Academic Report (2020-21)

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

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

This report covers the period from April 2020 to March 2021. In Sep last year we were near the peak of the first wave of the covid pandemic, in March 2021 we were at the onset of the second wave. The pandemic has disrupted the natural rhythm of life worldwide and HRI was no exception. However, being a self contained campus we could continue most of our academic activities, albeit in the online mode. A summary of events during this period is given below.

1. Covid response:

In March 2020 as covid numbers started rising the students and postdocs were advised to go home if they wanted, and work online from there. Institute facilities like the mess were shut down. As the first wave eased students were allowed to return, the mess was reopened, and the campus population was back to normal by Feb 2021. When the second wave hit there was no time to send people back again. Institute facilities were kept running but completely avoided physical gathering.

2. Teaching:

We had lost time in 2020 due to disruption of the academic cycle caused by covid. To ensure that M.Sc students who joined in 2020 graduate by July 2022 we have restructured the academic calendar of 2021, essentially running three semesters during the year. The usual three month break in summer will be an active semester this year. All online classes have continued through the pandemic.

3. Faculty appointments:

We had made four offers in Jan 2021 and three of these were accepted (two in physics one in mathematics). One physics and one mathematics faculty member have joined. These are Dr. Tathagata Ghosh and Dr. Sudip Chakrabarty in physics and Dr. Aprameyo Pal in mathematics.

4. Academic events:

Physical meetings have been ruled out in the last 15 months. We had the Young Quantum 2020 (YouQu2020) meeting in the online mode during 12-14 Oct 2020. Several HRI members also participated in the Vaibhav Summit organised by the Govt of India. HRI participation was mainly in the area of Quantum Information and Condensed Matter Physics.

5. Students:

During this period 18 Ph.D students and 5 M.Sc students joined the Institute, and 8 students have submitted their Ph.D thesis.

6. Extramural funding:

HRI has obtained significant funding under the QUEST project of the DST for work on quantum information and communication. Condensed matter faculty have obtained funding for work on energy materials.

Pinaki Majumdar

Director

List of Governing Council Members (2020 - 21)

1. Shri K.N. Vyas (Chairman)	Chairman, Atomic Energy Commission (AEC) & Secretary, Department of Atomic Energy, Govt. of India, Anushakti Bhawan, Chhatrapati Shivaji Maharaj Marg, Mumbai – 400 001
2. Smt. Sushma Taishete	Joint Secretary (R & D) Deptt. of Atomic Energy, Govt. of India, Anushakti Bhavan, Chhatrapati Shivaji Maharaj Marg, Mumbai – 400 001
3. Mrs. Richa Bagla	Joint Secretary (Finance) Deptt. of Atomic Energy, Govt. of India, Anushakti Bhavan, Chhatrapati Shivaji Maharaj Marg, Mumbai – 400 001
4. Prof. V. Srinivas	Senior Professor TIFR & Chairman NBHM, School of Mathematics, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai – 400 005
5. Prof. V. Arvind	Director Institute of Mathematical Sciences, CIT Campus, Taramani, Chennai – 600 113
6. Prof. Sanghamitra Bandopadhyay	Director Indian Statistical Institute, 203, B.T. Road, Kolkata – 700 108
7. Prof. S.M. Chitre (upto 11.01.2021 due to his death)	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

Prof. Mustansir Barma (w.e.f. March 2021 vice Prof. S.M. Chitre)	Professor Emeritus, Tata Institute of Fundamental Research, 36/P Gopanpally Village, Serilingampally Madal, Hyderabad – 500 046
8. Director, Higher Education (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. Shri Rajnish Mehta	4, Penn Road, Kolkata – 700 027
12. Prof. Pinaki Majumdar (Ex-Officio)	Director Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad – 211 019
Shri Ravindra Singh	Registrar, HRI was the Non-Member Secretary of the Governing Council.

Academic Staff

Faculty Members (Mathematics)

1. Batra, Punita
2. Chakraborty, Kalyan (on lien)
3. Dalawat, C.S.
4. Dubey, Umesh Kumar V.
5. Kumar, Manoj
6. Prakash, Gyan
7. Raghavendra, N.
8. Ramana, D. Surya
9. Ratnakumar, P. K.
10. Shah, Hemangi M.
11. Thangadurai. R.

Faculty Members (Physics)

1. Basu, Anirban
2. Das, Tapas Kumar
3. Datta, AseshKrishna
4. De, Aditi Sen
5. Jatkar, Dileep
6. Maharana, Anshuman
7. Majumdar, Pinaki
8. Pareek, T. P.
9. Pati, Arun Kumar
10. Rai, Santosh Kumar
11. Rao, Sumathi
12. Sen, Ashoke
13. Sen, Prasenjit
14. Sen, Ujjwal

Administrative Staff

1. Shri Ravindra Singh [Registrar]
2. Shri Manish Sharma [Scientific Officer 'E']
3. Shri K.K. Suresh Kumar [Librarian]
4. Shri Sanjai Verma [Systems Manager]
5. Shri A.K. Srivastava [SO(C)]
6. Shri V.K. Srivastava [SO(C)]
7. Shri R.P. Sharma [Manager Guest House]
8. Smt. Anju Verma [SO(SB)]
9. Shri U.K. Dwivedi [Cashier]
10. Shri D. Malhotra [Upper Division Clerk]
11. Shri K.K. Srivastava [Upper Division Clerk]
12. Shri Yashpal Singh [Store/Purchase Officer]
13. Smt. Sumitra [Office Superintendent]
14. Smt. Seema Agarwal [P.A. to Director]
15. Shri Sudheer Kumar Singh [Accountant]
16. Shri Sanjeev Nagar [Jr. Hindi Translator]
17. Shri Vivek Kumar [Junior Library Assistant]
18. Shri Kamlesh Thakur [Bearer (Canteen Cadre)]
19. Shri Kamta Prasad [Peon/Watchman]
20. Shri Rajesh Kumar [Safaiwala]

Visiting Fellow

Mathematics

1. Banwait, Barinder Singh
2. Bag, Nilanjan
3. Banerjee, Kalyan
4. Bhanja, Jagannath
5. Chandel, Vikramjeet Singh
6. Dey, Arindam
7. Jana, Arindam
8. Khurana, Suraj Singh
9. Kumar, C. P. Anil
10. Lahiri, Animesh
11. Maitra, Anwoy
12. Mohamed, Ebtsam Hassan Taha
13. Naik, Muna
14. Pradhan, Soham S.
15. Ray, Chiranjit
16. Sarkar, Amar Deep
17. Sarkar, Subham
18. Sen, Sourav
19. V., Pramath A.

Physics

1. Abdallah, Waleed Mohammed
2. Das, Tisita
3. Fernandes, Karan
4. Ghosh, Nivedita
5. Ghosh, Purusottam
6. Halder, Saronath

7. Hegde, Subramanya
8. Kumari, Asmita
9. Rahaman, Rafiqul
10. Roy, Pratim
11. Mitra, Arpan Krishna
12. Saha, Mihir Ranjan
13. Sahoo, Arnab Priya
14. Samui, Tousik

Visiting Scientist

1. Deo, Satya (Maths)
2. Girdhar, Aarti (Principal Investigator)
3. Rai, Pradeep Kumar (INSPIRE Faculty)
4. Dutta, Jayanta (Physics)

Research Scholar

Mathematics

1. Agnihotri, Rishabh
2. Aquib, Mohammad
3. Bhowmick, Kushal
4. Chakraborty, Priyanshu
5. Choudhury, Srijonee Shabnam
6. Das, Arpan
7. Das, Bhargab
8. Gupta, Shubham
9. Kanrar, Arpan
10. Karmakar, Debasish
11. Kaushik, Rahul
12. Keshari, Parul
13. Krishnarjun, K.
14. Maity, Arup Kumar
15. Mishra, Mohit
16. Nishant
17. Pal, Souvik
18. Patel, Uday Sureshbhai
19. Sahoo, Gopinath
20. Tantubay, Santanu
21. Tripathi, Aparna
22. Vaishya, Lalit

