference/Workshops Attended:

1. *Advanced School and Workshop on Correlations in Electron Systems- from Quantum Cricticality to Topology*, Italy, August, 2018.

Sreetama Das

Research Summary:

In the academic year "2018-2019", I have worked on various directions of fundamentals and applications of quantum information which includes quantum walk, resource theory of coherence, particleness of a quantum state, and randomness in a quantum process.

Introducing disorder or inhomogeneity in the medium of a system, can result in localization of the wave function of the system, in certain regions of the medium. In the field of condensed matter theory, such localization was first observed by Anderson, and the effect was called Anderson effect. In the field of quantum random walk (QRW), it has been observed that introducing disorder in the coin parameter or in the lattice nature, can result in a reduced spread of the quantum walker, i.e., it leads to localization of the wave function of the walker. We introduce a new type of disorder in QRW, which has not been explored properly before. We assume that, after each coin toss, instead of taking just one step left / right, the particle can take arbitrary no. of steps. This number of steps are chosen randomly, after each coin-toss, from Poisson distribution. We quenched averaged the standard deviation of the probability distribution of the walker over a large number of random configurations. Analyzing the scaling behaviour of this average standard deviation with respect to the number of steps, we see that the scaling exponent is approximately 0.8, which is less than the scaling exponent 1 in the ordered quantum random walk. This implies that the speed of the random walker is reduced compared to the ordered random walk, i.e., the introduction of this kind of disorder indeed leads to localization of the particle.

We study another scenario in quantum random walk where localization of the wave-function of the particle happens without any disorder in the system. This is when a quantum walker moves on a cyclic graph. Due to the closed nature of the graph, there is an inherent interference between the right-propagating and the left-propagating components of the wave function of the particle. This particular localization is absent in classical random walk on a cyclic graph. We quantify the spread of the quantum walker by the Shannon entropy of the probability distribution on the position space of the walker. We find that for a given number of vertices on a cyclic graph, the entropy with respect to number of steps for the quantum walker saturates, on average, to a value lower than that for the corresponding classical one. We also analyze variations of the entropies with respect to system size, and look at the corresponding asymptotic growth rates.

In the field of resource theory, we propose coherence measures based on fidelity and affinity distance, and we show that these measures satisfy the strong monotonicity condition of resource measures.

Matter can have both particle and wave nature. The coherence of a quantum state is a manifestation of the wave nature of matter. We conceptualize a parallel notion of particleness of a quantum state. We construct a resource theoretic structure of particleness; we identify the free states, free operations and distance-based resource measures of particleness. We also demonstrate numerically that there exists a complementarity between the particleness measure of a state and coherence of that state, which we believe to be another face of "wave-particle duality".

Quantum processes, which aim to achieve a particular task, are in most cases cannot be executed perfectly. This may be due to the non-achievement of ideal physical conditions, or the reason may be inherent in quantum mechanics, e.g.- quantum cloning of two arbitrary states, quantum teleportation. Usually, the quantity used to measure the efficiency of a quantum process is Fidelity, which is equal to the mean of Born probabilities of different outcomes at the output. But the optimization of a quantum process, based on fidelity may not be the best optimization possible. We deduce a quantity, "quantum randomness", which is equal to the standard deviation of the Born probabilities. We propose that the optimization of a quantum process should be done by optimizing the ratio of fidelity and randomness, or by optimizing their difference.

Publications:

1. Chunhe Xiong, Asutosh Kumar, Minyi Huang, Sreetama Das, Ujjwal Sen, Junde Wu, *Partial coherence and quantum correlation with fidelity and affinity distances,* Phys. Rev, A **99**, 032305, (2019)

2. Sreetama Das, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Inhibition of spreading in quantum random walks due to quenched Poisson-distributed disorder,* Phys. Rev. A **99**, 042329, (2109)

Preprints:

1. Sreetama Das, Asutosh Kumar, Aditi Sen De, Ujjwal Sen, *Quantum Process Randomness,* arXiv:1903.03564

2. Sreetama Das, Indranil Chakrabarty, Arun Kumar Pati, Aditi Sen, Ujjwal Sen, *Quantifying the particle aspect of quantum systems* ,arXiv:1812.08656

3. Jayanth Jayakumar, Sreetama Das, Aditi Sen De, Ujjwal Sen, *Interference-induced localization in quantum random walk on clean cyclic graph,* arXiv:1812.05158

Conference/Workshops Attended:

1. *Summer school on Quantum Information*, China, July 2018.

Visits to other Institutes:

1. Zhejiang University, Hangzhou, China, July 2018.

Academic recognition/Awards:

- INFOSYS Award, 2018.

Other Activities:

1. Local Organizer at QIPA-2018, HRI, India, December 2019.

Satadal Datta

Research Summary

My main focus of work this year is about different aspects in analogue gravity and it's implications in astrophysical systems, as below:
We explore nonlinear perturbations in different static fluid systems. We find that the equations, corresponding to the perturbation of the integrals of motion, i.e; Bernoulli's constant and the mass flow rate, satisfy massless scalar field equation in a time dependent acoustic metric. When one is interested up to the second order behaviour of the perturbations, the emergent time dependent acoustic metric of the system, derived from the massless scalar field equations of the perturbations of the integrals of motion, has some astounding similarities with the metric describing gravitational wave in Minkowski spacetime.
We make use of the Lagrangian description of fluid motion to highlight certain features in the context of spacetime geometry as emergent phenomena in fluid systems. We find by using Lagrangian Perturbation Theory (LPT), that not all kind of perturbations on a steady state flow can produce analogue spacetime effect. We also explore the manifold structure of emergent spacetime by using the Lagrangian description of fluid motion. We restrict ourselves to nonrelativistic flows.
We consider time dependent problem in perturbative approach for a nonrelativistic inviscid spherically symmetric accretion model where the effect of the gravity of the medium is considered in Newtonian gravity framework. We consider spherically symmetric nonrelativistic accretion, i.e. Bondi accretion with self-gravity. Our approach is perturbative in the linear order of perturbation regime. We introduce linear perturbation over the existing steady state solution of the system. The analysis has two features, one is that the linear perturbation in mass accretion rate in such irrotational inviscid model of accretion gives rise to emergent gravity and on the other hand, we get some significant insights about instabilities in the flow due to the effect of gravity in the medium, whereas the instabilities are absent in the absence of self-gravity.
I am also working with Prof. Jayanta Kumar Bhattacharjee on a different topic, i.e. Dynamical System. Limit cycles (attractors for neighbouring periodic orbits in a dissipative dynamical system) have been widely studied but the corresponding generalization for quasi periodic orbits have rarely been discussed. Here we investigate higher dimensional limit cycles by analyzing a pair of coupled Van der Pol ocsillators and also the Kuznetsov oscillator. We find that the renormalization group based approach introduced by Chen, is ideally suited for analyzing the quasi periodic analogues of limit cycles. We also address entrainment issues in a pair of forced and coupled Van der Pol oscillators. Our principle finding there is that if two such independent oscillators one with fequency entrainment and the other without are coupled linearly, then it is possible to produce an entrained state via the coupling.

Publications

1. Satadal Datta, *Acoustic analog of gravitational wave,*Phys. Rev. D **98**, 064049, (2018)

2. Satadal Datta, *Instabilities in nonrelativistic spherically symmetric self-gravitating accretion*, arXiv:1902.00359 (2019).

Preprints

1. Satadal and Tapas K. Das, *Lagrangian Description in the context of Emergent space-time (under modification)*, arXiv:1807.02586 (2018)

2. Satadal Datta, Dibya Kanti Mukherjee and Jayanta Kumar Bhattacharjee, *Renormalization Group analysis of dynamical systems with higher dimensional liimit cycles* (in preparation)

Visits to other Institutes:

1. IACS (Indian Association of Cultivation of Science), Kolkata, India, Sep-Oct 2018,

2. IACS (Indian Association of Cultivation of Science), Kolkata, India, Nov-Jan 2018.

Academic recognition/Awards:

- Infosys award, 2018-19.

Suman Jyoti De

Research Summary:

The research work that I have done during the academic year "2018-2019", is given below

My first part of research work is dedicated to study the effect of linear background potential on quantum hall system in presence of electron-electron interaction using hatree-fock approximation. It was found earlier that in this scenario the edge of the quantum hall system will under go some reconstruction.I have studied the case near the interface of $\nu = 4$ and $\nu = 3$ where the $\nu = 4$ region is unpolarised and $\nu = 3$ is fully polarised, there we found that we have two region one with one chiral mode and other having three chiral mode over some region of space.

I am also working on a 2D Topological system where I have a 2d p-wave second order topological superconductor. It is found that this system host majorana bound state at four corners of the sample. We have found that in this system when it is in topological phase it has a $\phi_0 = hc/e$ flux periodicity and if one tune this topological superconductor to a trivial superconductor it has found to have flux periodicity of $\phi_0/2$ using self-consistent study.

Atri Dey

Research Summary:

- In our first work we study model-independent analysis, with h couplings to standard model particles scaled by quantities that are taken to be free parameters and the additional loop contributions to $h \to \gamma\gamma$ and $h \to Z\gamma$, mediated by charged scalar contributions in the extended scalar sector and we treate this in terms of gauge-invariant effective operators. After thus obtaining model-independent fits, the allowed values of the coefficients are translated into permissible regions of the parameter spaces of several specific models like 2HDMs and Higgs triplet models.

- In our second work we mainly do collider analysis. We explore the possibility of a heavier scalar in an extended electroweak sector can fit as dark matter portal in the context of two Higgs doublet models (2HDM), with considering all current experimental constrains. We do cut-based analyses and also use some machine learning techniques as gradient boosted decision trees (XGboost) and artificial neural network (ANN), where the statistical significance distinctly improves.

Publications:

1. Atri Dey, Jayita Lahiri, Biswarup Mukhopadhyaya, *Extended scalar sectors, effective operators and observed data,* JHEP **1811 (2018) 127**, 38, (2018).

Preprints:

1. Atri Dey, Jayita Lahiri, Biswarup Mukhopadhyaya, *LHC signals of a heavy doublet Higgs as dark matter portal: cut-based approach and improvement with gradient boosting and neural networks,* arXiv:1905.02242.

Conference/Workshops Attended:

1. *DAE symposium*, India, December, 2018.
2. *ICTP summer school on Particle Physics*, Italy, June, 2019.

Invited Lectures/Seminars:

1. *Extended scalar sectors, effective operators and observed data,* DAE symposium, IIT Madras, Chennai, December, 2018.

Arijit Dutta

Research Summary:

We had developed a zero temperature mean field scheme to study strongly correlated systems out of equlibruim at steady state. We have generalised that to incorporate thermal fluctuations at any finite temperature and applied this scheme to study the repulsive Hubbard model connected to leads, where a chemical potential difference in the leads gives rise to a voltage bias. This allows us to extend the equilbrium phase diagram, by adding a new control parameter - the bias voltage. More importantly, it leads to the possibilty of finding new "phases" which do not exist in equilibrium. For the repulsive Hubbard model we find that the characteristic temperature scales in equilibrium - the Néel temperature and the temperature characterising insulator to metal transition get suppressed by the applied bias and ultimately go to zero at large values of the applied voltage.

We have also been working on the spin-orbit coupled correlated bosonic system in presence of an optical lattice. Using a static auxiliary field Monte Carlo scheme we had mapped out the phase diagram of the model. We have, now, derived an effective Landau- Ginzburg theory which controls Mott-superfluid phase boundary at zero temperature and the superfluid to Bose liquid transition temperature at strong coupling.

Publications:

1. Arijit Dutta, Abhishek Joshi, Krishnendu Sengupta and Pinaki Majumdar, *Thermal transitions of the modulated superfluid for spin-orbit coupled correlated bosons in an optical lattice,* Phys. Rev. B **99**, 195126, (2019)

Conference/Workshops Attended:

1. *National conference on quantum condensed matter*, India, July 2018
2. *Complex quantum systems in many-body physics and beyond*, Armenia, May-June 2019.

Academic recognition/Awards:

- *Best short talk* at the National Conference on Quantum Condensed Matter, 2018

Juhi Dutta

Research Summary:

The presence of a higgsino-like neutralino NLSP and a keV scale gravitino ($\widetilde{G}$) LSP opens up new decay modes of the NLSP, mainly to a Higgs/Z boson and the LSP. Besides, a keV-scale gravitino as a warm dark matter candidate salvages a relatively-light Higgsino-like NLSP from dark matter constraints. We focus on the prospects of observing $\geq 1b + \ell^+\ell^- + E_T$ signal at the LHC. A distinguishing feature of this scenario is the production of longitudinal Z bosons in neutralino decays, unlike in the case of gaugino-like neutralinos, where the Z is mostly transverse. The polarisation information of the parent Z boson gets reflected in the angular distributions of the decay leptons and in some other variables derived therefrom. We are also working on the prospects of observing such a scenario using compressed spectra in hadronic as well as leptonic channels using substructure techniques.

A simple extension of the minimal supersymmetric standard model (MSSM) with right-handed neutrino superfields addresses the issue of mass generation of the light neutrinos. We study such a scenario in the context of natural supersymmetry where the presence of a right sneutrino as the LSP candidate opens up new decay modes of the higgsinos. In a previous work we had shown that the decay patterns of the higgsinos is crucially controlled by the mass splitting amongst the higgsinos as well as the left-right sneutrino mixing angle. We focus on exploring further prompt as well as late decaying signatures of the higgsinos in such an extension at the upcoming runs of the LHC in this work.

Preprints:

1. Juhi Dutta, Biswarup Mukhopadhyaya, Santosh Kumar Rai, *Identification of a Higgsino-like neutralino with a keV-scale dark matter,* arXiv: 1904.08906

Conference/Workshops Attended:

1. *IMHEP 2019*, IOP Bhubaneswar, India, January 2019.
2. *XXIII DAE High Energy Physics Symposium*, IIT Madras, India, December, 2018
3. *(Re)interpretation of the results of new physics searches at the LHC*, CERN, Geneva, May, 2018
4. *Searching for long-lived particles at the LHC*, CERN, Geneva, May, 2018
5. *Sangam@HRI 2018: Instructional Workshop in Particle Physics*, HRI Prayagraj(Allahabad), India, March, 2018
6. *NuHRIzons VII*, HRI Prayagraj(Allahabad), India, February, 2018

Visits to other Institutes:

1. LPSC, Grenoble, France, May-June 2018

Participatory Seminars:

1. *Light Higgsinos at LHC with Right-sneutrino LSP*, XXIII DAE High Energy Physics Symposium, IIT Madras, Chennai, December 2018.