Physics

1. Abdulla, Faruk
2. Alam, Khorsed
3. Bakshi, Sankha Subhra
4. Bakshi, Sovan
5. Banerjee, Ratul
6. Barik, Anjan Kumar
7. Basak, Nirnoy
8. Bhattacharyya, Aparajita
9. Bhowmik, Swapnil
10. Bose, Debraj
11. Chandra, L. L. Ganesh
12. De, Suman Jyoti
13. Dey, Atri
14. Dey, Shyamashish
15. Ghosh, Avirup
16. Ghosh, Priya
17. Ghosh, Srijon
18. Ghoshal, Ahana
19. Grover, Sachin
20. Gupta, Rivu
21. Halder, Pritam
22. Kadge, Samrat Suresh
23. Kar, Arpan
24. Konar, Tanoy Kanti Konar
25. Mahanta, Ratul
26. Maity, Susovan
27. Mal, Sourav
28. Md., Abhishek

29. Mohan, Brij
30. Mondal, Tanmoy
31. Pal, Kalyanbrata
32. Pandey, Vivek
33. Patra, Ayan
34. Reja, Afsar
35. Roy, Saptarshi
36. Roy, Shubhojit
37. Roy, Tanaya
38. Sen, Kornikar
39. Shrimali, Divyansh
40. Singh, Kajal
41. Sohail
42. Srivastav, Abhay
43. Srivastava, Chirag

M.Sc. Students

Physics

1. Bora, Sankalpa
2. Chauhan, Aman
3. Das, Sujit
4. Goswami, Priyangshu
5. Kundu, Sukalpa
6. Majumdar, Anish
7. Mondal, Sayan
8. Raghuvanshi, Shubham
9. Rajgadia, Harshit
10. Sahoo, Ayan
11. Singhi, Kaustubh

Academic Report - Mathematics

Punita Batra

Research Summary:

In a joint work with Santanu, I have classified integrable representations for extended affine Lie algebras, where the center is acting trivially on the modules. Along with Hiroyuki Yamane, I am trying to give a serre type presentation for higher rank toroidal Lie superalgebras.

Preprints:

1. Santanu Tantubay, Punita Batra, *Classification of irreducible integrable modules for extended affine Lie algebras with center acting trivially,* arXiv:2105.02000v1 [math.RT].

Conference/Workshops Attended:

1. *The 35th Annual Conference of the Ramanujan Mathematical Society (online)* at the Central Univ. of Rajasthan, December 27-30, 2020.

Invited Lectures/Seminars:

1. *Integrable representations of loop-toroidal Lie algebras*, Invited online talk in the Algebra Symposium, The 35th Annual Conference of the Ramanujan Mathematical Society, Central University of Rajasthan, December 27, 2020.

Other Activities:

1. A member of the DST-FIST subject expert committee- Mathematical Sciences since September 2020.
2. As part of an outreach activity of HRI, I gave an online talk for High achool students on March 21, 2021.
3. Taught a Ph. D course Algebra-I to first year students during January-May 2021 at HRI.
4. My Ph.D student Souvik Pal has submitted his Ph.D thesis in June 2021 under my supervision.
5. I am a member of the Outreach Programme at HRI. Also serving as a member in the Sports and Entertainment Committee and the Rajbhasha Committee at HRI.

Kalyan Chakraborty

Research Summary:

During the last academic year 2020-2021 my research was focussed on the arithmetic problems related to Selmer groups and Tate - Shafarevich groups associated to algebraic cycles on a variety defined over a number field. We have been able to prove some finiteness result for some quotient of the group of algebraic cycles by using these new constructions of Selmer and Tate Shafarevich groups and asymptotic formulae for sums of the form $\sum_{m \leq X} a_K^l(m)$. One important application is the weak Mordell-Weil theorem for the Chow group of zero cycles of any smooth projective variety defined over a number field. We are also trying to relate various questions related to the class number of algebraic number fields with that of Selmer groups and Tate-Shafarevich groups associated to elliptic curves and also with other higher genus curves.

I am also involved into other questions like sums of integral squares, Diophantine tuples and that of various interesting Diophantine equations in the ring of integers or that of S-integers in number fields.

Publications:

1. C. Ray and K. Chakraborty, *Certain eta-quotients and l-regular overpartitions*, The Ramanujan Journal, (2021).

2. K. Chakraborty and A. Hoque, *Exponents of class groups of certain imaginary quadratic fields,* Czechoslovak Mathematical Journal **70**, 1167-1178, (2020).

3. K. Chakraborty, A. Hoque and R. Sharma *Complete solutions of certain Lebesgue-Ramanujan-Nagell equations,* Publicationes Mathematicae Debrecen **97**, 339-352, (2020).

4. K. Chakraborty , A. Hoque and R. Sharma, *On the solutions of certain Lebesgue-Ramanujan-Nagell equations,* Rocky Mountain Journal of Mathematics **51(2)**, 459-471, (2021).

5. K. Chakraborty, A. Hoque and M. Mishra, *On the structure of order* 4 *class groups of* $\mathbb{Q}(\sqrt{n^2+1})$, Annales mathématiques du Québec **45**, 203-212, (2021).

6. K. Chakraborty, A. Hoque and S. Kotyada, *On the Diophantine equation* $cx^2+p^{2m} = 4y^n$, Results in Mathematics **57**, (2021).

7. R. Agnihotri, K. Chakraborty and M. Mishra, *Primary rank of class groups of real cyclotomic fields,* Rocky Mountain Journal of Mathematics **50(6)**, 2149-2155, (2020).

8. R. Agnihotri and K. Chakraborty, *Sign changes of certain arithmetical functions at prime powers,* Czechoslovak Mathematical Journal, (2021).

9. R. Agnihotri and K. Chakraborty, *On the Fourier coefficients of certain Hilbert modular forms,* The Ramanujan Journal, (2021).

10. S. Banerjee, K. Chakraborty and A. Hoque, *An analogue of Wilton's formula and values of Dedekinf zeta functions,* Journal of Mathematical Analysis and Applications **495(1)**, pp 124675, (2021).

11. K. Chakraborty, K. Banerjee and A. Hoque, *Divisibility of class groups and selmer groups,* Hardy-Ramanujan Journal **42**, (2020). https://doi.org/10.46298/hrj.2020.6460

12. Kalyan Chakraborty and Chiranjit Ray, *Distribution of generalized mex related integer partitions,* Hardy-Ramanujan Journal **43**, May 6, 2021.. https://doi.org/10.46298/hrj.2021.7425

Preprints:

1. K. Chakraborty AND K. Krishnarjun, *On moments of non-normal number fields.* (communicated)

2. K. Chakraborty, S. Kenmitsu and A. Laurinčikas, *Complex powers of L-functions and integers without large prime factors.* (communicated)

3. K. Chakraborty and A. Hoque, *On the plus parts of the class numbers of cyclotomic fields.* (communicated)

4. K. Banerjee and K. Chakraborty, *Tate-Shafarevich group and Selmer group constructions for Chow group of an abelian variety.* (communicated)

5. K. Banerjee and K. Chakraborty, *On the Chow group of the self-product of a cm elliptic curve defined over a number field.* (communicated)

6. R. Sharma, S. Batter and K. Chakraborty, *On a family of elliptic curves of rank at least 2.* (communicated)

7. Kalyan Chakraborty and Azizul Hoque, *On the Diophantine equation* $dx^2+p^{2a}q^{2b} = 4y^p$. (communicated)

Invited Lectures/Seminars:

1. *Unique factorization, its failure and its measure*, International Conference on Number Theory and Algebra, IIT(BHU), December, 2020.