2. *Natural SUSY at LHC with Right-Sneutrino LSP*, LPSC, Grenoble, June 2018.

Avirup Ghosh

Research Summary:

I, Avirup Ghosh, have worked on two projects in this year.

1. I have studied the possibility of right-handed sneutrino being a non-thermal dark matter component of the present day relic density. Such studies have been so far carried out assuming the neutrinos to be dirac particles whereas we have carried out the study assuming Majorana masses for neutrinos. Appearence of Majorana masses brings in additional constraints on the neutrino Yukawa coupling and hence the possible parameter space for right-sneutrino non-thermal dark matter is severely constrained. All these constraints have been thoroughly studied by me and my collaborators.

2. I have also studied a new indirect detection signature arising from the multicomponent scalar dark sector. UV complete scenario where such situation may arise is studied in detail and also lifetime of dark matter have been constrained using the observed gamma-ray flux from several experimental collaboration. The manuscript is under preparation.

Publications:

1. Avirup Ghosh, Tanmoy Mondal, Biswarup Mukhopadhyaya, *Right sneutrino with* $\Delta L = 2$ *masses as nonthermal dark matter,* Phys.Rev. D99 **no.3, 035018** (2019)

Conference/Workshops Attended:

1. *XXIII DAE-BRNS High Energy Physics Symposium*, India, December, 2018

Visits to other Institutes:

1. IACS, Kolkata, India, May-June 2019,

Invited Lectures/Seminars:

1. . *Long-lived stau, sneutrino dark matter and right-slepton spectrum* , DAE-BRNS High Energy Physics Symposium talk, IIT Madras, Chennai, December 2018.

2. *Collider signature of feebly interacting Dark sectors*, Theoretical Physics Group Seminar, IACS, Kolkata, May 2019.

Stav Haldar

Research Summary:

I have been learning about the connections between condensed matter physics and quantum information. In order to understand better the recently discovered phenomena of dynamical quantum phase transitions we report the dynamical quantum phase transition portrait in alternating field transverse XY spin chain with Dzyaloshinskii-Moriya interaction by investigating singularities in the Loschmidt echo and the corresponding rate function after a sudden quench of system parameters. Unlike the Ising model, the analysis of Loschmidt echo, analytically, yields non-uniformly spaced transition times in this model. Comparative study between the equilibrium and the dynamical quantum phase transitions in this case reveals that there are quenches where one occurs without the other, and the regimes where they co-exist. However, such transitions happen only when quenching is performed across at least a single gapless or critical line. Contrary to equilibrium phase transitions, bipartite entanglement measures do not turn out to be useful for the detection while multipartite entanglement emerges as a good identifier of this transition when the quench is done from a disordered phase of this model.

Preprints:

1. Stav Haldar, Saptarshi Roy, Titas Chanda, Aditi Sen De, Ujjwal Sen, *Multipartite entanglement at dynamical quantum phase transitions with non-uniformly spaced criticalities* , arXiv:1811.12796

Conference/Workshops Attended:

1. *Meeting on Quantum Information Processing and Applications* , India, December, 2018

Other Activities:

1. Tutor for Electronics course, Jan-Aug, 2019
2. Delivered two lectures on basic quantum mechanics at the Scientific Workshop in Hindi for 11th and 12th class students. June, 2019

Samrat Kadge

Research Summary:

Langevin dynamics enables one to draw temporal information on order parameter and thus excitation spectra,in addition to spatial correlations readily possible with approaches like static path approximation.One arrives at an equation of motion from the effective action employing abiatic approximation to obtain a time local equation.Such an approach was employed in studying charge-ordered polaronic system(see publications).

Currently, a similar approach is being applied to attractive Hubbard model.In contrast to polaronic systems,the effective action here is invariant under local gauge U(1) transformation leading to Goldstone modes.Efforts are underway to arrive at equation of motion starting from phase-only action valid at large coupling values.

Publications:

1. Sauri Bhattacharya, Sankha Subhra Bakshi, Samrat Kadge and Pinaki Majumdar, *Langevin approach to lattice dynamics in a charge-ordered polaronic system,* Phys. Rev. B **99**, 165150, (2019)

Arpan Kar

Research Summary:

In the academic year 2018-2019, I have worked on the following projects.

1. I have studied the possibilty of indirect detection of dark matter through diffuse radio synchrotron observation in the upcoming radio telescope Square Kilometre Array (SKA). Dark matter annihilation in our local dwarf spheroidal galaxies (which are promising target for dark matter search) leads to energetic $e^{\pm}$ which diffuse through the interstellar medium and interacting with the magnetic field present there create radio synchrotron flux. In my study I have analysed the potential of SKA in detecting this radio signal for a wide range of dark matter mass and found that the constraints drawn by SKA on dark matter parameter space are much more stronger than others coming from γ-ray or anti-proton observations. With minimal supersymmetric standard model (MSSM) as an illustration, I have shown that even for a conservative choice of diffusion and magnetic field, SKA can detect signal of dark matter mass upto a scale which is about an order of magnitude higher than the reach of high luminosity LHC.

2. In the context of the aforementioned topic I have studied in detail the particle physics and various astrophysics effects which can enhance the radio flux originated from the annihilation of heavy (TeV range) dark matter particles.

3. I have also calculated the constarints on dak matter parameter space from the recent radio observation of 14 local dwarf galaxies. The observation was carried out by Murchison Widefield Array (MWA) radio telescope which is a precursor to the SKA. I have found that these constarints are not compatiable with other already existing limits, but observation in the next phase can do some significant improvements.

Publications:

1. Arpan Kar, Sourav Mitra, Biswarup Mukhopadhyaya, Tirthankar Roy Choudhury, *Can SKA–Phase 1 go much beyond the LHC in supersymmetry search?*, Phys. Rev. D 99 (R) **021302** (2019)

Preprints:

1. Arpan Kar, Sourav Mitra, Biswarup Mukhopadhyaya, Tirthankar Roy Choudhury, *Heavy dark matter particle annihilation in dwarf spheroidal galaxies: radio signals at the SKA telescope*, arXiv:1905.11426 [hep-ph]

2. Arpan Kar, Sourav Mitra, Biswarup Mukhopadhyaya, Tirthankar Roy Choudhury, Steven Tingay, *Constraints on dark matter annihilation in dwarf spheroidal galaxies from low frequency radio observations*, (in preparation)

Conference/Workshops Attended:

1. *Summer School on Cosmology 2018 (ICTP)*, Italy, June, 2018.
2. *XXIII DAE-BRNS High Energy Physics Symposium*, India, December, 2018

Visits to other Institutes:

1. IACS, Kolkata, India, May-June 2019,

Invited Lectures/Seminars:

1. . *Can SKA-Phase1 go much beyond the LHC in supersymmetry search?*, DAE-BRNS High Energy Physics Symposium talk, IIT Madras, Chennai, December 2018.
2. *Heavy dark matter particle annihilation in dwarf spheroidal galaxies: radio signals at the SKA telescope*, Theoretical Physics Group Seminar, IACS, Kolkata, June 2019.

Abhass Kumar

Research Summary:

During the academic year 2018-2019, I continued and finished my work on combining inflation with dark matter, baryogenesis and neutrino masses using the scotogenic model in which the inert doublet is coupled non-minimally to gravity. We showed that in the scotogenic model, the inert doublet coupled non-minimally to gravity can successfully produce inflation in the early Universe. After inflation, the inert doublet particles annihilate to produce the gauge bosons and the Higgs bosons. These further annihilate to produce relativistic standard model particles. The inert doublet particles can directly decay into leptons and right handed neutrinos however, this forms a minor contribution to reheating. In later stages of the Universe, the lightest right handed neutrino decays to the leptons and the inert doublet particles which has a CP violating part as well that generates the lepton asymmetry which is converted to baryon asymmetry. I have also constructed a toy model with a fermion coupled non-minimally to gravity such that the scalar bilinear is the inflaton. This model has the potential to be a very minimal setup for unification of inflation with dark matter, baryogenesis and neutrino masses.

Publications:

1. Debasish Borah, P.S. Bhupal Dev and Abhass Kumar, *TeV scale leptogenesis, inflaton dark matter and neutrino mass in a scotogenic model,* Physical Review D **99**, 055012, (2019)

Preprints:

1. Abhass Kumar, *Inflation and Reheating with a Fermionic Field,* arXiv:1811.12237 [gr-qc]

Conference/Workshops Attended:

1. *23^{rd} DAE-BRNS HEP Symposium*, IIT Madras, India, December 2018
2. *Neutrino & Dark Matter Activity*, HRI, India, February 2018

Talks:

1. *TeV Scale Leptogenesis, Inflaton Dark Matter & Neutrino Mass in the Scotogenic Model*, 23^{rd} DAE-BRNS HEP Symposium, IIT, Madras, December, 2018.
2. *Linking Inflation with Dark Matter and Baryogenesis*, Neutrino & Dark Matter Activity, HRI, Allahabd, February 2019

Ratul Mahanta

Research Summary:

During this academic year 2018-2019, I worked to answer a question related to crossing properties of correlators in Wess-Zumino-Witten (WZW) models with my advisor, Prof. Anshuman Maharana. In this work we showed that correlators (in a particular class) can be expressed as modular averages revealing level-rank duality between two WZW models. Apart from reporducing some analytical results this work indicates connection between holographic computations and level-rank duality.

Apart from the above I am studying mathematical tools from axiomatic quantum field theory in a motive to seek application in string theory.

Preprints:

1. Ratul Mahanta and Anshuman Maharana, *Crossing, Modular Averages and $N \leftrightarrow k$ in WZW Models,* arXiv:1905.02816v2 [hep-th].

Conference/Workshops Attended:

1. *Indian Strings Meeting 2018*, IISER Thiruvananthapuram, India, December, 2018.

Susovan Maity

Research Summary:

I, along with my supervisor Dr. Tapas Das and his collaborators from outside HRI have been concentrating on two scientific works.

The first one is the generalization of our previous work of defining sound speed in inhomogeneous media where the low angular momentum accretion disc is in hydrostatic equilibrium and rotating around a Schwarzchild black hole. In this first line of work generalization of this work for rotating (Kerr) black holes have been done. In the previous case of Schwarzchild black holes, it was noticed that the way the sound speed was derived, could only be used to define it locally, i.e, at the sonic horizons. Thus a novel method for defining the sound speed globally was put forward by me, by analysing the entire causal structure with Penrose-Carter diagram. In the case of a complicated analogue space-time like ours, it is non-trivial to find out the affine parameter. So, the approach of expanding the null co-ordinate near horizon was taken to define global affine parameters. But due to the formation of shocks and two critical points on the two sides of shock, in case of multi transonic flow, the global nature of the parameters were not same. The recipe was implemented numerically that generated the Penrose diagram of the entire analogue space time. Wormhole like structures have been found and now mathematical condition of negetive energy density has to be checked for this wormholes confirming the stability. The early version of this work has been submitted in arxiv and will be soon be submitted for publication in peer reviewed journal.

In the second work, spherically symmetric Bondi accretion with one sonic point is being used as the theoretical probe for understanding the non universality of analogue Hawking radiation which will show deviation from Hawking radiation as dispersion relation will be present in moving media in general. Previous works persued by other researchers in the field mainly worked with hypothetical systems considering constant sound speed in the media, which in our case is a variable of position and is derived from background fluid equation. The classical field theoretical model for this kind of model and it's difference from previous simplistic models have been derived by us. The quantum theoretical description is currently being pursued and also non trivial fluid configuration will be considered in future.

Publications:

1. Md. Arif Shaikh, Susovan Maity, Sankhasubhra Nag, Tapas K. Das *Effective sound speed in relativistic accretion discs around Schwarzschild black holes* New Astronomy **69**, 48-57, (2019)

Preprints:

1. Susovan Maity, Md. Arif Shaikh, Tapas K. Das *Effective Sound Speed in Relativistic Accretion Discs around Rotating Black Holes* arxiv 1811.04975

Visits to other Institutes:

1. Physics and Applied Mathematics Unit (PAMU), Indian Statistical institute, Kolkata, India, Several visits in 2019.

2. Sarojini Naidu College for Women, Kolkata, India, Several visits in 2018.

Brij Mohan

Research Summary:

In the last academic year 2018-2019, I mainly worked on fast and slow charging and discharging of quantum battery. Using the upper and lower bound of quantum speed limit, we obtained the minimum and maximum charging/discharging time of quantum battery (for both dissipative and non dissipative charging/discharging). We found that for non dissipative charging/discharging upper and lower bound of speed limit saturates, so that provides the maximum charging/discharging power.

Along with this I also studied the quantum speed limit of closed and open dynamics of quantum systems, quantum state tomography, entropic uncertainty relations and quantum processes with indefinite causal order.

Conference/Workshops Attended:

1. *Quantum Information Processing and Applications(QIPA)* at HRI Prayagraj, India, 02 - 08 December, 2018.

2. *Asia Pacific Conference and Workshop on Quantum Information Science(APCWQIS)* at IISER Kolkata, India, 19 - 23 December, 2018.

Other Activities:

1. Tutor for 'Mathematical Methods I' Course, August - December, 2018.

Chiranjib Mukhopadhyay

Research Summary:

In the last year, apart from ensuring the publication of the preprints from previous years, I have substantially concentrated on two topics. The first one is the consideration of indefinite causal order as a new resource for quantum technologies. While quantum circuits show the effects of spatial superposition, it has recently been shown that temporal superposition of various circuits, each with distinct causal order between processes, can confer significant operational advantage. We showed that such an effect can increase the fidelity of teleportation channels, a very practical task for upcoming quantum technologies. We also show, using an explicit protocol, that such indefinite causal order, may help in determining the temperature of a system more precisely. I have also worked on thermometry in more detail, and together with my collaborators, have come up with a scheme of thermometry through weak value estimation - which is going to become relevant in practical situations where allowing the probe to strongly interact with the heat bath will destroy the probe itself. I shall continue to work on the ramifications of indefinite causal order and coherent control on quantum systems and their practical applications.