2. *Prime numbers and some related conjectures*, Conference of the Indian Mathematical Society , VIT, Vellore, December, 2020.

3. *Divisibility of class numbers*, BHU, September, 2020.

Other Activities:

1. Chief Organiser of International conference commemorating Srinivasa Ramanujan December, 2020 (https://sites.google.com/ksom.res.in/conference2020/).

2. Reviewed five papers for of AMS and refereed four manuscripts for various leading journals.

Chandan Singh Dalawat

Research Summary:

Designed and delivered an advanced course of thirty-six lectures on the arithmetic theory of local fields with finite residue field. The following topics were covered : projective limits and inductive limits, the ring $\mathbf{Z}_p$ of p-adic integers, Hensel's lemma, structure of the group $\mathbf{Z}_p^\times$, the field of $\mathbf{Q}_p$ of p-adic numbers, the structure of the group $\mathbf{Q}_p^\times$, the Hilbert symbol, quadratic extensions of $\mathbf{Q}_p$, the theory over $\mathbf{F}_p[[t]]$, p-fields, rings of integers, residue fields, uniformisers, multiplicative representatives, the structure theorem, ramification index, residual degree, the filtration on the multiplicative group, valuations, norms, completions, extensions of a valuation, integral closures, Krasner's lemma, ramification index and residual degree, unramified extensions, totally ramified extensions, tamely ramified extensions, Eisenstein polynomials, the trace map, the different and the discriminant, transitivity formulae, Serre's mass formula in the tame case, inertia subgroup and ramification subgroup, higher ramification groups, lower numbering, upper numbering, cyclotomic extensions, cyclic extensions, abelian extensions of prime exponent, the Hasse-Arf theorem, solvable extensions of prime degree, Serre's mass formula in prime degree, the norm map and the ramification filtration, the local Kronecker-Weber theorem, primitive solvable extensions, irreducible $\mathbf{F}_p$-representations of the absolute Galois group of a p-field, the Galois module structure of units modulo p-th powers in a tamely ramified split extension of a p-field, primitive extensions of p-fields.

Other Activities:

1. A course of six lectures on linear algebra, January, 2021.

Umesh K V Dubey

Research Summary:

A. Vistoli proved the Segal type of formula for the K-group of varieties with finite group action. We obtained a similar formula for the Grothendieck group of tensor triangulated (tt-) category with a tt-action in some particular cases. We extended the proof of Vistoli in a more general setup. We will use these results in our problem of finding a formula for the tt-Chow group of Balmer-Klein. This is a joint project with Vivek M. Mallick.

A t-structure on a triangulated category was defined by Beilinson, Bernstein and Deligne (Gabber). We continued the study of t-structure on some unbounded derived categories and properties of its heart with Gopinath Sahoo. Some progress towards the classification of compactly generated t-structure on scheme case was made using concrete geometric data. The results are quite similar to Deligne's result on bounded derived categories of coherent sheaves.

We studied Grothendieck's Tannaka duality with Parul Keshari. We also looked at Nori's construction of fundamental groups using essentially finite vector bundles. The functoriality of some of his definitions and constructions makes it possible to obtained some results for vector bundles with extra structures.

We started studying the combinatorial structure of the category of perverse sheaves on some surfaces with Subham Sarkar.

Publications:

1. Umesh V Dubey and Sanjay Amrutiya, *Moduli of filtered quiver representations* , Bull. Sci. Math. **164**, Article No. 102899, 29 pp, (2020).

2. Umesh V Dubey and Sanjay Amrutiya, *Moduli of parabolic sheaves and filtered Kronecker modules* , Kyoto J. Math., 26 pp, (2021). (accepted)

Preprints:

1. Umesh V Dubey and Vivek M Mallick, *Grothendieck group of equivariant tt-category*. (in preparation)

Conference/Workshops Attended:

1. *(Online) Seshadri Memorial Lectures*, Tifr, Mumbai, July 31, 2020.

2. *(Online) Vector Bundles and Algebraic Curves (VBAC) Webinars*, ICMAT, Spain, September 9, 2020, November 23, 2020, January 18, 2021 and March 15, 2021.

Other Activities:

1. Involved in refereeing few manuscripts, writing AMS Mathematical reviews and supervising research scholars.

2. Attended few online seminars/webinars like Manchester seminars, Tifr Algebraic Geometry seminars, HBNI webinars etc.

3. Member of Mathematics Graduate Programme Committee.

Manoj Kumar

Research Summary:

An algebraic structure $(E, +, \circ)$ is said to be a left skew brace if $(E, +)$ and $(E, \circ)$ are groups and, for all $a, b, c \in E$, the following compatibility condition holds:

$$a \circ (b + c) = (a \circ b) - a + (a \circ c).$$

A right skew brace can be defined analogously. A left skew brace is called a left brace if $(E, +)$ is an abelian group. This concept was introduced by Guarnieri and Vendramin in connection with set theoretic solutions of the quantum Yang-Baxter equation. Cohomology theory for braces acting trivially on abelian groups (viewed as trivial braces) was recently introduced and investigated by Lebed and Vendramin. Bachiler suggested some ideas about non-trivial actions. Let H be a left skew brace and I an abelian groups viewed as a trivial left brace. Generalising the ideas developed so far, we investigate second cohomology group of H acting on I non-trivially. A bijective correspondence between the following is established: (i) second cohomology group of a left skew brace H with coefficients in a trivial brace I; and (ii) class of extensions $0 \to I \to E \to H \to 0$ of H by I with the given action of H on I. We develop general cohomology theory in case the extension $0 \to (I, +) \to (E, +) \to (H, +) \to 0$, viewed as an extension of $(H, +)$ by $(I, +)$, splits. Further, we construct a fundamental exact sequence connecting the second cohomology group of a skew brace with the automorphism group of extensions of the skew brace. Such a sequence for groups was constructed by Wells in 1971.

A long standing well known problem in group theory is to classify finite groups in which every element of the commutator subgroup is a commutator. It has already been proved that in a finite simple group every element of the commutator subgroup is a commutator. At the extreme end, for finite p-groups the situation is quite different. It has been recently proved that if the commutator subgroup of a finite p-group, $p \geq 5$, is minimally generated by at most 3 elements, then every element of the commutator subgroup is a commutator. It is also known that the same happens for all p-groups upto order p^5. We recently classified finite p-groups G, p odd, such that the commutator subgroup $\gamma_2(G)$ of G is of order p^4 and exponent p, and $\gamma_2(G)$ contains a non-commutator. Continuing in this direction, we investigate finite p-groups of order p^7, and present a fine characterisation of those groups G of order p^7 whose $\gamma_2(G)$ contains elements which are not commutators in G. Our work, along with the existing theory, suggests a general phenomenon that might take place in all finite p-groups.

Publications:

1. Rahul Kaushik and Manoj K. Yadav, *Commutators and commutator subgroups in finite p-groups*, Journal of Algebra **568**, 314-348, (2021).

2. Silvio Dolfi, Anupam Singh and Manoj K. Yadav, *p-power conjugacy classes in $U(n, q)$ and $T(n, q)$*, Journal of Algebra and Its Applications **20**, 2150121 (13 pages), (2021).

Preprints:

1. Nishant and Manoj K. Yadav, *Cohomology, extensions and automorphisms of skew braces,* https://arxiv.org/abs/2102.12235.

2. Rahul Kaushik and Manoj K. Yadav, *Commutators in groups of order p^7,* http://arxiv.org/abs/2106.07205.

Conference/Workshops Attended:

1. *35th Annual Conference of RMS*, India, December, 2020.

2. *Group Theory Sangam*, India, January - May (weekly), 2021.

Invited Lectures/Seminars:

1. *The Schur multiplier of central product of groups*, GOThiC, Online version of Ischia Group Theory Conference, University of Salerno, Ischia, Virtual, June, 2020.

2. *Surjectivity of commutator map for finite p-groups*, Algebra Seminar, Haifa University (Israel), Haifa, Virtual, November, 2020.

3. *Commutators in finite groups*, 80th Refresher Course, Punjabi University, Patiala, Virtual, November, 2020.

4. *Surjectivity of commutator map for finite p-groups*, Departmental Seminar, IISER TVM, Virtual, December, 2020.

5. *Group theory is the living room*, Refresher Course (Mathematics and Statistics) , Guru Jambheshwar University of Science and Technology, Hisar, Virtual, January, 2021.

6. *Left braces*, In house Symposium, IISER Bhopal, Virtual, March, 2021.

Other Activities:

1. Organised a semester long online weekly seminar series "Group Theory Sangam", January - May, 2021 (jointly with Anupam Singh, IISER Pune).

2. Served as an editorial board member of Proc. Math. Soc., IASc.

3. Refereed research papers for national and international journals.

4. Instructed Arpan Kanrar for him first semester graduate Project Course at HRI.

5. Served HRI on several committees.

Gyan Prakash

Research Summary:

Let G be a finite commutative group and $A \subset G$. We write $A + A$ to denote the set consisting of those elements of G which can be written as a sum of two elements of A. For any integers k_1, k_2 with $k_1 \leq k_2$, let $S(k_1, k_2, G)$ denotes the set containing those subsets A of G with $|A| = k_1$ and $|A + A| \leq k_2$. The question of obtaining the correct order of $|S(k_1, k_2, G)|$ remains open, though various upper bounds are known. Ben Green was the first one to study this problem and had obtained an upper bound for $|S(k_1, k_2, G)|$ when G is a vector space over a finite field. In 2007, in an unpublished note, we generalised the methods of Green and obtained upper bound for $|S(k_1, k_2, G)|$ when G is a general finite commutaive group. Recently in 2020 Campos, using the method of hypergraph container lemma developed by Balogh, Morris, Samotij, improved these bounds when k_2 is such that there are no subgroups of G with cardinality around k_2. In a work in progress we explore the possibility of improving the upper bounds for $|S(k_1, k_2, G)|$ for general k_2. So far, we have managed to provide a shorter and neater proof of hypergraph container lemma.

Publications:

1. Kummari Mallesham, Gyan Prakash and D. S. Ramana, *Representation of integers as monochromatic squares of primes,* Journal of Number Theory. (to appear) https://doi.org/10.1016/j.jnt.2020.11.020

2. François Hennecart, Gyan Prakash, Eyyunni Pramod *On thin sum-product bases,* Combinatorica. (to appear)

Raghavendra Nyshadham

Research Summary:

I have been working mainly on formalisation over the univalent foundations. I have also been discussing Tannakian reconstructions of principal bundles in various contexts with colleagues in the algebraic geometry group at the Institute.

Invited Lectures/Seminars:

1. *Vector bundles*, six online lectures at the DDU College, Delhi University, March, 2021.

D. Surya Ramana

Research Summary:

My research activity over the last several years has been centered around investigating if large but otherwise arbitrary subsets of "interesting subsets" of the natural numbers retain certain properties of these interesting sets. For instance, it is a classical result, called Lagrange's theorem, that every non-negative integer is the sum of four squares of integers. For any integer $k \geq 1$, a k-colouring of the squares is a partition of the set of squares of integers into k disjoint but otherwise aribitrary subsets. The various subset of the partition are called colours. Some years ago, with my collaborators Gyan Prakash and O. Ramaré, we obtained a nearly optimal bound for the smallest number $t = t(k)$ with the property that, given any k-colouring of the squares, every integer large enough can be represented as the sum of at most t squares, all of the same colour. An analogue of this result for the set of squares of prime numbers is the main result of the paper below. The question of improving this bound and the bound for the squares to the optimal form involves a problem of counting points on a certain variety over finite fields. This past year, renewed efforts, still in progress, were made to settle this problem.

Publications:

1. Kummari Mallesham, Gyan Prakash and D.S. Ramana, *Representation of Integers as Monochromatic Sums of Squares of Primes*,Journal of Number Theory, pp. 18, (2020). https://doi.org/10.1016/j.jnt.2020.11.020

Invited Lectures/Seminars:

1. *Five lectures titled "Halasz's Theorem"*, Workshop titled "Number Theory in India", IIT Kanpur, online, April, 2021.

2. *Talk titled "A Problem of A. Sárközy"*, Conference titled "Balu Fest", IMSc Chennai, online, March, 2021.

Other Activities:

1. Mithun Kumar Das defended his thesis "Some Topics on Dirichlet L-functions" written under my supervision on 20 January 2021.

2. Refereed papers for the Journal of Number Theory, Canadian Math. Bulletin, Journal of the RMS, Proc. Indian Acad. Sciences.

3. Serving as Dean (Administration), HRI from 30 August 2019. Also served on a number of academic and administrative committees of HRI including the Mathematics Faculty Appointments Committee (as member), Library Committee (as convenor).

4. Member and Co-convenor, Board of Studies in Mathematical Sciences, HBNI.

5. Member, Library Committee, National Board for Higher Mathematics (NBHM).

6. Member, Committees for IST (Instructional Schools for Teachers) and TEW (Teacher's Enrichment Workshops) of the National Centre for Mathematics (NCM).

Ratnakumar Peetta Kandy

Research Summary:

In the last one year, I have been continuing with three ongoing projects. The first one concerns with local smoothing of Fourier integral operators, jointly with Ramesh Manna. This is an extension of our previous result, based on a new approach that allows a larger class of amplitude functions and more general phase functions. This work is finalised and submitted for publication.

The other work, jointly work with Anupam Gumber started a couple of years ago, concerns characterisation of Weyl multipliers on modulation spaces. We were able to develop the theory of twisted modulation spaces and established a natural characterisation of Weyl multipliers on them. This work is in the final stage and will be submitted soon. We prefer to establish one more remaining specific property of these spaces.

The third problem concerns the fourier multipliers on Euclidean spaces, and is jointly with my current Ph. D. student Arup Maity. We are able to obtain an $L^p \to L^q$ multiplier theorem for a new class of multipliers. Similar problems are studied for Weyl multipliers as well. This work is also in the final stage.

Publications:

1. Ramesh Manna, P. K. Ratnakumar, *Local Smoothing of Fourier Integral Operators and Hermite Functions,* Advances in Harmonic Analysis and Partial Differential Equations. Trends in Mathematics. Birkhäuser, Cham (Georgiev V., Ozawa T., Ruzhansky M., Wirth J. (eds)), 1-35, (2020).

Preprints:

1. Ramesh Manna, P.K. Ratnakumar, *Global Fourier integral operators in the plane and the square function.* (submitted)

Conference/Workshops Attended:

1. *Online NCM workshop on Harmonic Analysis*, organised jointly by IISER Mohali and IIT Bombay, India, December, 2020.

Other Activities:

1. Taught the first semester course on Analysis -I, (January to May 2021).
2. Serving in the Mathematics Graduate Committee as convenor.

Hemangi Madhusudan Shah

Research Summary:

1. I have submitted the following article on arxiv: arXiv:1703.00341 [math.DG].

Geometry of Asymptotically harmonic manifolds with minimal horospheres: (M^n, g) be a complete Riemannian manifold without conjugate points. In this paper, we show that if M is also simply connected, then M is flat, provided that M is also asymptotically harmonic manifold with minimal horospheres (AHM). The (first order) flatness of M is shown by using the strongest criterion: $\{e_i\}$ be an orthonormal basis of T_pM and $\{b_{e_i}\}$ be the corresponding Busemann functions on M. Then, (1) The vector space $V = span\{b_v | v \in T_pM\}$ is finite dimensional and dim V = dim $M = n$. (2) $\{\nabla b_{e_i}(p)\}$ is a global parallel orthonormal basis of T_pM for any $p \in M$. Thus, M is a parallizable manifold. And (3)$F : M \to R^n$ defined by $F(x) = (b_{e_1}(x), b_{e_2}(x), \cdots, b_{e_n}(x))$, is an isometry and therefore, M is flat. Consequently, AH manifolds can have either polynomial or exponential volume growth, generalizing the corresponding result of Nikolayesky for harmonic manifolds. In case of harmonic manifold with minimal horospheres, the (second order) flatness was proved by Ranjan-Shah by showing that $span\{b_v^2 | v \in T_pM\}$ is finite dimensional. We conclude that, the results obtained in this paper are the strongest and wider in comparison to harmonic manifolds, which are known to be AH.