Publications:

1. Chiranjib Mukhopadhyay, *Generating steady quantum coherence and magic through an autonomous thermodynamic machine utilizing a spin bath,* Physical Review A **98**, 012102, (2018)

2. Chiranjib Mukhopadhyay, Sk Sazim, Arun Kumar Pati, *Coherence makes quantum systems magical,* Journal of Physics A : Mathematical and Theoretical **51**, 414006, (2018)

3. Gautam Sharma, Chiranjib Mukhopadhyay, Sk Sazim, Arun Kumar Pati, *Quantum uncertainty relations based on the mean deviation* Physical Review A **98**, 032106, (2018)

4. Chiranjib Mukhopadhyay, Avijit Misra, Samyadeb Bhattacharya, Arun Kumar Pati, *Quantum speed limit constraints on a nanoscale autonomous refrigerator* Physical Review E **97**, 062116, (2018)

5. Chiranjib Mukhopadhyay, Udit Kamal Sharma, Indranil Chakrabarti *A note on robustness of coherence for multipartite quantum states* Pramana Journal of Physics **Accepted**,

Preprints:

1. Chiranjib Mukhopadhyay, Arun Kumar Pati, *Stronger classes of sum uncertainty and reverse uncertainty relations* arXiv 1806.11347

2. Chiranjib Mukhopadhyay, Manish Kr. Gupta, Arun Kumar Pati, *Superposition of causal order as a metrological resource for quantum thermometry* arXiv 1812.07508

3. Chiranjib Mukhopadhyay, Arun Kumar Pati, *Superposition of causal order enables perfect quantum teleportation with very noisy singlets* arXiv 1901.07626

4. Arun Kumar Pati, Chiranjib Mukhopadhyay, Sagnik Chakrabarty, Sibasish Ghosh *Quantum precision thermometry with weak measurement* arXiv 1901.07415

Conference/Workshops Attended:

1. *Quantum Roundabout*, Nottingham, United Kingdom, July 2018.

2. *Quantum Mechanics and Open Quantum Systems*, Kodaikanal, India, Aug 2018

3. *Asia Pacific Conference and Workshop on Quantum Information Science*, Kolkata, India, Dec 2018

4. *Quantum Information Processing and Applications*, Prayagraj, India, Dec 2018

Visits to other Institutes:

1. University of Nottingham , Nottingham, United Kingdom , July 2018,

2. University College, London, United Kingdom, July 2018.

3. Institute of Mathematical Sciences, Chennai, India, December 2018.

Academic recognition/Awards:

- INFOSYS award for PhD studentship in quantum information (2018).

Other Activities:

1. Tutored one course in Fall 2018.

Dipyaman Pramanik

Research Summary:

Neutrino oscillation is one of the few examples of observations that suggest that our understanding of nature is not complete and we need to extend standard model of particle physics. Standard formalism of neutrino oscillation requires three mixing angles($\theta_{12}, \theta_{13}, \theta_{23}$), one phase($\delta_{CP}$) and two mass-squared differences($\Delta m^2_{sol}, \Delta m^2_{atm}$). Among these six parameters, θ_{12},θ_{13} and Δm^2_{sol} are well-known, however, we have currently little knowledge about the others. For example, we know nothing about the phase; we don't know if θ_{23} is larger that 45 degree or smaller or equal to 45 degree and we don't know the sign of the Δm^2_{atm}. There are many experiments proposed all over the world to find the unknowns of the neutrino oscillation physics and search for new physics. We have explored physics possibilities in these experiments.

One kind of experiments are the long-baseline experiments. DUNE, T2HK, P2O are some of the future long-baseline experiments. There are studies in literature that show that sterile neutrino, i.e. extra neutrino states, can affect the performances of the long-baseline experiments. We have shown existence of an interesting degeneracy in the parameter space of the sterile neutrino relevant for the long-baseline experiments like DUNE and T2HK.

In another work, we have done an optimization study of the future experiment P2O (Protvino to ORCA) assuming standard neutrino oscillation formalism. In this work, we have studied the roles of neutrino-antineutrino runtime ratio, effect of various backgrounds and systematics to the CP-violation, mass-hierarchy and octant sensitivity of the P2O experiment.

We are also pursuing a different kind of work than neutrino oscillation. The long-baseline experiments have in-general a near detector which as the name suggests is placed very near to the neutrino source. These detectors' primary aim are to measure the neutrino flux at the source precisely and thus reducing systematics due to the flux uncertainty. Other than this, these near detectors can also probe any new exotic particles or new physics effects which are created during the proton proton collision at the target. One can possibly do indirect search for dark-matter in these near detectors. We are currently trying to find new physics effects which can be probed in these near detectors of the long-baseline experiments.

Publications:

1. Sandhya Choubey, Debajyoti Dutta and Dipyaman Pramanik , *Measuring the Sterile Neutrino CP Phase at DUNE and T2HK,* Eur. Phys. Journal **C78, no.4**, 339, (2018)

2. Sandhya Choubey, Debajyoti Dutta and Dipyaman Pramanik, *Invisible neutrino decay in the light of NOvA and T2K data ,* JHEP **1808**, 141, (2018)

Preprints:

1. Sandhya Choubey, Debajyoti Dutta and Dipyaman Pramanik, *Exploring a New Degeneracy in the Sterile Neutrino Sector at Long-Baseline Experiments ,* 1811.08684

2. Sandhya Choubey, Monojit Ghosh and Dipyaman Pramanik, *On the Optimization of Protvino to ORCA (P2O) Experiment*, 1812.02608

Conference/Workshops Attended:

1. *PANE 2018, ICTP*, Italy, May 2018,
2. *INVISIBLES18, KIT*, Germany, September 2018.
3. *DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM,IIT-Madras*, India, December 2018.
4. *IITB-ICTP workshop on neutrino physics, IIT-Bombay*, India, December 2018.

Visits to other Institutes:

1. INFN, Padova, Italy, May 2018,

Samiran Roy

Research Summary:

During the period of last one year (from April 2018 to March 2019), I have worked on non unitarity of the leptonic mixing matrix and the effect of Non Standard Interaction (NSI) at long-baseline neutrino experiments such as DUNE. In presence of light sterile neutrino, the PMNS mixing matrix becomes non unitarity. The long-baseline experiments DUNE and T2HK will be able to put constraint on the non unitarity parameters. The neutral current measurements will help us to put significant bounds on α_{33} parameter which is not constrained by charged current measurements. We have also studied the role of different beam tune to constrain the NSI parameters and found that the combination of two different beam tune will help us to give better sensitivity to the $\epsilon_{e\mu}$ parameter than the standard flux.

Publications:

1. Mehedi Masud, Samiran Roy, Poonam Mehta, *Correlations and degeneracies among the NSI parameters with tunable beams at DUNE,* Phys. Rev. D 99, 115032 (2019)

Preprints:

1. Debajyoti Dutta, Samiran Roy, *Non Unitarity at DUNE and T2HK with Charged and Neutral Current Measurements,* arXiv:1901.11298

Conference/Workshops Attended:

1. *IITB - ICTP WORKSHOP ON NEUTRINO PHYSICS*, IIT Bombay, India, December 2018

2. *Neutrino & Dark Matter Activity*, HRI, India, February 2018

Visits to other Institutes:

1. *Fermilab, Batavia, Chicago (USA) (22/10/18 to 4/12/19)*

Saptarshi Roy

Research Summary:

In the academic year "2018-2019" (1st April 2018 to 31st March 2019), my research was mainly focused on three major directions – (1) continuous variable systems and quantum optics, (2) study of monogamy of quantum correlations, and (3) investigation of problems lying at the interface between quantum information and condensed matter physics. A brief report on the specific research works done during the last academic year is given below.

In the avenue of continuous variable systems and quantum optics, we investigate the consequence of the violation of local realism based on pseduospin operators when photons are added or subtracted in a single mode or in both the modes of the two-mode squeezed states of light in the presence of noise. In the noiseless situation, we show that for addition (subtraction) of photons in a single mode, there is an overall enhancement in the maximal violation, although we observe an interplay between monotonicity and nonmonotonicity in the violation of Bell inequality depending on the squeezing strength. Moreover, we report that for low squeezing or low number of photons added or subtracted, subtraction in both the modes can lead to higher violation of local realism than that in the case of addition. For any choice of parameters, such ordering is not seen if one compares their entanglement contents. In the event of a faulty twin-beam generator, we obtain a lower than expected squeezing in the state. In such a case, or in imperfect photon addition (subtraction) or under local noise, we find that the violation of local realism by the noise-affected two-mode squeezed states always decreases. Interestingly, however, we notice that photon addition (subtraction) can in general help to conquer the ill effects of noise by enhancing the violation of local realism or by transforming nonviolating states to violating ones, thereby acting as an activating agent.

In the direction of monogamy of quantum correlations, we find the critical exponent of these measures, above which randomly generated multiparty pure states satisfy the usual monogamy relation, and show that the critical power decreases with the increase in the number of parties. For three-qubit pure states, we detect that W-class states are more prone to being nonmonogamous as compared to the GHZ-class states. We also observe a different criticality in monogamy power up to which random pure states remain nonmonogamous. We prove that the average monogamy score asymptotically approaches its maximal value on increasing the number of parties. Analyzing the monogamy scores of random three-, four-, five-, and six-qubit pure states, we also report that almost all random pure six-qubit states possess maximal monogamy score, which we confirm by evaluating statistical quantities like mean, variance, and skewness of the distributions. In particular, with the variation of number of qubits, means of the distributions of monogamy scores for random pure states approach to unity which is the algebraic maximum thereby conforming to the known results of random states having maximal multipartite entanglement in terms of geometric measures.

Finally, we report dynamical quantum phase transition portrait in the alternating field transverse XY spin chain with Dzyaloshinskii-Moriya interaction by investigating singularities in the Loschmidt echo and the corresponding rate function after a sudden quench of system parameters. Unlike the Ising model, the analysis of Loschmidt echo,

analytically, yields non-uniformly spaced transition times in this model. Comparative study between the equilibrium and the dynamical quantum phase transitions in this case reveals that there are quenches where one occurs without the other, and the regimes where they co-exist. However, such transitions happen only when quenching is performed across at least a single gapless or critical line. Contrary to equilibrium phase transitions, bipartite entanglement measures do not turn out to be useful for the detection while multipartite entanglement emerges as a good identifier of this transition when the quench is done from a disordered phase of this model.

Publications:

1. S. Roy, T. Das, A. Kumar, A. Sen(De), U. Sen, *Activation of Nonmonogamous Multipartite Quantum States,* Phys. Rev. A. **98**, 012310, (2018)

2. S. Roy, T. Chanda, T. Das, A. Sen(De), U. Sen, *Deterministic quantum dense coding networks,* Phys. Lett. A **382**, 1709 (2018).

3. Saptarshi Roy, Titas Chanda, Tamoghna Das, Aditi Sen(De), and Ujjwal Sen, *Response in the violation of the Bell inequality to imperfect photon addition and subtraction in noisy squeezed states of light,* Phys. Rev. A **98**, 052131, (2018)

4. S. Roy, T. Chanda, T. Das, D. Sadhukhan, A. Sen(De), U. Sen, *Phase boundaries in alternating field quantum XY model with Dzyaloshinskii-Moriya interaction: Sustainable entanglement in dynamics,* Phys. Rev. B **99**, 064422 (2019)

5. Soorya Rethinasamy, Saptarshi Roy, Titas Chanda, Aditi Sen(De), and Ujjwal Sen, *Universality in distribution of monogamy scores for random multiqubit pure states,* Phys. Rev. A **99**, 042302, (2019)

Preprints:

1. S. Roy, T. Das, D. Das, A. Sen(De), U. Sen, *How efficient is transport of quantum cargo through multiple highways?,* arXiv:1802.10398.

2. Stav Haldar, Saptarshi Roy, Titas Chanda, Aditi Sen De, Ujjwal Sen, *Multipartite entanglement at dynamical quantum phase transitions with non-uniformly spaced criticalities,* arXiv:1811.12796 [quant-ph]

3. Saptarshi Roy, Anindita Bera, Shiladitya Mal, Aditi Sen De, Ujjwal Sen , *Recycling the resource: Sequential usage of shared state in quantum teleportation with weak measurements,* arXiv:1905.04164 [quant-ph]

4. Arkaprabha Ghosal, Debarshi Das, Saptarshi Roy, Somshubhro Bandyopadhyay , *Fidelity deviation in quantum teleportation with a two-qubit state,* arXiv:1906.01394 [quant-ph]

Conference/Workshops Attended:

1. *Quantum Frontiers and Fundamentals: Experimental Studies and Theoretical Ramifications*, India, May, 2018

2. *Quantum Information Processing and Applications*, India, December, 2018.

3. *Asia Pacific Conference and Workshop on Quantum Information Science*, India, December, 2018.

Other Activities:

1. Served as a tutor for the QIC-2 course, Jan-May, 2019.

Tanaya Ray

Research Summary:

During the academic year 2018-2019, I have been studying and working on the theoretical and practical aspects of Density Functional Theory.

Shouvik Roy Choudhury

Research Summary:

During the period April 2018-March 2019 I continued my work in neutrino cosmology from previous year.

In arXiv:1806.10832 (published in Journal of Cosmology and Astroparticle Physics) I and my Ph.D. guide Prof. Sandhya Choubey presented strong bounds on the sum of three active neutrino masses ($\sum m_\nu$) using selected cosmological datasets and priors in various cosmological models. We use the following baseline datasets: Cosmic Microwave Background (CMB) temperature data from Planck 2015, Baryon Acoustic Oscillations measurements from SDSS-III BOSS DR12, the newly released Type Ia supernovae (SNe Ia) dataset from Pantheon Sample, and a prior on the optical depth to reionization from 2016 Planck Intermediate results. We constrain cosmological parameters with these datasets with a Bayesian analysis in the background of ΛCDM model with 3 massive active neutrinos. For this minimal $\Lambda CDM + \sum m_\nu$ model we find a upper bound of $\sum m_\nu < 0.152$ eV at 95% C.L. Adding the high-l polarization data from Planck strengthens this bound to $\sum m_\nu < 0.118$ eV, which is very close to the minimum required mass of $\sum m_\nu \simeq 0.1$ eV for inverted hierarchy. This bound is reduced to $\sum m_\nu < 0.110$ eV when we also vary r, the tensor to scalar ratio ($\Lambda CDM + r + \sum m_\nu$ model), and add an additional dataset, BK14, the latest data released from the Bicep-Keck collaboration (which we add only when r is varied). This bound is further reduced to $\sum m_\nu < 0.101$ eV in a cosmology with non-phantom dynamical dark energy ($w_0 w_a CDM + \sum m_\nu$ model with $w(z) \geq -1$ for all z). Considering the $w_0 w_a CDM + r + \sum m_\nu$ model and adding the BK14 data again, the bound can be even further reduced to $\sum m_\nu < 0.093$ eV. For the $w_0 w_a CDM + \sum m_\nu$ model without any constraint on $w(z)$, the bounds however relax to $\sum m_\nu < 0.276$ eV. Adding a prior on the Hubble constant ($H_0 = 73.24 \pm 1.74$ km/sec/Mpc) from Hubble Space Telescope (HST), the above mentioned bounds further improve to $\sum m_\nu < 0.117$ eV, 0.091 eV, 0.085 eV, 0.082 eV, 0.078 eV and 0.247 eV respectively. This substantial improvement is mostly driven by a more than 3σ tension between Planck 2015 and HST measurements of H_0 and should be taken cautiously.