The following article (with E. Taha) is submitted: https://arxiv.org/abs/2005.03616v2.

2. *On Harmonic and asymptotically harmonic Finsler manifolds:* In the present paper we introduce and investigate various types of harmonic Finsler manifolds and find out the interrelation between them. We give some characterizations of such spaces in terms of the mean curvature of geodesic spheres and the Laplacian of the distance function induced by the Finsler structure. In addition, we prove that certain harmonic Finsler manifolds are of Einstein type and provide a technique to construct harmonic Finsler manifolds of Randers type. Moreover, we give some examples of non-Riemmanian Finsler harmonic manifolds of constant flag curvature and constant S-curvature. Finally, we investigate the Busemann functions in a general Finsler setting and in asymptotically harmonic Finsler manifolds. In particular, we show the Busemann functions are smooth in asymptotically harmonic Finsler manifolds.

I have revised the following article:

3. *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 asymptot-

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

Preprints:

1. H. Shah, *Geometry of Asymptotically harmonic manifolds with minimal horospheres.* (under review)
2. H. Shah and E. Taha, *On Harmonic and asymptotically harmonic manifolds.* (under review)
3. H. Shah, *Asymptotically harmonic manifolds of dimension* 4. (under review)
4. H. Shah, *Rigidity of cusp closing.* (in preparation)

Conference/Workshops Attended:

1. 2020 Virtual Workshop on Ricci and Scalar Curvature, USA, Aug - Sept, 2020.

Committees

1. Member of the Foreign Travel Committee, 2020-present.

Other Activities:

Mathscinet, Reviewer

I am a regular reviewer of Mathscinet. I have reviewed the following articles.

2020

Dec 31 MR4109576: *Carlos Gustavo Approximations of the Lagrange and Markov spectra*, Math. Comp., **89** (2020), 2521–2536.

Aug 20 MR4048448: *Round spheres are Hausdorff stable under small perturbation of entropy*, J. Reine Angew. Math. 758 (2020), 261–280.

Aug 17 MR4052610: *Gromov-hyperbolicity and transitivity of geodesic flows in n-dimensional Finsler manifolds*, Differential Geom. Appl. **68** (2020), 101588, 30 pp.

May 21 MR4033858: *Geodesics and geodesic circles in a geodesically convex surface: a sub-mixing property*, Publ. Math. Debrecen **95** (2019), 279–306.

Feb 18 MR3994254: *On the existence of convex functions on Finsler manifolds*, Balkan J. Geom. Appl. 24 (2019).

Jan 22 MR3985003: *Multiple closed geodesics on positively curved Finsler manifolds*, Adv. Nonlinear Stud. 19 (2019), no. 3, 495–518.

2021

Jun 05 MR4117061: *Pierre Orbital counting for some convergent groups*, Ann. Inst. Fourier (Grenoble) **70** (2020), 1307–1340.

May 18 MR4135865: *On the geometry in the large of Lichnerowicz type Laplacians and its applications*, Balkan J. Geom. Appl. **25** (2020), 76–93.

Jan 29 MR4082260: *Hyperbolic rank rigidity for manifolds of $\frac{1}{4}$-pinched negative curvature*, Ergodic Theory Dynam. Systems **40** (2020), 1194–1216.

Jan 07 MR4084180 *Flexibility of geometric and dynamical data in fixed conformal classes*, Indiana Univ. Math. J. **69** (2020), 517–544.

Ravindranathan Thangadurai

Research Summary:

During this academic year, we studied the linear independence of some real numbers. More precisely, we proved the following result. *Let β be a P-V number and $m \geq 2$ be any integer. Let $a_1, \ldots, a_m$ be distinct positive integers. Then the numbers*

$$1, \sum_{n=1}^{\infty} \frac{1}{\beta^{a_1 n^2}}, \sum_{n=1}^{\infty} \frac{1}{\beta^{a_2 n^2}}, \ldots, \sum_{n=1}^{\infty} \frac{1}{\beta^{a_m n^2}}$$

are $\mathbb{Q}(\beta)$-linearly independent. Note that by a result of Elsner, Luca and Tachiya, it follows each one of the series in the above result is transcendental. However, when $m \geq 3$, these numbers are algebraically dependent over $\mathbb{Q}$. As a consequence of the above result, we obtain the following. *Let β and a_i's be as in the above Theorem. By letting $\tau_n = \frac{i \log \beta}{\pi} + 2n$ for each natural number $n \geq 1$, we have the m-Jacobi theta values*

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

are $\mathbb{Q}(\beta)$-linearly independent with 1. Also, another consequence is: *Let $\beta > 1$, a_i's and τ_n be as in the above Corollary. Then for every integer $n \geq 1$, the m-theta values*

$$\theta_4(a_1\tau_n), \quad \theta_4(a_2\tau), \ldots, \theta_4(a_m\tau_n)$$

are $\mathbb{Q}(\beta)$-linearly independent with 1. Here $\theta_3(\tau)$ and $\theta_4(\tau)$ are Jacobi-Theta functions on complex upper half plane. Other than this result, we also studied the simultaneous approximation of algebraic numbers and as a consequence, we proved a transcendental criterion.

Most of this academic session is devoted to a well-thought book on Algebraic number theory from scratch to advanced topics. The first draft of the book was completed in this academic session.

Publications:

1. R. Thangadurai and N. Saradha, *Pillars of Transcendental Number Theory,* Springer, Singapore, (2020)

Preprints:

1. R. Thangadurai, Debasish Karmakar and Veekesh Kumar, *Linear Independence of special values of Jacobi-Theta constants*, 2021.
2. R. Thangadurai and Veekesh Kumar, *On Simultaneous Approximation of Algebraic numbers,* arXiv:2001.00386v2.
3. R. Thangadurai and S. A. Katre, *Algebraic Number Theory* (In preparation).
4. R. Thangadurai and S. D. Adhikari, *Zero-sum Theorems in Additive Combinatorics: An introduction* (In preparation).

Conference/Workshops Attended:

1. *Teacher Enrichment Workshop*, India, February, 2021.
2. *Balu 70 Number Theory Fest*, India, March, 2021.

Invited Lectures/Seminars:

1. *Decimal Expansion, Gauss Conjecture and Borel Conjecture*, National Webinar, Dwaraka Doss Goverdhan Doss Vaishnav College, Chennai, July, 2020.
2. *Quadratic Reciprocity Law*, Refresher Course, Vaishnav College, Chennai, November, 2020.
3. *On simultaneous approximation of algebraic numbers*, Algebra/Number Theory Seminar, Indian Institute of Science, Bangalore, December, 2020.
4. *3 by 3 magic squares and A.P. in rational points on elliptic curves*, Ramanujan Birthday Seminar, Pi Institute, Chennai, December, 2020.
5. *Introduction to Complex Analysis*, Teacher Enrichment Workshop, Kongu Engineering College, Perundurai, February, 2021
6. *Linear Independence of Special Values of Jacobi Theta Constants*, Balu 70 Number Theory Fest, Institute of Mathematical Sciences, Chennai, March, 2021.

Academic recognition/Awards:

- Managing Editor, Hardy Ramanujan Journal, 2020-21.