In arXiv:1807.02860 (published in The European Physical Journal C) I with Abhishek Naskar obtained constraints on a 12 parameter extended cosmological scenario including non-phantom dynamical dark energy (NPDDE) with CPL parametrization. We also include the six ΛCDM parameters, number of relativistic neutrino species ($N_{\rm eff}$) and sum over active neutrino masses ($\sum m_\nu$), tensor-to-scalar ratio ($r_{0.05}$), and running of the spectral index (n_{run}). We use CMB Data from Planck 2015; BAO Measurements from SDSS BOSS DR12, MGS, and 6dFS; SNe Ia Luminosity Distance measurements from the Pantheon Sample; CMB B-mode polarization data from BICEP2/Keck collaboration (BK14); Planck lensing data; and a prior on Hubble constant (73.24 ± 1.74 km/sec/Mpc) from local measurements (HST). We have found strong bounds on the sum of the active neutrino masses. For instance, a strong bound of $\sum m_\nu < 0.123$ eV (95% C.L.) comes from Planck+BK14+BAO. Although we are in such an extended parameter space, this bound is stronger than a bound of $\sum m_\nu < 0.158$ eV (95% C.L.)

obtained in ΛCDM + $\sum m_\nu$ with Planck+BAO. Varying $A_{\rm lens}$ instead of $r_{0.05}$ however leads to weaker bounds on $\sum m_\nu$. Inclusion of the HST leads to the standard value of $N_{\rm eff} = 3.045$ being discarded at more than 68% C.L., which increases to 95% C.L. when we vary $A_{\rm lens}$ instead of $r_{0.05}$, implying a small preference for dark radiation, driven by the H_0 tension.

In arXiv:1807.10294 (submitted for publication) I and my Ph. D. guide Prof. Sandhya Choubey explored the thermal light sterile neutrino situation from cosmological perspective in the ΛCDM+$r_{0.05}$+$N_{\rm eff}$+$m_{\rm s}^{\rm eff}$ model using combinations of latest data sets available. Among CMB datasets, we use Planck 2015 temperature and low-l polarization data and the latest data release on the B-mode polarization from the BICEP2/Keck collaboration (BK14). We also use the latest Baryon Acoustic Oscillations (BAO) data from SDSS-III BOSS DR12, MGS, and 6dFS; and a Gaussian prior (HST) on the Hubble constant ($H_0 = 73.24 \pm 1.74$ km/sec/Mpc) from direct measurements by Hubble Space Telescope. We find that inclusion of BK14 data makes the constraints on the effective mass of sterile neutrino ($m_{\rm s}^{\rm eff}$) slightly stronger by preferring higher σ_8 values. The bound of $m_{\rm s}^{\rm eff} < 0.46$ eV (95% C.L.) is found for the combination of Planck 2015, BAO and BK14 datasets, whereas the bound is $m_{\rm s}^{\rm eff} < 0.53$ eV (95% C.L.) without the BK14 data. Our most aggressive bound of $m_{\rm s}^{\rm eff} < 0.28$ eV (95% C.L.) is obtained with Planck 2015, HST and BK14. Our analysis indicates that fully thermalized sterile neutrinos with mass ~ 1 eV are slightly more disfavoured with the inclusion of BK14 data. It also seems to make the agreement between Planck 2015 and CFHTLenS (weak gravitational lensing data) worse due to the higher σ_8 values.

Publications:

1. Shouvik Roy Choudhury and Sandhya Choubey, *Updated Bounds on Sum of Neutrino Masses in Various Cosmological Scenarios*, Journal of Cosmology and Astroparticle Physics **1809 no. 09**, 017, (2018)

2. Shouvik Roy Choudhury and Abhishek Naskar, *Strong Bounds on Sum of Neutrino Masses in a 12 Parameter Extended Scenario with Non-Phantom Dynamical Dark Energy ($w(z) \geq -1$)*, The European Physical Journal **C79 no.3**, 262, (2019)

Preprints:

1. Shouvik Roy Choudhury and Sandhya Choubey, *Constraining light sterile neutrino mass with the BICEP2/Keck Array 2014 B-mode polarization data*, arXiv:1807.10294

Visits to other Institutes:

1. Indian Statistical Institute, Kolkata, India, 31 Aug - 17 Sep, 2018,

2. Aarhus University, Aarhus, Denmark, 27 Oct - 29 Nov, 2018.

Invited Lectures/Seminars:

1. Talk on *Neutrino mass constraints from cosmology*, Indian Statistical Institute, Kolkata, India, September 2018.

2. Talk on *Constraints on neutrino masses from cosmology*, Aarhus University, Aarhus, Denmark, November 2018.

Other Activities:

1. Teaching Assistant in Research Methodology and Numerical Methods, January-May, 2019

Biswajit Sahoo

Research Summary:

My reserch work in this academic year was mainly directed towards exploration of Soft Photon and Graviton theorem in four and higher space-time dimensions.

In collaboration with Ashoke Sen, We explored the logarithmic terms in the soft theorem in four dimensions by analyzing classical scattering with generic incoming and outgoing states and one loop quantum scattering amplitudes. The classical and quantum results are consistent with each other. Although most of our analysis in quantum theory is carried out for one loop amplitudes in a theory of (charged) scalars interacting via gravitational and electromagnetic interactions, we expect the results to be valid more generally.

In collaboration with Sayali Atul Bhatkar, We obtained the subleading soft theorem for a generic theory of quantum gravity, for arbitrary number of soft photons and gravitons and for arbitrary number of finite energy particles with arbitrary mass and spin when all the soft particles are soft in the same rate. This result is valid at tree level for spacetime dimensions equal to four and five and to all loop orders in spacetime dimensions greater than five. We verified that in classical limit, low energy photon and graviton radiation decouple from each other.

Publications:

1. Biswajit Sahoo, Ashoke Sen, *Classical and Quantum Results on Logarithmic Terms in the Soft Theorem in Four Dimensions* , JHEP **1902**, 086, (2019)

2. Sayali Atul Bhatkar, Biswajit Sahoo, *Subleading Soft Theorem for arbitrary number of external soft photons and gravitons,* JHEP **1901**, 153, (2019)

Preprints:

1. Sayali Atul Bhatkar, Arnab Priya Saha, Biswajit Sahoo, *Logarithmic Terms in Soft Theorem as Ward Identity in Four dimentions* , To appear.

Conference/Workshops Attended:

1. *Strings 2018*, Japan, June, 2018.

2. *Soft Holography*, INDIA, March, 2019.

Invited Lectures/Seminars:

1. *Classical and Quantum Results on Logarithmic Terms in the Soft Theorem in Four Dimensions*, CMI, Chennai, February, 2019.

2. *Status of Soft Theorem in Four Dimensions*, IISER, Pune, March, 2019.

Arpita Sen

Research Summary:

In the academic year 2018-2019 my research works involved studies of permanent magnet without rare earth elements using first principle Density Functional Theory. I have finished the works involving small Co cluster doped with non magnetic elements. Now I have started furher works on these clusters supported on magnetic and no-magnetic substrates. I have also finished the studies of wurtzite polar oxides. I am trying to study the properties of wurtzite polar oxides surface when interfaced with hexagona Co surface.

Preprints:

1. Arpita Sen & Prasenjit Sen *Designing rare earth free permanent magnets: Insights from small Co clusters,* (in preparation)
2. Arpita Sen, Umesh V Waghmare & Prasenjit Sen *Emergence of two dimentional spin polarized electron gas at the surface of polar oxides,* (in preparation)

Conference/Workshops Attended:

1. *International Confernce on Magnetic Materials and Applications*, India, December 2018.
2. *19th International Workshop on Computational Physics and Material Sciences: Total Energy and Force Methods*, Italy, January 2019 *Workshop on Crystal Structure Prediction : Exploring the Mendeleev Table as a Pallette to Design New Materials* , Italy, January 2019.
3. *International Workshop on Advanced Materials*, RAK, UAE, Februay 2019.

Visits to other Institutes:

1. ICTP, Trieste, Italy, 9th January-19th January 2019,
2. RAKCAM, RAK, UAE, 23rd February-27th February 2019

Invited Lectures/Seminars:

1. *TaSi16 cluster on HOPG: structures and electronic properties*, Workshop on Crystal Structure Prediction : Exploring the Mendeleev Table as a Pallette to Design New Materials , ICTP, Trieste,Italy, January 2019.

Other Activities:

1. Tutorship of the course Quantam Mechanics of MSc 1st Semester, August 2018-Decembe 2018.

Md Arif Shaikh

Research Summary:

I have been working on the emergence of analogue gravity phenomena in transonic fluid systems. It is observed that in transonic fluid systems, the sonic horizon emits thermal spectrum of sound waves similar to the Hawking radiation from the event horizon of a black hole in general relativity. In the past, we showed that black hole accretion systems could be considered as an analogue gravity system found in nature by performing a linear perturbation of the accretion flow. Black hole accretion systems are very unique kind of analogue systems as there are two types of horizon in such a system–the general relativistic event horizon and the acoustic event horizon. The acoustic event horizon coincides with the critical points of the stationary accretion flow. The critical points are defined as the locations where the gradient of the advective velocity i.e., du_0/dr has $0/0$ form. In order to study stationary accretion flow on to black holes, three different flow geometries are considered in general. These are the constant height flow (CH), conical flow (CF) and the flow in hydrostatic equilibrium along the vertical direction (VE). It is noticed that the critical points and the transonic points (where the advective speed becomes equal to the local sound speed $c_s = \sqrt{dp/d\rho}$, p is the pressure and ρ is the density of the flow) coincide for flow with CH and CF geometries. However, for flow with VE geometry, the critical points and the transonic points are located at different radial points. For accretion on to Schwarzschild black hole, we showed that this non-isomorphism of the critical points and the transonic points could be removed if we redefine the sound speed as the speed of propagation of the acoustic perturbations as obtained from the perturbation equations resulting form linear perturbation analysis of the accretion flow. The effective sound speed is given by $c_s^{\rm eff} = c_s/\sqrt{1+\beta}$, where β depends on the particular VE model used in the calculation.

However, it is belived that most the astrophysical black holes possess non-zero spin a. Therefore, we used the same method as mentioned above to show that the non-isomorphism of the critical points and the transonic points could also be removed by introducing an effective sound speed to replace the local sound speed defined by $\sqrt{dp/d\rho}$ and thus redefining the Mach number as the ratio of u_0 to $c_s^{\rm eff}$.

Publications:

1. Md Arif Shaikh, Susovan Maity, Sankhasubhra Nag and Tapas Kumar Das, *Effective sound speed in relativistic accretion discs around Schwarzschild black holes,* New Astronomy **69**, 48-57, (2019).

2. Md Arif Shaikh and Tapas K. Das, *Linear perturbations of low angular momentum accretion flow in the Kerr metric and the corresponding emergent gravity phenomena,* Physical Review D, **98**, 123022, (2018).

Preprints:

1. Susovan Maity, Md Arif Shaikh and Tapas Kumar Das, *Effective sound speed in relativistic accretion discs around rotating black holes,* arXiv:1811.04975 [astro-ph.HE]

Conference/Workshops Attended:

1. *Exploring the Universe: Near Earth Space Science to Extra-Galactic Astronomy*, S N Bose National Centre for Basic Sciences, Kolkata, 14–17 November, 2018.

2. *Theoretical Aspects of Astroparticle Physics, Cosmology and Gravitation*, the Galileo Galilei Institute for Theoretical Physics, Florence, Italy, 11–22 March, 2019.

Visits to other Institutes:

1. Physics and Apllied Mathematics Unit, Indian Statistical Institute, Kolkata, 2018.

2. International Centre for Theoretical Sciences - TIFR, Bengaluru, India, 26 March - 06 April, 2019.

Other Activities:

1. Refereed paper for Classical and Quantum Gravity.

Gautam Sharma

Research Summary:

During the academic year 2018-2019, I continued my work on coherence and measurement problem. In particular, I worked with my supervisor were able to show in a particular measurement model that quantum coherence sets an upper limit on the maximum extractable information. Earlier it was known that entanglement developed between the system and apparatus upper bounds the information gain, which was a weak result in the sense that we don't have access to entanglement formed. Where as, initial coherence of the system is a quantity which we can control. We were also able to show that one can extract maximum information by using a more robust apparatus. Another part of the work was focused on how we can increase the information gain by manipulating various parameters like initial coherence of the system and apparatus and final entanglement between system and apparatus.

Preprints:

1. Gautam Sharma, Sk Sazim, and Arun Kumar Pati, *Quantum Coherence, Coherent Information and Information Gain in Quantum Measurement,* arXiv:1903.09622

Conference/Workshops Attended:

1. *Quantum Frontiers and Fundamentals*, Raman Research Institute, India, May, 2018
2. *QIPA*, Harish-Chandra Research Institute, India, December, 2018.

Sohail

Research Summary:

My research work during the academic year "2018-2019" constitutes of the following. I have studied the relation between the uncertainty and complementarity relation and have obtained some non-trivial results. We have used coherent control to obtain better bound for the quantum speed limit for open quantum system. I have also done some work related to Hahn-Banach theorem. Currently, I am trying to understand the algebraic approach to Entanglement and entropy for system of identical particles. For this purpose, I am going through the books "Algebraic methods in Statistical mechanics and Quantum field theory" by Gerard G. Emch and " Methods of modern mathematical physics, vol-1 (Functional analysis) " by Michael Reed , Barry Simon.

Conference/Workshops Attended:

1. *Meeting on Quantum Information Processing and Applications, Harish-Chandra Research Institute, Allahabad* , India, December 2018.

Chirag Srivastava

Research Summary:

In the previous academic year, I worked on quantum super dense coding and on foundations of quantum mechanics. In super dense coding, there are senders and receivers of the classical information, the task of the senders is to send classical information to the receivers using shared entangled state and a quantum channel as resources. These resources provide an advantage called "quantum advantage" in performing the mentioned task. There are already lot of works on the generalization of dense coding. Specifically, I worked on particular form of dense coding called conclusive dense coding with single copy of shared pure entangled state. Its conclusive because when the decoding protocol is successful by the receivers then they also succeed in fetching the exact classical information which was sent by the senders.