Other Activities:

1. *Given reading course on 'Rational Approximations and Introduction to Transcendental Number Theory*, Mr. Kevin Alex, Centre for Basic Sciences, Mumbai, January - May, 2021.
2. *Reading course on 'Algebraic Number Theory'*, Mr. Arpan Das, HRI, January - July, 2021.
3. *Member of HRI Covid Monitoring Committee*, Since March, 2020
4. *Done NAAC exercise for HBNI* during 2020-21.
5. *Nodal officer for PSA exercise*, August-November, 2020.

Satya Deo

Research Summary:

Recall the famous Tverberg theorem of convexity theory: **Let** $d \geq 1; r \geq 2$ **and** $N = (d+1)r-d$**. Then any set of N points in** R^d**, distributed arbitrarily, can be partitioned into r-disjoint subsets whose convex hulls in** R^d **will have a nonempty intersection.** The nonempty intersection of the above theorem is called the Tvernerg set. One of the main problems with which I have been involved is to determine the dimension of this set. There is already a result on this dimension by J.R.Reay. We give a different proof of his theorem which is more transparent and geometric. On the way we have clarified the concept of strongly independent, weakly independent, and other kinds of sets of points in the Euclidean space and have studied their relationships.

The other problem that we have studied is the well-known **disjoint support property of continuous maps from spheres to its triangulations.** This was a very useful tool when the early versions of the Tverberg theorems were proved by Lovas, Barany and others. Let $f : S^d \to \partial(\Delta^{d+1})$ be a contiouous map. We say that this map has the disjoint support property provided the image of any two antipodal points lie in disjoint faces of the simplex. We have obtained several results for maps from 2-sphere to its various triangulations. The case of homeomorphisms is also studied exhaustively. The case of higher dimensional spheres is also under our active consideration.

Publications:

1. Satya Deo and Snigdha Choudhury, *Continuous maps with disjoint support property,* Periodica Mathematica Hungarica **83-1**, (2020).
   DOI 10.1007/s10998-020-00360-z

2. Satya Deo and Snigdha Choudhury, *Strong independence and the dimension of a Tverberg set,* Expositiones Mathematicae **39**, 62-77, (2021).

Preprints:

1. Satya Deo, Snigdha Bharti and Shubhankar Podder, *Existence of continuous maps from d-sphere* $(d \geq 1)$ *to its various triangulations having the disjoint support property.* (submitted)

Conference/Workshops Attended:

1. *Annual conference of the Indian Mathematical Society*, VIT, Vellore, December, 2020.

2. *Annual session of the National Academy of Sciences, India*, Prayagraj HQ, February, 2021.

Visits to other Institutes:

NIL: Due to the Corona Pandemic I could not visit any institution but attended the meetings virtually at LNMIIT (Board of Studies), Jaipur, SMVD University, Jammu (PhD viva voce exam).

Invited Lectures/Seminars:

1. *History of ancient Indian mathematics*, Webinar in mathematics, Anand International Engineering College, Jaipur, September, 2020.

2. *Role of local chapters of NASI*, Inauguration of Kerala local chapter, University of Kerala, Tiruvanantpuram, September, 2020.

3. *Role of multivariate calculus in approximation theory*, Webinar in Mathematics, Sonebhadra Degree College, Sonebhadra, October, 2020.

4. *History of ancient Indian mathematics*, Webinar in mathematics, NIT, Nagaland, Dimapur, November, 2020.

5. *Vedic mathematics and afterwards*, Two talks in Refresher course in mathematics for college teachers, University of Delhi, Delhi, December, 2020.

6. *Plenary talk on Recent results on Tverberg theorem*, Annual session of Ramanujan Math Society , Central University of Rajasthan, Kishangarh, December, 2020.

7. *Two lectures on Inverse function theorem and implicit function theorem*, Faculty development programme of Jammu University, University of Jammu, Jammu, January, 2021.

Academic recognition/Awards:

- General Secretary, Indian Mathematical Society, 2021
- General Secretary, National Academy of Sciences, India, 2021.

Other Activities:

1. Expert in Faculty Recruitment Selection Committee, IIIT, Allahabad, January, 2021.

2. Jagrukta Abhiyaan of NASI, four webinars, 2020.

Pradeep Kumar Rai

Research Summary:

The Schur multiplier of a finite group G is defined as the second cohomology group of G with coefficients in multiplicative group of non-zero complex numbers. It plays an important role in the theory of extensions of groups and has been proved to be a powerful tool in group theory. Finding the bounds on the order, exponents and ranks of the Schur multiplier of prime power groups has been one of the main line of investigation in the past. Our past, and recent works this year refines the existing bounds for the order of the Schur multiplier of prime power groups.

A bound on the order of the Schur multiplier of p-groups was given by Green in 1956. This bound is a function of the order of the group and is best possible. Since then the bound has been refined many times by adding other inputs to the function such as minimal number of generators of the group and the order of the derived subgroup. We strengthen these bounds by incorporating nilpotency class of the group. The particular cases of nilpotency class 2 and maximal class are given a further treatment.

We also have been working on the following problem regrading Schur multiplier of prime power groups.

Is it true that every finite abelian p-group is isomorphic to the Schur multiplier of some nonabelian finite p-group? [Ya. G. Berkovich, Kourovka Notebook]

Or more generally,

Which abelian groups occur as Schur multipliers of nonabelian finite groups? [Moravec]

Preprints:

1. Pradeep Kumar Rai, *Bounds for the order of the Schur multiplier of prime power groups.* (in preparation)

2. Pradeep Kumar Rai, *On the occurrence of elementary abelian p-groups as the Schur multiplier of nonabelian p-groups.* (in preparation)

Invited Lectures/Seminars:

1. Schur multiplier of prime power groups, Group Theory Sangam, Online Seminar Series.

Other Activities:

1. Refereed research papers for journals such as Journal of Algebra, Canadian Mathematical Bulletin, Publicationes Mathematicae Debrecen and others.

Barinder Singh Banwait

Research Summary:

I joined HRI only in February 2021. I have continued my research into arithmetic geometry and algebraic number theory with a computational flavour. I have produced two preprints during the past academic year, both concerning rational isogenies over abelian varieties, and have begun several collaborations in new directions with researchers in the USA, The Netherlands, and Croatia, as well as one with a PhD student in HRI.

Preprints:

1. B. S. Banwait, *Explicit isogenies of prime degree over quadratic fields,* arxiv:2101.02673.
2. B. S. Banwait, *Examples of abelian surfaces failing the local-global principle for isogenies,* arxiv:2007.13583.
3. B. S. Banwait, A. Brumer, H. J. Kim, Z. Klagsbrun, J. Mayle, P. Srinivasan, and I. Vogt, *Computing non-surjective primes associated to Galois representations of genus 2 curves,* (in preparation)
4. B. S. Banwait and M. Derickx, *Explicit isogenies of prime degree over number fields,* (in preparation)
5. O. Adascalitei, B. S. Banwait and F. Najman, *Cyclic isogeny degrees over quadratic fields,* (in preparation)
6. B. S Banwait and K. Krishnarjun, *Sign changes in Fourier coefficients of Bianchi modular forms,* (in preparation)

Conference/Workshops Attended:

1. *Eurocrypt*, Zagreb, Croatia (online), May 2020
2. *Arithmetic Geometry, Number Theory, and Computation*, ICERM (online), Providence (RI), USA, June 2020
3. *Algorithmic Number Theory Symposium*, Auckland, New Zealand (online), June 2020
4. *Lean for the Curious Mathematician*, Germany (online), July 2020
5. *Modern breakthroughs in Diophantine Problems*, Banff International Research Station, Banff, Canada (online), September 2020

Invited Lectures/Seminars:

1. *Explicit isogenies of prime degree over quadratic fields*, Number Theory Seminar, Zagreb University, Zagreb, Croatia, January 2021.
2. *Explicit isogenies of prime degree over quadratic fields*, Joining Seminar, Harish-Chandra Research Institute, Prayagraj, India, February 2021.