The following is the abstract of my work on quantum super dense coding. We introduce a probabilistic version of the one-shot quantum dense coding protocol in both two- and multiport scenarios, and refer to it as conclusive quantum dense coding. Specifically, we analyze the corresponding capacities of two-qubit, two-qutrit, and three-qubit shared states. We identify cases where Pauli and generalized Pauli operators are not sufficient as encoders to attain the optimal one-shot conclusive quantum dense coding capacities. We find that there is a rich connection between the capacities, and the bipartite and multipartite entanglements of the shared state.

Preprints:

1. Chirag Srivastava, Anindita Bera, Aditi Sen De, Ujjwal Sen, *One-shot conclusive multiport quantum dense coding capacities*, arXiv:1903.11709

Conference/Workshops Attended:

1. *Quantum Information Processing and Applications*, India, December, 2018
2. *Asia Pacific Conference And Workshop On Quantum Information Science*, India, December, 2018.

Other Activities:

1. I was member of science talent search examination conducting committee, conducted at HRI, Allahabad in the previous academic year in which students from various schools in Allahabad participate.

Waleed Mohammed Abdallah

Research Summary:

I have joined HRI as a post-doctoral fellow in Physics on March 21, 2018. My research has focused on studying Dark Matter (DM) in models beyond the Standard Model (SM) and analysing their signatures at the Large Hadron Collider (LHC). In the first paper, *"Long-lived $B-L$ symmetric SSM particles at the LHC"*, we studied two examples of possible Long-Lived Particles (LLPs), predicted by the Supersymmetric $B-L$ extension of the SM (BLSSM), namely the lightest left-handed sneutrino and the left-handed stau, which act as neutral and charged LLPs, respectively. After combining all results, we concluded that unlike MSSM the BLSSM naturally provides long-lived candidates with clean signatures that can be reachable at the next run of the LHC.

In the second paper, *"Searching for charged Higgs bosons in the $B-L$ supersymmetric standard model at the high luminosity LHC"*, we assessed the scope of the high luminosity LHC in accessing charged Higgs bosons ($H^{\pm}$) produced in pairs from Z' decays in the BLSSM. We showed that, by pursuing both di-jet and tau-neutrino decays, several signals can be established for $H^{\pm}$ masses ranging from about M_W to above m_t and Z' masses between 2.5 TeV and 3.5 TeV. The discovery can be attained, owing to the fact that the very massive resonating Z' ejects $H^{\pm}$ at very high transverse momentum, a kinematic region where any SM noise is hugely depleted.

In the third paper, *"FIMP dark matter candidate(s) in a $B-L$ model with inverse seesaw mechanism"*, we considered a popular $U(1)_{B-L}$ extension of the SM with inverse seesaw mechanism which has at least one (fermionic) FIMP DM candidate. Due to the added Z_2 symmetry, a SM gauge singlet fermion, with mass of order keV, is stable and can be a warm DM candidate. Also, the same Z_2 symmetry helps the lightest right-handed neutrino, with mass of order GeV, to be a stable or long-lived particle. This provides a possibility of a two component DM scenario as well. Firstly, in the absence of a GeV DM component, we considered only a keV DM as a single component DM, which is produced by the freeze-in mechanism and can consistently explain the DM relic density measurements. Secondly, we studied a two component DM scenario and emphasized that the current DM relic density bound can be satisfied for a wide range of parameter space.

Finally, in the Z_3-symmetric next-to-minimal supersymmetric SM, we study the possibility of having a singlino-like DM candidate and light singlet-dominated scalars away from compressed particle spectra region. As mentioned in the literature that it is difficult to satisfy simultaneously results from the LHC and DM experiments for such a scenario, we proceed to demonstrate how exactly and to what extent could such a singlino-like DM candidate still remains plausible.

Publications:

1. W. Abdallah, A. Hammad, A. Kasem and S. Khalil, *Long-lived $B-L$ symmetric SSM particles at the LHC,* Phys. Rev. D **98**, 095019, (2018).

2. W. Abdallah, A. Hammad, S. Khalil and S. Moretti, *Searching for charged Higgs bosons in the $B-L$ supersymmetric standard model at the high luminosity large hadron collider,* Phys. Lett. B **788**, 65, (2019).

Preprints:

1. W. Abdallah, S. Choubey and S. Khan, *FIMP dark matter candidate(s) in a $B - L$ model with inverse seesaw mechanism,* arXiv:1904.10015, to appear in JHEP.

2. Waleed Abdallah, Arindam Chatterjee and AseshKrishna Datta, *Revisiting singlino dark matter of the natural Z_3-symmetric NMSSM in the light of LHC,* (in preparation).

Conference/Workshops Attended:

1. *International meeting on high energy physics*, IOP, Bhubaneswar, India, January, 2019.

2. *RECAPP activity week*, HRI, Allahabad, India, March, 2019.

3. *Neutrino and dark matter activity week*, HRI, Allahabad, India, February, 2019.

4. *RECAPP activity week*, HRI, Allahabad, India, July, 2018.

Visits to other Institutes:

1. Physics and Applied Mathematics Unit, Indian Statistical Institute, Kolkata, India, December, 2019.

Invited Lectures/Seminars:

1. *Dark matter in SUSY B-L model with inverse seesaw mechanism*, International meeting on high energy physics, dark matter working group, IOP, Bhubaneswar, India, January, 2019.

2. *Searching for a light wino-like dark matter in the MSSM at the LHC*, Neutrino and dark matter activity week, HRI, Allahabad, February, 2019.

Atreya Chatterjee

Research Summary:

During the period 6th August, 2018 - 31st March 2019 I was engaged in two research projects. The first project on Soft theorem is being done collaboratively with Arnab Priya Saha and Sayali Bhatkar under the guidance of Prof. Ashoke Sen. Our goal is to understand the origin of logarithmic soft factors for radiation from massless particles. Radiation from two black holes in probe-scatterer limit is given by Peter's paper , "Relativistic Gravitational Bremsstrahlung" and "Perturbations in the Schwarzschild Metric". We boosted the result to a frame where both the black holes are in ultra-relativistic regime. Finally, the goal is to match the result with Veneziano's results in the paper 1812.08137 and find higher order terms in soft expansion.

My second project is on understanding relation between partition and metric. Given a configuration of black hole deriving temperature and entropy is somewhat well-posed problem. Now one can reverse the question. If a partition is given, is it possible to define a metric out of that? Partition is defined by ordered set of elements with an operation. Given a partition one can ask how to form bigger partitions by merging smaller partitions. Key is to see the process of merger of two separate partitions into one as an interaction. Suitable measure of oneness defines "distance" of multiplicity from unity.

The set we consider is following $\{n^2 : n \geq 1\} = \{1, 4, 9, 16, 25, ...\}$. Suppose a partition is $n^2 = \sum_i^j k_i n_i^2$ then we define following weighted partition $P(n^2) = \prod_i^j w^{k_i}$. For an infinite series asymptotes are interesting observables. l^{th} asymptote grows like $c_l e^{Gn^2/l^2}$, $G = \ln w$ and c_l is some coefficient. Interesting thing is that leading asymptote grows like e^{Gn^2} which is similar to degeneracy of Schwarzschild black hole. The next question we ask is what happens when a $P(n^2) \to P((n+m)^2)$? For $m << n$, change in l^{th} asymptote is $2G\frac{nm}{l^2} c_l e^{Gn^2/l^2}$. We show that with suitable choice of observables, certain features of gravitational system can be seen in merger of partition.

Conference/Workshops Attended:

1. *Indian Strings Meeting*, India, December, 2018

Debmalya Das

Research Summary:

My research spans the areas of quantum information, foundations of quantum physics and quantum thermodynamics. Some of the problems I am recently interested in are quantum entanglement, Quantum Chesire Cat and quantum heat engines.

In a previous work, we studied a quantum Stirling cycle which extracts work using quantized energy levels by inserting and removing a partition and operating between two temperatures. The work and the efficiency of the engine was found to depend on the length of the potential well, and the Carnot efficiency was approached in a low temperature limiting case. We showed that the lack of information about the position of the particle inside the potential well can be converted into useful work without resorting to any measurement. In the low temperature limit, we calculated the amount of work extractable from distinguishable particles, fermions and bosons.

As a continuation of this study, we have now embarked upon treating the process of insertion/ removal of the partition as occuring in a finite time. The engine is modelled as a one dimensional infinite potential well with the partition as a Gaussian function of vanishing width. As the heat engine, we considered previously, showed some very promising characteristics, the present study is important to reach more realistic situtations and finally an experimental implementation.

In a separate direction, we are working on Quantum Chesire cats. Quantum Chesire Cat is a counterintuitive phenomenon that decouples two degrees of freedom of the same physical entity, in the domain of quantum systems, from each other. This can be realized by using an interferometric setup in which the position of a photon travels through one arm of the interferometer and the polarization travels through the other. This is similar to the Chesire Cat of Alice in Wonderland where the grin of the cat existed without the cat itself. Our main focus is to explore the possibility of using a separated property of a quantum system for quantum information processing purposes. Some success has been achieved in this regard in the context of quantum teleportation i.e. the property of a system can be teleported between two parties who actually do not possess the system. We are also examining what might be the implications of such possibilities for foundations of quantum physics.

Specifically, we present a thought experiment where we decouple two photons from their respective polarizations and then interchange them during recombination. Thus, our proposal shows that that the belongingness of a property for a physical system is very volatile in the world of quantum mechanics.

Publications:

1. Anindita Bera, Debmalya Das, Aditi Sen (De) and Ujjwal Sen, *Universal quantum uncertainty relations: minimum-uncertainty wavepacket depends on the measure of spread,* Physics Letters A **383**, 1850-1855, (2019).

Preprints:

1. Debmalya Das and Arun Kumar Pati, *Teleporting the Grin of a Quantum Chesire Cat without cat,* arXiv:1903.04152.

2. Debmalya Das and Arun Kumar Pati, *Can two Quantum Chesire Cats exchange Grins,* arXiv:1904.07707.

Conference/Workshops Attended:

1. *Asia Pacific Conference and Workshop on Quantum Information Science 2018*, India, December 2018,

2. *Meeting on Quanutm Information Processing and Applications*, India, December 2018.

Visits to other Institutes:

1. Universite de Namur, Namur, Belgium, May 2019,

2. Aalto University, Helsinki, Finland, April-May 2019,

3. Research Centre for Quantum Information, Bratislava, Slovakia, April 2019,

4. Friedrich-Alexander Universitat, Erlangen, Germany, April 2019.

Dhargyal

Research Summary:

In this academic report 2018-19 I have included all my research work that are published, in pre-print form on arXiv, as well as work that I presented to various conferences.

Publications:

1. Lobsang Dhargyal, *Full angular spectrum analysis of tensor current contribution to* $A_{cp}(\tau \to K_s \pi \nu_\tau)$. Letters in High Energy Physics (LHEP), **LHEP 1 (2018) no.3, 9-14**

Preprints:

1. Lobsang Dhargyal, *Search for an exotic-leptonic solution to observed anomalies in lepton universality observables in B decays and more.* arXiv:1808.06499 (2018)

2. Lobsang Dhargyal, *Phenomenological consequences of introducing new fermions with exotic charges to* $R(K^{(*)})$*, muon (g-2), the primordial Lithium problem, and dark matter.* arXiv:1810.10611 (2018)

3. Lobsang Dhargyal, *Phenomenology of a universal super weak* $SU(N)_w$ *color hypothesis.* arXiv:1901.10940 (2019)

Conference/Workshops Attended:

1. Lobsang Dhargyal, *Exotic Leptonic solutions to observed anomalies in lepton universality observables and more.* arXiv:1901.01170 (2019). DAE-BRNS 2018 IIT-Chennai (Conference: C18-12-10.1) (Accepted to be published in the conference proceedings.)

2. I have also attended the FPCP2018 (Hydrabad) conference.

1. *A Brief Review of Present Status of Standard Model of Particle Physics.*, Talk Given at Tibetan Science Conclave - V, New Delhi, December 19-22, 2018.

Manish Kumar Gupta

Research Summary:

In the first work, we propose a magnetometer for the precise measurement of AC magnetic fields that uses a Terbium-doped optical fiber with half-waveplates built into it at specified distances. Our scheme uses an open-loop quantum control technique called dynamical decoupling to reduce the noise floor and thus increase the sensitivity. We show that dynamical decoupling is extremely effective in preserving the photon state evolution due to the external AC magnetic field from random birefringence in the fiber, even when accounting for errors in pulse timing. Hence we achieve high sensitivity. For a given inter-waveplate distance, the minimum detectable field is inversely proportional to fiber length, as is the bandwidth of detectable frequencies.

In the second work, we propose a novel approach to qubit thermometry using a quantum switch, that introduces an indefinite causal order in the probe-bath interaction, to significantly enhance the thermometric precision. The resulting qubit probe shows improved precision in both low and high-temperature regimes when compared to optimal qubit probes studied previously. It even performs better than a Harmonic oscillator probe, in spite of having only two energy levels rather than an infinite number of energy levels as that in a harmonic oscillator. We thereby show unambiguously that quantum resources such as the quantum switch can significantly improve equilibrium thermometry. We also derive a new form of thermodynamic uncertainty relation that is tighter and depends on the energy gap of the probe. The present work may pave the way for using indefinite causal order as a metrological resource.

Preprints:

1. Manish K. Gupta, Jonathan Kunjummen, Xiaoting Wang and Jonathan P. Dowling, *High precision Optical AC Magnetometry using Dynamical Decoupling,* arXiv:1807.08760

2. Chiranjib Mukhopadhyay, Manish K Gupta, Arun Kumar Pati, *Superposition of causal order as a metrological resource for quantum thermometry,* arXiv:1812.07508

Invited Lectures/Seminars:

1. *Enhanced communication and metrology with superposition of trajectories*, QuIC, Talk, Harish-Chandra Research Institute, Allahabad, April 2019.

Conference/Workshops Attended:

1. *Quantum Information Processing and Applications (QIPA-2018)*, India, December 2018.

Visits to other Institutes:

1. National Institute of Technology Patna, Patna, India, February 2019.

Academic recognition/Awards:

- New Journal of Physics, Reviewer Award, 2018.

Shiladitya Mal

Research Summary:

1) We investigate sharing of bipartite entanglement in a scenario where half of an entangled pair is possessed and projectively measured by one observer, called Alice, while the other half is subjected to measurements performed sequentially, independently, and unsharply, by multiple observers, called Bobs. We find that there is a limit on the number of observers in this entanglement distribution scenario. In particular, for a two-qubit maximally entangled initial shared state, no more than twelve Bobs can detect entanglement with a single Alice for arbitrary–possibly unequal–sharpness parameters of the measurements by the Bobs. Moreover, the number of Bobs remains unaltered for a finite range of near-maximal pure initial entanglement, a feature that also occurs in the case of equal sharpness parameters at the Bobs. Furthermore, we show that for non-maximally entangled shared pure states, the number of Bobs reduces with the amount of initial entanglement, providing a coarse-grained but operational measure of entanglement.

2) We consider a quantum particle (walker) on a line that coherently chooses to jump to the left or right depending on the result of a toss of a quantum coin. The lengths of the jumps are considered to be independent and identically distributed quenched Poisson random variables. We find that the spread of the walker is significantly inhibited, whereby it resides in the near-origin region, with respect to the case when there is no disorder. The scaling exponent of the quenched-averaged dispersion of the walker is subballistic but superdiffusive. We also show that the features are universal to a class of sub-and super-Poissonian-distributed quenched randomized jumps.

3) Nonclassicality of temporal correlations pertaining to noncommutative sequential measurements is defined through the violation of macrorealistic inequalities, known as Leggett-Garg inequalities (LGI). We investigate the energy cost of the process associated with the Leggett-Garg test in the context of noiseless and Markovian noise for arbitrary initial states. We prove that in noiseless and in certain noisy scenarios, the maximal violations of LGI under the energy constraint occurs when the average energy of the process is equal to the negative of the energy of the initial state. Such a dependence of LGI on the choice of the initial state is not seen in the unconstrained case. Moreover, we find that in the presence of a moderate amount of Markovian noise, the amount of violation of LGI remains almost unaltered with a suitable choice of the evolution and dephasing operators in the neighborhood of the maximal violation line, thereby showing the robustness of temporal correlations under environmental effects.

4) Complete measurements, while providing maximal information gain, results in destruction of the shared entanglement. In the standard teleportation scheme, the sender's measurement on the shared entangled state between the sender and the receiver has that consequence. We propose here a teleportation scheme involving weak measurements which can sustain entanglement upto a certain level so that the reusability of the shared resource state is possible. The measurements are chosen in such a way that it is weak enough to retain entanglement and hence can be reused for quantum tasks, yet adequately strong to ensure quantum advantage in the protocol. In this scenario, we report that at most six sender-receiver duos can reuse the state, when the initial shared state is entangled in a finite neighborhood of the maximally entan-

gled state and for a suitable choice of weak measurements. However, we observe that the reusability number decreases with the decrease in the entanglement of the initial shared state. Among the weakening strategies studied, Bell measurement admixed with white noise performs better than any other low-rank weak measurements in this situation.

Publications:

1. Anindita Bera, Shiladitya Mal, Aditi Sen(De), and Ujjwal Sen, *Witnessing bipartite entanglement sequentially by multiple observers,* Phys. Rev. A **98**, 062304, (2018)

2. Titas Chanda, Tamoghna Das, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Canonical Leggett-Garg Inequality: Nonclassicality of temporal quantum correlations under energy constraint,* Phys. Rev. A **98**, 022138, (2018)

3. Sreetama Das, Shiladitya Mal, Aditi Sen, Ujjwal Sen, *Inhibition of spreading in quantum random walks due to quenched Poisson-distributed disorder,* Phys. Rev. A **99**, 042329, (2019)

4. Sougato Bose, Dipankar Home, Shiladitya Mal, *Nonclassicality of the Harmonic-Oscillator Coherent State Persisting up to the Macroscopic Domain,* Phys. Rev. Lett. **120**, 210402, (2018)

5. Debarshi Das, Arkaprabha Ghosal, Souradeep Sasmal, Shiladitya Mal, AS Majumdar, *Facets of bipartite nonlocality sharing by multiple observers via sequential measurements,* Phys. Rev. A **99**, 022305, (2018)

Preprints:

1. Shounak Datta, Shiladitya Mal, AS Majumdar, *Protecting temporal correlations of two-qubit states using quantum channels with memory,* arXiv: 1808.10345

2. Sumit Mukherjee, Anik Rudra, Debarshi Das, Shiladitya Mal, *Effects of coarsening measurement times on quantum violations of macrorealism for multilevel spin systems,* arXiv: 1811.03397

Conference/Workshops Attended:

1. *Quantum Frontiers and Fundamentals*, Raman Research Institute, India, May, 2018

2. *QIPA*, Harish-Chandra Research Institute, India, December, 2018.

Visit to other Institute

S N Bose National Centre for Basic Sciences, January, 2019.

Soumita Pramanick

Research Summary:

Radiative generation of neutrino mass and mixing at one-loop level using discrete flavour symmetries like $A4$ and $S3$ as explored in some single-author enterprises are discussed below.

Realistic neutrino mass and mixing were obtained at one-loop level using particles that could be dark matter candidates. Such models are also called 'scotogenic' models. The name is derived from the Greek word 'scotos' that means darkness. Thus these models address two extremely important issues of contemporary paticle physics research viz. origin of neutrino mass and dark matter in one stroke.

- In arXiv: 1903.04208 [hep-ph] by Soumita Pramanick, such a scotogenic model based on $A4 \times Z_2$ symmetry was proposed. The model has three right-handed neutrinos along with other particles. Here non-zero θ_{13} was obtained through some mass splitting in the right-handed neutrino sector. There were three inert $SU(2)_L$ doublet scalar fields the lightest among which can serve as a dark matter candidate. This is submitted for publication.

- In arXiv:1904.07558 [hep-ph] by Soumita Pramanick, $S3 \times Z_2$ symmetry was used to obtain a scotogenic model for realistic neutrino mass and mixing at one-loop level. The model comprises of two right-handed neutrinos which when maximally mixed gave $\theta_{13} = 0$. A small shift from the maximal mixing in the right-handed neutrino sector yields non-zero θ_{13}. The model consists of two inert $SU(2)_L$ doublet scalars, lightest of which can be a potential dark matter candidate. This paper is submitted for publication.

- The paper *'Ameliorating the popular lepton mixings with A4 symmetry: A see-saw model for realistic neutrino masses and mixing'*, arXiv:1711.03510 [hep-ph], Soumita Pramanick was published in Physical Review D [Physical Review D 98, 075016 (2018)]. In this paper a tree-level model for realistic neutrino mass and mixing based on $A4$ was studied.

Publications:

1. Soumita Pramanick, *Ameliorating the popular lepton mixings with A4 symmetry: A see-saw model for realistic neutrino masses and mixing*, Physical Review D **98**, 075016, (2018)

Preprints:

1. Soumita Pramanick, *Scotogenic S3 symmetric generation of realistic neutrino mixing*, 1904.07558 [hep-ph]

2. Soumita Pramanick, *Radiative generation of realistic neutrino mixing with A4*, arXiv: 1903.04208 [hep-ph]

Conference/Workshops Attended:

1. *XXIII DAE BRNS High Energy Physics Symposium*, Indian Institute of Technology (IIT), Madras, Chennai, India, December, 2018.

2. *IITB - ICTP Workshop on Neutrino Physics*, Indian Institute of Technology (IIT), Bombay, Mumbai, India, December, 2018.

3. *International Meeting on High Energy Physics 2019 (IMHEP 2019)*, Institute Of Physics (IOP), Bhubaneswar, India, January, 2019.

4. *Neutrino Dark Matter Activity Week*, HRI, Allahabad, India, February-March, 2019.

5. *HEP Activity Period (RECAPP)*, HRI, Allahabad, India, March, 2019.

Talks/ Oral Presentations:

1. *Alignment in A4 symmetric three-Higgs-doublet model*, XXIII DAE BRNS High Energy Physics Symposium, Indian Institute of Technology (IIT), Madras, Chennai, India, December, 2018.

2. *Using A4 to ameliorate popular lepton mixings: A model for realistic neutrino masses and mixing based on see-saw*, Indian Institute of Technology (IIT), Madras, Chennai, India, December, 2018.

3. *Applying A4 to Neutrino and Higgs sectors*, International Meeting on High Energy Physics 2019 (IMHEP 2019), Institute Of Physics (IOP), Bhubaneswar, India, January, 2019.

4. *Some uses of A4 in Neutrino and Higgs sectors*, Neutrino Dark Matter Activity Week, HRI, Allahabad, India, February-March, 2019.

Poster Presentation:

1. *Alignment in A4 symmetric three-Higgs-doublet model*, International Meeting on High Energy Physics 2019 (IMHEP 2019), Institute Of Physics (IOP), Bhubaneswar, India, January, 2019.

Academic recognition/Awards:

1. Selected to receive Fermilab Neutrino Physics Center (NPC) Fellowship Award (Fall 2018), and invited to go to Fermilab for a 45 days visit.

2. Selected for a 10 days visit to Fermilab under the Summer Visitors Program in the Theoretical Physics Department, Fermilab.

Other Activities:

1. Participated and organized Neutrino Dark Matter Activity Week held at HRI, February-March, 2019.

2. Participated and organized HEP Activity Period (RECAPP) held at HRI, March, 2019.

Arnab Priya Saha

Research Summary:

I have been studying soft theorems mainly in the context of gravitational or electromagnetic scattering amplitudes since August, 2018. My area of research is mainly focused on classical limits of the soft graviton and photon theorems. In four dimension because of long range interactions there are infrared divergences in S-matrix. As a consequence in four dimension sub-leading soft graviton and photon theorems receive loop corrections. Loop corrected sub-leading soft graviton and photon theorems have been discovered by Biswajit Sahoo and Ashoke Sen. Classical limits of multiple soft graviton theorem give low frequency spectra of gravitational radiation. Another aspect of soft theorems is that they are related to asymptotic symmetries of asymptotically flat spacetimes. In one ongoing project we are trying to obtain Ward identities of S-matrix related to sub-leading soft photon theorem in presence of gravity for asymptotically flat spacetimes. We also plan to extend our analysis for sub-leading soft graviton theorem.

Conference/Workshops Attended:

1. *Indian Strings Meeting*, India, December, 2018,
2. *Soft Holography*, IISER Pune, India, March, 2019.

Visits to other Institutes:

1. Institute of Mathematical Sciences, place, Country, Month year,
2. Name of the institute, Chennai, India, April, 2019.

Invited Lectures/Seminars:

1. *Soft theorems in gauge and gravity theories*, tutor, SERC main school, IISER, Pune, November-December, 2019.

Tousik Samui

Research Summary:

In one of our works, we studied the experimental constraints on a model of a two-component dark matter, consisting of the QCD axion, and a scalar particle, both contributing to the dark matter relic abundance of the universe. The global Peccei-Quinn symmetry of the theory can be spontaneously broken down to a residual Z_2-symmetry, thereby identifying this scalar as a stable weakly interacting massive particle, i.e., a dark matter candidate, in addition to the axion. We perform a comprehensive study of the model using the latest data from dark matter direct and indirect detection experiments, as well as new physics searches at the Large Hadron Collider. We find that although the model is mostly constrained by the dark matter detection experiments, it is still viable around a small region of the parameter space where the scalar dark matter is half as heavy as the Standard Model Higgs. In this allowed region, the bounds from these experiments are evaded due to a cancellation mechanism in the dark matter-Higgs coupling. The collider search results, however, are shown to impose weak bounds on the model.
[with Suman Chatterjee, Anirban Das, and Manibrata Sen, arXiv:1810.09471 [hep-ph]]

In an ongoing work, we use jet substructure technique to distinguish different types of dijet resonances produced at the Large Hadron Collider (LHC). Extending the idea of quark versus gluon tagging, jet substructure observables along with event variables in a dijet event can give important information regarding the type of the resonance. This will be a useful tool to differentiate different models which gives rise to dijet resonances at the LHC.
[with Santosh Kumar Rai, (in preparation)]

Preprints:

1. Suman Chatterjee, Anirban Das, Tousik Samui, Manibrata Sen, *A tale of two dark neighbors: WIMP n' axion,* arXiv:1810.09471 [hep-ph]

Conference/Workshops Attended:

1. *International Meeting on High Energy Physics*, Institute of Physics, Bhubaneswar, India, January, 2019,

2. *Academic Program – HEP activity weeks*, Harish-Chandra Research Institute, Prayagraj, India, February – March, 2019.

Invited Lectures/Seminars:

1. *Missing Energy Signal in $t\bar{t}$ to Probe Large Extra Dimensions at Collider*, Academic Program – HEP activity weeks, Harish-Chandra Research Institute, Prayagraj, India, March 2019.

Other Activities:

1. Organised *High Energy Physics Journal Club* in HRI from 31st October 2018 to 14th May 2019. The Journal Club was held from 3:30 pm to 5:00 pm every Wednesday.

2. Participated in organising *Academic Program – HEP activity weeks* from 4th March 2019 to 15th March 2019.

Sk Sazim

Research Summary:

1. A measurement is deemed successful, if one can maximize the information gain by the measurement apparatus. Here, we ask if quantum coherence of the system imposes a limitation on the information gain during quantum measurement. First, we argue that the information gain in a quantum measurement is nothing but the coherent information or the distinct quantum information that one can send from the system to apparatus. We prove that the maximum information gain from a pure state, using a mixed apparatus is upper bounded by the initial coherence of the system. Further, we illustrate the measurement scenario in the presence of environment. We argue that the information gain is upper bounded by the entropy exchange between the system and the apparatus. Also, to maximize the information gain, both the initial coherence of the apparatus, and the final entanglement between the system and apparatus should be maximum. Moreover, we find that for a fixed amount of coherence in the final apparatus state the more robust apparatus is, the more will be the information gain.

2. Quantum entanglement plays a pivotal role in a number of communication protocols, like secret sharing and quantum cryptography. We consider a scenario where more than two parties are involved in a protocol and they share a multipartite entangled state. In particular, we introduce the protocol of cooperative quantum key distribution (CoQKD). In this protocol, two parties, Alice and Bob establish a key with the cooperation of other parties. Other parties control whether Alice and Bob can establish the key, its security and the key rate. We discuss the case of three parties in detail and find the necessary suitable resource states. We discuss the controlling power of the third party, Charlie. We also examine the usefulness of this new resource state for generating conference key and for cooperative teleportation. In the case of conference key, we find that recently introduced Bell inequalities can be useful to establish the security. We also generalize the scenario to more than three parties.

Preprints:

1. Gautam Sharma, Sk Sazim, and Arun Kumar Pati, *Quantum Coherence, Coherent Information and Information Gain in Quantum Measurement,* arXiv:1903.09622

2. Arpan Das, Sumit Nandi, Sk Sazim, and Pankaj Agrawal, *Resource state structure for cooperative quantum key distribution,* arXiv:1903.10163

Conference/Workshops Attended:

1. *YQIS conference and CoQuS Summer School 2018*, University of Vienna, Austria, September 2018.