Academic recognition/Awards:

- Postdoctoral Fellowship, Harish-Chandra Research Institute, November 2020.

Other Activities:

1. Referee for paper submitted to *Research in Number Theory*, March 2021.

Nilanjan Bag

Research Summary:

I have joined HRI on February, 2021. In this short span I have mainly focused on studying exponential sums and character sums. In two joint works with Prof. Antonio Rojas-León and Prof. Zhang Wenpeng we mainly made progress towards a conjecture of Zhang Wenpeng. In the first article we studied 10th power moments of generalized quadratic Gauss sums weighted by L-functions and gave a few conjectures which are related to an asymptotic formula for arbitrary power moment of generalized quadratic Gauss sums weighted by L-functions. In the second article we were able to prove one of the conjectures which is a conceptual advancement towards the main conjecture of Zhang Wenpeng.

Preprints:

1. N. Bag, A. Rojas-León, W. P. Zhang, *An explicit evaluation of* 10*th power moment of quadratic Gauss sums and some applications.* (submitted)

2. N. Bag, A. Rojas-León, W. P. Zhang, *On some conjectures on generalized quadratic Gauss sums and related problems.* (submitted)

Invited Lectures/Seminars:

1. HRI PDF joining talk. (March 25, 2021)
   Title: Bounds on some double exponential sums.

Other Activities:

1. Attended Analytic Number Theory course, University of Virginia, Course No - MA 8510, Instructor - Prof. Ken Ono.

Kalyan Banerjee

Research Summary:

In the last academic year my research has been around the question of generalised Bloch conjecture over uncountable fields and over number fields. Joint with Kalyan Chakraborty we have been able to prove that the triviality of the Chow group of zero cycles on a smooth, projective surface over number field follows from the triviality of Chow groups of codimension two cycles on a smooth spread of it over the ring of integers. Also we have been able to prove for an elliptic surface with branched double cover satisfying certain conditions gives the finite dimensionality of the Chow group of zero cycles which are invariant under the involution on the branched cover. This says something about existence of smooth, projective curves of low genus on the branched double cover of an elliptic K3 surface.

Publications:

1. Kalyan Banerjee, *Representability of Chow groups of codimension three cycles*, Advances in Geometry. (accepted)

2. Kalyan Banerjee, *Chow groups of conic bundles in P5 and the generalised Bloch's conjecture*, Journal of Ramanujan Math. Society, **36**, Issue 1, pp. 1-12, (2021).

3. Kalyan Banerjee, *On finite dimensionality of Chow groups*, Beitrage zur Algebra und Geometrie, (2021). https://link.springer.com/article/10.1007/s13366-021-00575-2

4. Kalyan Banerjee, Jaya Iyer and James Lewis, *Push-forwards of Chow groups of smooth ample divisors*, Mathmatische nachrichten. (accepted)

Preprints:

1. Involutions on algebraic surfaces and the generalised Bloch conjecture

2. Selmer groups associated to the Chow groups of codimension two cycles on the spread of a smooth projective surface over a number field, joint with Kalyan Chakraborty.

Invited Lectures/Seminars:

1. Invited lecture in KSOM on "Weak Mordell Weil theorem for Chow groups over global function fields", 26th March 2021.

Jagannath Bhanja

Research Summary:

Additive Number Theory is primarily the study of set additions of sets of integers, or more generally, subsets of abelian groups. For nonempty finite sets $A_1, A_2, \ldots, A_h$ of an abelian group G, two common set additions in additive number theory are the sumset $A_1 + A_2 + \cdots + A_h$ and the restricted sumset $A_1 \hat{+} A_2 \hat{+} \cdots \hat{+} A_h$. The *sumset* $A_1 + A_2 + \cdots + A_h$ is defined by $A_1 + A_2 + \cdots + A_h := \{a_1 + a_2 + \cdots + a_h : a_i \in A_i \text{ for } i = 1, 2, \ldots, h\}$ and the *restricted sumset* $A_1 \hat{+} A_2 \hat{+} \cdots \hat{+} A_h$ is defined by $A_1 \hat{+} A_2 \hat{+} \cdots \hat{+} A_h := \{a_1 + a_2 + \cdots + a_h : a_i \in A_i \text{ for } i = 1, 2, \ldots, h \text{ and } a_i \neq a_j \text{ for } i \neq j\}$. When $A_i = A$ for $i = 1, 2, \ldots, h$, the sumset $A_1 + A_2 + \cdots + A_h$ is denoted by hA and the restricted sumset $A_1 \hat{+} A_2 \hat{+} \cdots \hat{+} A_h$ by $h\hat{}A$. The set hA is called the *h-fold sumset* of A and the set $h\hat{}A$ is called the *h-fold restricted sumset* of A.

Two of the classical problems in additive number theory are the direct and inverse problems. A *direct problem* is to find the best possible lower bound for the size of the sumsets hA and $h\hat{}A$. An *inverse problem* is to find the structure of the finite set A for which the sumsets hA and $h\hat{}A$ contain minimum number of elements.

In the work **A note on sumsets and restricted sumsets**, we obtained the optimal lower bound for the size of the sumsets HA and $H\hat{}A$ over finite sets H, A of nonnegative integers, where $HA = \bigcup_{h \in H} hA$ and $H\hat{}A = \bigcup_{h \in H} h\hat{}A$. We also classified the underlying algebraic structure of the sets A and H for which the size of the sumsets HA and $H\hat{}A$ is minimum. Our results generalizes the well known direct and inverse results for the sumsets hA and $h\hat{}A$, i.e., when the set H is a singleton.

In another work **The sizes of restricted sum of multisets**, we studied the multiset analogue of the restricted sumset $h\hat{}A$. By using some simple combinatorial arguments we proved the best possible lower bound for the restricted sumset $h\hat{}\mathcal{A}$, when $\mathcal{A}$ is a multisubset of the group of integers. Furthermore, using another combinatorial method called the "Combinatorial Nullstellensatz", we proved a nontrivial lower bound for the sumset $2\hat{}\mathcal{A}$, when $\mathcal{A}$ is a multisubset of the group $\mathbb{Z}/p\mathbb{Z}$ and p is a prime number.

Publications:

1. J. Bhanja, *A note on sumsets and restricted sumsets,* Journal of Integer Sequences **24**, Article 21.4.2, (2021).

Preprints:

1. J. Bhanja and R. K. Mistri, *The sizes of restricted sum of multisets,* Submitted for publication, (2021).

Conference/Workshops Attended:

1. *Heilbronn Annual Conference 2020*, Heilbronn Institute for Mathematical Research, United Kingdom, September, 2020.

2. *Online Workshop on Algebraic Number Theory*, Department of Mathematics, Assam University, Silchar, India, 31 Aug.–5 Sep., 2020.

3. *International Webinar on Recent Developments in Number Theory 2020*, KIIT Deemed to be University, Bhubaneswar, India, August 17–20, 2020.

4. *Combinatorial and Additive Number Theory (CANT 2020)*, New York Number Theory Seminar, New York, June 1–5, 2020.

Invited Lectures/Seminars:

1. *On the minimum size of sumsets in finite abelian group*, PDF extension seminar, Harish-Chandra Research Institute, Prayagraj, India, 1st December, 2020.

Vikramjeet Singh Chandel

Research Summary:

I joined the institute as a postdoctoral fellow on **December 28, 2020**. During this time-period, I completed a few of my projects that I was working on before I joined the institute. A brief summary of these completed projects is given below.

Certain non-homogeneous matricial domains and Pick–Nevanlinna interpolation problem. In this article, we consider certain matricial domains that are naturally associated to a given domain of the complex plane. To define these domains, let $M_n(\mathbb{C})$ denote the set of $n \times n$ complex matrices and given $W \in M_n(\mathbb{C})$, $\sigma(W)$ denotes the set of eigenvalues of W which is called the *spectrum* of W. For a domain Ω in the complex plane, we consider the matricial domain $S_n(\Omega)$ consisting of those $n \times n$ complex matrices whose spectrum is contained in Ω. These are the matricial domains alluded to in the first line of this paragraph.