2. *Entanglement Days 2018*, Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest, Hungary, September 2018.

Visits to other Institutes:

1. International Institute of Information Technology (IIIT), Gachibowli Hyderabad, India, 20 March - 20 April 2019,

2. International Institute of Information Technology (IIIT), Bhubaneswar, India, 14 - 25 February 2019.

3. Jagiellonian University, Krakow, Poland, 23 - 25 September 2018.

Invited Lectures/Seminars:

1. *Coherence makes quantum system 'magical'*, invited Talk, IIIT, Hyderabad, Gachibowli, Hyderabad, 5 April 2019.

2. *Quantum correlations: entanglement and beyond*, course lecture, IIIT, Hyderabad, Gachibowli, Hyderabad, 26 March 2019.

3. *Mutual uncertainty, conditional uncertainty and strong sub-additivity*, Entanglement Days 2018, Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest, Hungary.

4. *Mutual uncertainty, conditional uncertainty and strong sub-additivity*, Entanglement Days 2018, Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest, Hungary.

Sorokhaibam Nilakash Singh

Research Summary:

My research work during the academic year 2018-2019 has been concentrated on the study of non-equilibrium dynamics in Sachdev-Ye-Kitaev(SYK) model. SYK model has been rigorously studied in the last 4-5 years both by high-energy physics community as well as condensed-matter physics community. It a chaotic system which is also tractable to some extent. Normally chaotic systems are very difficult to study.

We studied non-equilibrium dynamics in SYK models using quantum quench. We considered models with two, four, and higher fermion interactions ($q = 2$, 4, and higher) and use two different types of quench protocol, which we call step and bump quenches. We analyse evolution of fermion two-point functions without long time averaging. We observe that in $q = 2$ theory the two-point functions do not thermalize. We find thermalization in $q = 4$ and higher theories without long time averaging. We also calculate two different exponents of which one is equal to the coupling and the other is proportional to the final temperature. This result is more robust than thermalization obtained from long time averaging as proposed by the eigenstate thermalization hypothesis(ETH). Thermalization achieved without long time averaging is more akin to mixing than ergodicity.

Preprints:

1. Nilakash Sorokhaibam, Ritabrata Bhattacharya and Dileep P. Jatkar, *Quantum Quenches and Thermalization in SYK models,* arXiv:1811.06006, submitted to JHEP for publication.

Conference/Workshops Attended:

1. *AdS/CFT at 20 and beyond*, ICTS Bangalore, India, May 2018.
2. *Strings 2018*, OIST Okinawa, Japan, June 2018.
3. *Indian Strings Meeting*, IISER Trivandrum, India, December 2018.

Visits to other Institutes:

1. SINP, Kolkata, India, September 2018.
2. NISER, Bhubaneshwar, India, April 2019.
3. IISER, Bhopal, India, April 2019.

Invited Lectures/Seminars:

1. *Thermalization in $q = 2$ and $q = 4$ Sachdev-Ye-Kitaev(SYK) models*, Departmental seminar, SINP, Kolkata, India, September 2018.
2. *Non-equilibrium dynamics in SYK models*, Departmental seminar, NISER, Bhubaneshwar, India, April 2019.

3. *Non-equilibrium dynamics in SYK models*, Departmental seminar, IISER, Bhopal, India, April 2019.

HRI Colloquia

1. Roop Malik : *Tossing coins inside living cells.*
2. Dhruv Raina : *Theories and Imaginations of Science, Technology and Society: Utopias and Dystopian Visions.*
3. Srikanth Sastry : *Yielding in amorphous solids and related transitions in driven systems.*
4. Alok Bajpai : *Is the mind trainable?.*
5. Rajaram Nityananda : *Undergraduate science education: the experience at Azim Premji University.*
6. Palash Baran Pal : *Measurement of lenghts and other simple things.*
7. Benoy K Behl : *The Murals of India.*
8. Suman Bhattacharjea : *Are we preparing our youth for adulthood? Major findings from ASER 2017.*
9. Kavita Singh : *Mughal Chronicles: Words, Images and the Gaps in.*
10. Mahesh Rangarajan : *At Nature's Edge, Longer views of history, ecology and the human predicament.*
11. Alok Rai : *An orwell for our time.*
12. Abhijit Gupta : *'Virgil on the Hugli' or how to get your term paper published.*
13. Eluvathingal D. Jemmis : *Nature Plays Dice with Boron: Inevitability of Uncertainties.*

Mathematics Talks and Seminars

1. Rohit Gupta : *On permutation trinomials over finite fields with even characteristic.*
2. Anupam Gumber : *Orthogonality of translation invariant frame pairs over locally compact abelian groups.*
3. Manish Mishra : *Depth preservation in Local Langlands correspondence for tori.*
4. NSN Sastry : *Coxeter Groups.*
5. Sanjay Amrutiya : *Tannakian fundamental group schemes.*
6. Ashish K. Srivastava : *An approach toward supersymmetric cluster algebras.*
7. Atul Dixit : *Ramanujan's formula for odd zeta values and subsequent developments.*
8. Stephan Baier : *Moments of the error term in the Sato-Tate law for elliptic curves.*
9. Jean-Marc Deshouillers : *Distribution of P-S seqences in arithmetic progressions and applications.*
10. Saurabh Singh : *Sub-convexity problems : some history and recent developments.*
11. Anupam Singh : *Shalev's conjecture for type A_n.*
12. Jayakumar Ravinder : *Quiver Representation and Gabriel's Therorem.*
13. Francois Hennecart : *On the density of sumsets, product sets and subset sums.*
14. Shubhankar Podder : *Reflexivity of Operators.*
15. William Mance : *Normal numbers in various numeration systems.*
16. S. G. Dani : *Diophantine approximation with nonsingular integral linear transformations.*

Mathematics Colloquia

1. S. G. Dani : *Glimpses of ancient and medieval Indian mathematics.*
2. Arun Muktibodh : *Short film "Euler's Spoiler: A living Legend"; a tribute to Prof. Sharadchandra S.Shrikhande.*

Physics Talks and Seminars

1. Arunabha Saha : *The large D Membrane Paradigm For Einstein-Gauss-Bonnet Gravity.*
2. Masazumi Honda : *Resurgence and Exact results in supersymmetric gauge theories.*
3. Masazumi Honda : *Introduction to reseurgence and complex saddle point analysis.*
4. Lavneet Janagal : *Chern-Simons Matter Dualities in the Higgsed Phase.*
5. Harold Erbin : *Towards a cubic closed string field theory?*
6. Raghu Mahajan : *Entanglement entropy / black hole entropy from the string world sheet.*
7. Debajyoti Sarkar : *Some recent progress on spacetime reconstruction from CFT.*
8. Akash Jain : *Magnetohydrodynamics and one-form superfluidity.*
9. Subhroneel Chakrabarti : *Scattering of massive states in pure spinor superstrings.*
10. K. Sravan Kumar : *Non-local R^2 inflation and quantum gravity.*
11. Deshdeep Sahdev : *A Practical Approach to Strengthening our Scientific Ecosystem.*
12. Deshdeep Sahdev : *A Robust Signature of Electron Hydrodynamics in 2-Dimensional Materials.*
13. C. Jebarathinam : *Simultaneous correlations in complementary bases as quantitative resource for quantum steering.*
14. Md. Manirul Ali : *Non-equilibrium dynamics of open quantum systems and quantum thermodynamics.*
15. Samyadeb Bhhacharyya : *Convex Resource Theory of non-markovianity.*
16. Priyabrata Bag : *t-Frobenius Negacyclic Codes.*
17. Sagnik Chakrabarty : *Aspects of Markovianity in Open quantum systems and Applications of weak values.*
18. Swati Singh : *Using macroscopic quantum systems as detectors.*
19. Namitha C V : *Control of Entanglement Longevity in Open Interacting Two-Qubit System.*
20. Arpan Das : *Entanglement, Nonlocality and Quantum Thermodynamics.*
21. Vishwa Pal : *Phase locking of large network of coupled lasers.*
22. Ish Dhand : *Proposal for Quantum Simulation via All-Optically Generated Tensor Network States.*
23. Shreya P Kumar : *Quantum-optical tests of Planck-scale physics.*

24. Noufal Jaseem : *Practical restrictions and environmental effects on quantum-limited measurements.*

25. Naqueeb Warsi : *Building blocks for communication over quantum networks.*

26. Meenu Kumari : *Untangling entanglement and chaos.*

27. Tousik Samui : *Jet Substructure at the LHC.*

28. Dinesh K. Srivastav : *Charm production in pp and AA collisions in parton cascade model.*

29. Nabarun Chakrabarty : *Charged scalars confronting neutrino mass and muon g and 2 anomaly.*

30. Ambresh Shivaji : *Probing Higgs self-coupling at Future Colliders.*

31. Priyotosh Bandyopadhay : *Perspective of extended Higgs sectors in supersymmetric scenarios at the LHC.*

32. Arun Nayak : *Multivariate Methods (Boosted Decision Trees).*

33. Arun Nayak : *Higgs boson production in association with a top quark pair at CMS.*

34. Dilip Kumar Ghosh : *Higgs sector of the Type II Seesaw model at the LHC.*

35. Partha Konar : *Boosted objects - Fat jet Jet substructure at the LHC.*

36. Mrinal Dasgupta : *Jets in QCD Lecture 1.*

37. Bruce Mellado : *The Anomalous production of multiple leptons and new bosons at the LHC.*

38. Mrinal Dasgupta : *Jet Substructure Lecture 3.*

39. Satyaki Bhattachraya: *Machine Learning in High Energy Physics.*

40. Partha Konar : *Jet Image Classification with Deep Neural Networks.*

41. Kaoru Hagiwara : *Prof Kaoru Hagiwara lecture series.*

42. Firoz Islam : *Magnetotransport properties of 2D Dirac material with tilted Dirac cones.*

43. Arijit Saha : *Few transport phenomena through superconducting hybrid junctions of Dirac materials.*

44. Sushil K Mishra : *Quantum Computing/Quantum Information Processing in view of Electron Magnetic /Electron Paramagnetic Resonance Technique/Spectroscopy.*

45. Ankur Das : *CMP Seminar.*

46. Ganpathy Murthy : *Prof. Ganpathy Murthy's Lecture series.*

47. Tanusri Saha Dasgupta : *Electrons in Complex Materials: from Theory to Practice.*

48. Sayak Ray : *Fate of Many Body Localization under Periodic Drive: Connection to Chaos and Random Matrix Theory.*

49. Arijit Kundu : *Finite geometry Weyl semimetals and Fermi arcs.*

50. G.Sreejith : *Exact Hamiltonians for General FQH States in the Lowest Landau Level.*

51. Yuval Gefen : *Strong to weak measurement is a topological transition.*

52. Sananda Biswas : *Modelling pressure and temperature effects for frustrated magnets.*

53. Ankita Katre : *Modelling Thermal Transport in Material.*

54. Ankita Katre : *Development and Application of Thermal Transport Modelling and Machine Learning for Nanomaterials.*

55. Jesus Carrete Montana : *High-throughput studies in computational solid-state physics: a review.*

56. Sutapa Samanta : *Talks by Sutapa Samanta.*

Physics Colloquia

1. Thomas Schwetz : *Neutrinos and implications for the Standard Model of particle physics.*
2. Tanusri Saha Dasgupta : *Electrons in Complex Materials: from Theory to Practice.*
3. Soumya Sadhukhan : *Effect of Neutrino Absorption on the IceCube Spectrum.*

Recent Graduates

1. **Udit Khanna**, *Edge states and transport in topological systems*.
2. **Debasis Sadhukhan**, *Effects of Disorder on Nonclasicality in Many-Body Systems*.
3. **Siddharth Dwivedi**, *Traces of new physics in collider data*.
4. **Jyotiranjan Beuria**, *Some aspects of LHC collider phenomenology and vacuum stability in the NMSSM*.
5. **Titas Chanda**, *Trends of Quantum Correlations under Open System Dynamics*.
6. **Somyarup Banerjee**, *Asymptotic behaviour of sum of coefficients of a class of Dirichlet series*.
7. **K.Mallesham**, *Some Additive problems on Primes, Prime Squares and Chen Primes*.
8. **Mrityunjay Verma**, *Some Aspects of Amplitudes in Quantum Field Theories*.
9. **Nabin Meher**, *Some problems in Number Theory*.
10. **Tushar Kant Naik**, *Finite p-groups of conjugate rank 1*.
11. **Dibya Kanti Mukherjee**, *Transport and Collective Modes in Dirac Materials*.
12. **Sumana Hatui**, *On Schur multiplier of groups*.
13. **Ruchi Saxena**, *Dirac materials with spin-orbit (SO) coupling*.
14. **Kasinath Das**, *Collider Studies of vector-like Quarks in some Gauge- Extended Models*.

Publications

Publications (Mathematics)

1. Punita Batra and S. Eswara Rao, *On integrable modules for the twisted full toroidal Lie algebra,* Journal of Lie Theory **Vol.28**, No.1, 79-105 (2018)

2. Punita Batra, Hiroyuki Yamane, *Natural elements of center of generalized quantum groups,* Accepted to appear in Contemporary Mathematics

3. K. Chakraborty, A. Hoque, Y. Kishi and P.P. Pandey, *Divisibility of class numbers of imaginary quadratic fields,* J. Number Theory **185**, 339–348, (2018)

4. K. Chakraborty and A. Hoque, *Pell-type equations and class number of the maximal real subfield of a cyclotomic field,* Ramanujan J **46**, 727–742, (2018)

5. K. Chakraborty and A. Hoque, *Divisibility of class number of certain families of quadratic fields,* J. Ramanujan Math. Soc. (To appear)

6. K. Chakraborty and A. Hoque, *Class groups of imaginary quadratic fields of 3 - rank at least 2,* Annales UMCS Mathematica **47** 179–183, (2018)

7. K. Chakraborty, S. Kanemitsu and T. Kuzumaki, *Seeing the invisible : Kubert identities,* Annales UMCS Mathematica **47** 185–195, (2018)

8. Sarthak Gupta and Kalyan Chakraborty, *A problem related to prime numbers,* The Mathematics Student **87** (2018)

9. S. Banerjee and K. Chakraborty, *Asymptotic behaviour of a Lambert series a La Zagier: Maass case,* Ramanujan J., **48** 567–575 (2019)

10. K. Chakraborty, A. Hoque and M. Mishra, *A note on certain real quadratic fields with class number upto three,* Kyushu J. Math. (To appear)

11. K. Chakraborty, A. Hoque and R. Sharma, *Divisibility of class numbers of quadratic fields: Qualitative approach,*Advances in Mathematical inequalities and Application. Trends in Mathematics. Birkhauser, Springer, Singapore, 247–264 (2018)

12. C. S. Dalawat, *The ramification filtration in certain p-extensions*, to appear in the Rocky Mountain Journal of Mathematics

13. Rahul D. Kitture and Manoj Kumar Yadav, *Finite p-groups with abelian automorphism groups - A survey,* Group Theory and Computation, Indian Statistical Institute Series, Springer, Singapore, 119-140, (2018).

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18. R. Thangadurai and J. M. Deshouillers, *A sufficient condition for $(\theta^N)_N$ to have a distribution modulo one, when θ is in $F_2(X)$*, Integers **17**, 11pp, (2018).

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21. R. Thangadurai, Jaitra Chattopadhyay and Veekesh Kumar, *Set Equidistribution of subsets of $(\mathbf{Z}/n\mathbf{Z})^*$,* Hardy-Ramanujan Journal **41**, 104-112, (2018)

22. R. Thangadurai and Veekesh Kumar, *Distribution of a subset of non-residues modulo p*, Geometry, algebra, number theory and their information technology applications, Springer Proc. Math. Stat. **251**, 445-459, (2018).

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28. Pradeep Das, *A natural Hermitian line bundle on the moduli space of semistable representations of a quiver,* Indian Journal of Pure and Applied Mathematics, To appear

29. Veekesh Kumar and B. Mance, *On the transcendence of certain real numbers,* Bull. Aust. Math. Soc., (doi.org/10.1017/S0004972719000194).

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2. Saptarshi Roy, Titas Chanda, Tamoghna Das, Debasis Sadhukhan, Aditi Sen(De), and Ujjwal Sen, *Phase boundaries in an alternating-field quantum XY model with Dzyaloshinskii-Moriya interaction: Sustainable entanglement in dynamics,* Phys. Rev. B **99**, 064422 (2019)

3. Sreetama Das, Avijit Misra, Amit Kumar Pal, Aditi Sen De, Ujjwal Sen, *Necessarily transient quantum refrigerator,* Europhys. Lett. **125**, 20007 (2019)

4. Anindita Bera, Shiladitya Mal, Aditi Sen(De), and Ujjwal Sen, *Witnessing bipartite entanglement sequentially by multiple observers,* Phys. Rev. A **98**, 062304 (2018)

5. Saptarshi Roy, Titas Chanda, Tamoghna Das, Aditi Sen(De), and Ujjwal Sen, *Response in the violation of the Bell inequality to imperfect photon addition and subtraction in noisy squeezed states of light,* Phys. Rev. A **98**, 052131 (2018)

6. Sreetama Das, Sudipto Singha Roy, Himadri Shekhar Dhar, Debraj Rakshit, Aditi Sen(De), and Ujjwal Sen, *Adiabatic freezing of entanglement with insertion of defects in a one-dimensional Hubbard model,* Phys. Rev. B **98**, 125125 (2018)

7. Asutosh Kumar, Indranil Chakrabarty, Arun Kumar Pati, Aditi Sen De, Ujjwal Sen, *Quantum no-go theorems in causality respecting systems in presence of closed timelike curves: Tweaking the Deutsch condition,* Europhys. Lett. **122(1)**, 10007 (2018)

8. Titas Chanda, Tamoghna Das, Shiladitya Mal, Aditi Sen(De), and Ujjwal Sen, *Canonical Leggett-Garg inequality: Nonclassicality of temporal quantum correlations under energy constraint,* Phys. Rev. A **98**, 022138 (2018)

9. Mehedi Masud, Samiran Roy, Poonam Mehta, *Correlations and degeneracies among the NSI parameters with tunable beams at DUNE,* Phys. Rev. D 99, 115032 (2019)

10. Saptarshi Roy, Tamoghna Das, Asutosh Kumar, Aditi Sen(De), and Ujjwal Sen, *Activation of nonmonogamous multipartite quantum states,* Phys. Rev. A **98**, 012310 (2018)

11. Titas Chanda, Tamoghna Das, Debasis Sadhukhan, Amit Kumar Pal, Aditi Sen(De), and Ujjwal Sen, *Scale-invariant freezing of entanglement,* Phys. Rev. A **97**, 062324 (2018)

12. Kavan Modi, Arun Kumar Pati, Aditi Sen(De), and Ujjwal Sen, *Masking Quantum Information is Impossible,* Phys. Rev. Lett. **120**, 230501 (2018)

13. Atri Dey, Jayita Lahiri, Biswarup Mukhopadhyaya, *Extended scalar sectors, effective operators and observed data,* JHEP **1811 (2018) 127**, 38, (2018).

14. Sudipto Singha Roy, Himadri Shekhar Dhar, Debraj Rakshit, Aditi Sen(De), and Ujjwal Sen, *Response to defects in multipartite and bipartite entanglement of isotropic quantum spin networks,* Phys. Rev. A **97**, 052325 (2018)

15. G. Nirala, S. N. Sahoo, A. K. Pati, U. Sinha, *Measuring average of non-Hermitian operator with weak value in a Mach-Zehnder interferometer*, Phys. Rev. A 99, 022111 (2019).

16. Sk Sazim, S. Adhikari, A. K. Pati, and P. Agrawal, *Mutual Uncertainty, Conditional Uncertainty, and Strong Subadditivity*, Phys. Rev. A 98, 032123 (2018).

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19. C. Datta, Sk Sazim, A. K. Pati, P. Agrawal, *Coherence of quantum channels*, Annals of Physics, 397, 243-258 (2018).

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21. C. Mukhopadhyay, Sk Sazim, A. K. Pati, *Coherence makes quantum systems magical*Coherence makes quantum systems magical,J. Phys. A: Math. Theor. 51, 414006 (2018).

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23. Anirban Basu, *Supergravity limit of genus two modular graph functions in the world-line formalism,* Phys.Lett. **B782**, 570, (2018)

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39. Avirup Ghosh, Tanmoy Mondal, Biswarup Mukhopadhyaya, *Right sneutrino with* $\Delta L = 2$ *masses as nonthermal dark matter,* Phys.Rev. D99 **no.3, 035018** (2019)

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Computer Centre

1. The computing facilities of the Institute are one of the best in the country. It provides the required support to the academics and research activities and to administrative activities. The computing facilities are available to users round the clock i.e 24x7x365 all over the campus.

2. The entire HRI campus is connected with OFC based 1 Gbps backbone providing the network and Internet connectivity to each and every office, hostel and guest house rooms helping the scientists, researchers and all the other members on campus to work from any place in the campus round the clock.

3. The desktop computers of the faculty, students, post doctoral fellows and visiting fellows were upgraded with the newer versions of different flavours of Linux operating systems.

4. Newer versions of several applications software and packages were loaded on users' desktop computers, computer centre desktop computers and conference room desktop computers, which provided the researchers to do their numerical and analytical calculations faster and obtain more precise results.

5. All the important and the necessary packages were upgraded on Mail, Webmail, DNS, SSH, DHCP+DDNS, Proxy, LDAP and Firewall servers for the better, reliable and secure running of the servers and its services without any failure. Firewall rules were much more fine tuned to enhance the security level of the servers and network services.

6. Some additional security features were added in the Mail Servers and all the other External Servers facing the Internet directly outside the DMZ.

7. During the various conferences, workshops and schools, computer facilities were provided in the conference computer room to all the participants. All the necessary computer support were provided to all the participants of the conferences, workshops and schools.

8. Additional computing support was provided to the visiting scientists and visiting students under Visiting Students Programme (VSP) and Summer Programme in Mathematics (SPIM).

9. The Video Conference facilitiy was provided to academic and administrative meetings, conducting the students Ph.D viva and for organising lectures with other academic institutes nationally and internationally.

10. Tendering exercise was initiated for the renewal of the secondary Internet bandwidth as a back up cum redundancy for the primary NKN Internet bandwidth.

Current activities and plans:

1. It is planned to upgrade all the old Linux / Windows based desktop computers of the students, post doctoral fellows and administrative members in the current financial year.

2. There is plan to buy a colour printer for the computer centre.
3. It is planned to further enhance the performance and security level of Mail, Webmail, NFS, LDAP and firewall servers by upgrading the operating system and its packages.
4. It is planned to replace the old SMF batteries of the UPS with the new ones.
5. It is planned to enhance the wi-fi network coverage area.

Library : Annual Report (2018-19)

In any academic/research institution library plays an important role in the dissemination of knowledge. In fact, the ambience of the library reflects the quality of the education/research imparted by the Institute. HRI library has recognized the importance of the academic vibrations required in the library and has been growing in this direction, right from its very inception. The Library of HRI serves as **knowledge hub** containing resources not only in the form of print but also in electronic form.

Library Hours: The library works on all days of the year except a few holidays of National and Social importance.

Monday to Saturday	08.00 AM to 02.00 AM
Sundays and Gazetted holidays	10.00 AM to 06.00 PM

Glimpse of the library:

Resources	**Details**
Total Collection/Books:	61238
No. of print books	21261
No. of Bound Volumes	38292
No. of Gift books	1685
Total Journals/Print	155
National	12
International	155
E-Resources/Databases:	
E-Journals:	
Print + Online (Int)	143
Online (Int)	68
E-books	2259 (LNM Book Series)
Databases:	
ScienceDirect	2400 + Jls, Elsevier Publication
AIP Archive	8 Jls, American Institute of Physics
MathScienet	Database of reviews, abstracts and bibliographic information, American Mathematical Society
DMJ 100	Duke Math. Jl - Back volumes from 1935 to 1999, Duke University Press
Euclid Prime	32 Jls + 15 Jls complimentary, Duke University Press
JSTOR	83 Jls, Ithaka Publication
IoP Journals Archive	56 Journals package, Institute of physics
Springer Journals Archive	123 Journals package, Springer
Theses	103
CDs/DVDs	100
General Magazines	5
Newspapers	7
Seating capacity	43
Carpet area	650 Sq. Mts
Computers for users	4 Nos
Library Mgt. Software	Libsys7, Electro Magnetic Gate and Tattle tapes.

The Institutes library is one of the best equipped libraries in India, it aims to put the motto **Books are for use** into practice. The Library houses Text Books, Reference Books, Print Journals, Technical Magazines, General Magazines, E-Resources and Digital Collections, CDs and DVDs, Thesis, Bound Volumes of Journals, Dailies, Faculty Publications and Institute Publications etc., added to this.

Newly added materials during April 2017 to March 2018:

Books	279
Gift books	336
Bound Volumes	208
Journals/Online	1

Rapid advances in Information and Communication Technology are changing the library and information services drastically. Besides this, expectations of the users have also risen manifold. Libraries are not mere spaces anymore; they are much more than that. It has become a challenge for library management to keep pace with changing information packaging and delivery methods on one hand and meet the user expectations on the other. HRI Library has been trying to do the same over the years and as per feedback from its patrons has been quite successful in this venture. HRI Library not only proactively work on its collection building and infrastructural augmentation, also put lot of emphasis on facilities and services for users. Like previous years, this year also focus was on the strengthening of print collection along with e-resources and implementation of latest information and communication technologies in its services.

Highlights:

Services / Facilities:	**Best Practices:** A Best Practice in simple terms is known as the practice, which paves the way for enhancing the existing functions and helps in effective implementation or use of the process.
Web enabled library catalogue service Circulation service (Issue/Return) Reference	Library Website/Web OPAC Self-Issue/Return System Electromagnetic Security Gate
Referral External Membership	Off-campus service through e-mail and Library Extension service Overnight issue of Reference Books
Reprographic	Stock Verification
New Arrivals	Display of Faculty/PDF/Student Publications
Spiral Binding	Lamination and Display of Institute Publications
Newspaper clipping	Library Advisory Committee
User Orientation	18 Hours uninterrupted Services
Book Exhibition	
Inter Library Loan	

Book Exhibition:

Details:	**Duration**
Exhibition of Scientific, Technical and General Reading Books	1^{st} and 2^{nd} Feb 2018

Library Advisory Committee: Library Advisory Committee is functioning to look into all aspects of continual improvement of the library activities, so that the library and its facilities achieve a fair degree of acceptability amongst the users. This Committee, co-coordinated by a faculty as the Chairman and other faculty-representatives as members, the librarian is the ex-officio member secretary of the committee. Library Advisory Committee plays an advisory and advocacy role regarding the library in its support of teaching, learning, research and communitybuilding needs of the Institution. It assists in the provision of high quality library service to the faculty and students of the HRI Community by advising the Director in all development activities of the library.

Library Team: Total 9 members

Library Staff	4
Other Staff members	5

Computerisation of in-house Activities: All in-house activities in the Library including Acquisition, Cataloguing, Circulation and Serials Control are fully computerized using Libsys version-7 (Library Management Software). The Online Public Access Catalogue (OPAC) of the Library is operational on Intranet. It can be accessed online to search more than 63,500+ bibliographic records, available in the Library database through a web-based search interface (Web OPAC).

Theses Consultation Facilities: HRI Library receives all the Ph.D. Thesis awarded by HBNI in Hard copy. Print copies of Theses are housed in Book Section of the library for consultation purpose only. The bibliographic information of Theses are made available through library Online Public Access Catalog (OPAC). Also through another interface especially designed for searching the Theses at: http://www.hri.res.in/ libweb/theses/thesis.html .

Hindi Book Collection: HRI Library has built up a good collection of books in Hindi Language. These books are prominently kept near the stack area in the library to promote its usage. To increase the use of **Rajbhasha Hindi**, HRI library regularly sending NEW ARRIVALS LIST of Hindi Books to HRI user community.

INFRASTRUCTURAL DEVELOPMENT WORKS AT THE HRI CAMPUS

DURING F.Y. 2018-19

Following works have been carried out during this financial year.

- Supply installation testing and commissioning of multi VRF-VRV AC System in Institute building .
- Precision Air-conditioning system in Cluster area .
- Associated electrical works related to air conditioning .
- Partition in living, Dining and Master bed room area in top floor D-type flat.
- Covering of 1st and 2nd floor balcony in D and D prime building.
- Parking shed with related approach road.

Some miscellaneous works related maintenance/modifications/development were also carried out which are hereunder.

- Renovation of mess in Hostel-1.
- Supply and laying new telephone cable for old E-type and nearby housing .
- Fencing of new developed lawn area.
- Lighting arrangement for new developed lawn area and approach road near community centre annexe.
- SITC of Air-conditioner for physics Lab. in Community Centre Annexe.
- Providing and fixing of RCC Garden benches.
- Providing and fabricating of enclosure of Garbage's containers.