Note, a particular example of such domains is $S_n(\mathbb{D})$, where $\mathbb{D}$ denotes the unit disc in the complex plane centered at 0. The domain $S_n(\mathbb{D})$, $n \geq 2$, is called the *spectral unit ball* and has been studied in the literature intensively. In this work, we studied the domain $S_n(\Omega)$ from function-theoretic point of view and established several results for these domains. Our first result shows – generalizing a result of Ransford–White for the spectral unit ball – that the holomorphic automorphism group of these matricial domains does not act transitively. We also consider 2-point and 3-point Pick–Nevanlinna interpolation problem from the unit disc to these matricial domains and present results providing necessary conditions for the existence of a holomorphic *interpolant* for these problems.

On a spectral version of Cartan's Theorem. Let Ω be a domain in the complex plane and given $n \geq 2$, we consider the matricial domain $S_n(\Omega)$ defined above. In a joint work with co-authors Prof. Sayani Bera of IACS, Kolkata and graduate student Mayuresh Londhe of IISc Bangalore, we investigated whether a spectral version of Cartan's theorem holds for the domains $S_n(\Omega)$. More precisely, given a holomorphic self-map Ψ of $S_n(\Omega)$ such that $\Psi(A) = A$ and the derivative of Ψ at A is identity for some $A \in S_n(\Omega)$, we examined when the map Ψ would be spectrum-preserving, i.e., $\sigma(\Psi(W)) = \sigma(W)$ and the algebraic multiplicity of each eigenvalue is preserved for every $W \in S_n(\Omega)$. We prove that if the matrix A is either diagonalizable or non-derogatory then for *most* domains Ω, Ψ is spectrum-preserving on $S_n(\Omega)$. Further, when A is arbitrary, we prove that Ψ is spectrum-preserving on a certain analytic subset of $S_n(\Omega)$.

Interpolating sequences for the Banach algebras generated by a class of test functions. Given a domain $\mathcal{D}$ in $\mathbb{C}^n$, consider a collection of functions Ψ on $\mathcal{D}$, satisfying the following two property:

1. $\sup\{|\psi(x)| : \psi \in \Psi\} < 1$ for each $x \in \mathcal{D}$.
2. For each finite subset F of $\mathcal{D}$, the collection $\{\psi|_F : \psi \in \Psi\}$ together with unity generates the algebra of all $\mathbb{C}$-valued functions on F.

Any such collection of functions Ψ on $\mathcal{D}$ is called a collection of *test functions* on $\mathcal{D}$. Let us denote by $\mathcal{K}_\Psi(\mathbb{C})$ the set of all $\mathbb{C}$-valued *positive kernels* k on $\mathcal{D}$ for which the operator $M_\psi : \mathcal{H}_k \longrightarrow \mathcal{H}_k$ defined by $M_\psi(f) := f\,\psi$, for all $f \in \mathcal{H}_k$, is a contraction for

each $\psi \in \Psi$. Here, H_k denotes the reproducing kernel Hilbert space associated with the positive kernel k. Also, a contraction on a Hilbert space is a bounded linear operator whose operator norm is atmost 1. We now introduce the Banach algebra associated to a class of test functions as alluded to in the title of this work.

Let us denote by $H^\infty_\Psi(\mathbb{C})$ the collection of such $\mathbb{C}$-valued functions $\phi : \mathcal{D} \longrightarrow \mathbb{C}$ for which there exists a $C > 0$ having the following property:

$(*)$ for each $k \in \mathcal{K}_\Psi(\mathbb{C})$, the bounded linear operator $M_\phi : \mathcal{H}_k \longrightarrow \mathcal{H}_k$ defined by $M_\phi(f) := f\,\phi$ for all $f \in \mathcal{H}_k$, is a bounded linear operator with $||M_\phi||_{\mathcal{H}_k} \leq C$.

Given $\phi \in H^\infty_\Psi(\mathbb{C})$, define:

$$||\phi||_\Psi := \inf\big\{C \,:\, C\ satisfying\ the\ property\ (*)\ above\big\}. \tag{1}$$

It turns out that $H^\infty_\Psi(\mathbb{C})$ is a Banach algebra with norm $||\cdot||_\Psi$. It is easy to see that if $\phi \in H^\infty_\Psi(\mathbb{C})$ then $||\phi||_\infty := \sup\{|\phi(z)| \,:\, z \in \Omega\} \leq ||M_\phi||_{\mathcal{H}_k}$ for all $k \in K_\Psi$. It follows from this that $||\phi||_\infty \leq ||\phi||_\Psi$.

In this article, we characterize interpolating sequences for the Banach algebra $H^\infty_\Psi(\mathbb{C})$. When $\mathcal{D}$ is the unit disc $\mathbb{D}$ in the complex plane centered at 0 and the class of test function includes only the identity function on $\mathbb{D}$, the aforementioned algebra is the algebra of bounded holomorphic functions on $\mathbb{D}$. In this case, our characterization reduces to the well-known result by Carleson. Furthermore, we present several other cases of the pair $(\mathcal{D},\, \Psi)$, where our main result could be applied to characterize interpolating sequences which also shows the efficacy of our main result.

Preprints:

1. Vikramjeet Singh Chandel, *Certain non-homogeneous matricial domains and Pick–Nevanlinna interpolation problem*, submitted, under review, math.arxiv: 2009.01834 (first version that appeared on math.arxiv).

2. Sayani Bera, Vikramjeet Singh Chandel, Mayuresh Londhe, *On a spectral version of Cartan's theorem*, math.arxiv:2105.11284.

3. Anindya Biswas, Vikramjeet Singh Chandel, *Interpolating sequences for the Banach algebras generated by a class of test functions*, submitted, math.arxiv:2104.05461.

Invited Lectures/Seminars:

1. *Real functions of more than one variable*, Undergraduate Intensive Workshop (online), Harish Chandra Mathematics Society (HCMS), Department of Mathematics, Deen Dayal Upadhyay College (University of Delhi), New Delhi-110078, Feb. 18-Feb. 21, 2021.

2. *An infinite universe of number system: the p-adic numbers*, National Undergraduate Interactive Workshop in Mathematics (online), Arya P. G. College, Panipat, Apr. 15, 2021.

Arindam Dey

Research Summary:

My research is concerned with the study of the derivation module of the ring of invariants of the polynomial ring $K[X, Y]$ (where K is an algebraically closed field of characteristic zero) under the linear action of a finite subgroup of $GL(2, K)$. It suffices to consider the case where the subgroup does not contain a non-trivial pseudo-reflection. Such subgroups have been classified (up to conjugacy) in an important paper by O. Riemenschneider; these are certain cyclic, dihedral, tetrahedral, octahedral, and icosahedral groups. Then the problem of describing generators for the module of K-derivations of the ring of invariants of $K[X, Y]$ under the action of such groups began to attract the attention of some researchers. The first case (the cyclic case) has been tackled by Gurjar and Wagh. The next natural step is thus to consider the dihedral case.

Let $D_{n,q}$ denote the dihedral group naturally attached to a pair of integers n, q with $1 < q < n$ and $\gcd(n, q) = 1$. Let R be the ring of invariants of $K[X, Y]$ under the action of D, and let $Der(R)$ be the R-module formed by the K-derivations of R. We prove two main results related to such objects. First, after clarifying why it suffices to consider the K-derivations of $K[X, Y]$ itself that are invariant under $D_{n,q}$, we characterize such derivations by means of describing their structure explicitly. Then we give an explicit generating set for the R-module $Der(R)$. In particular, it is shown that the minimal number of generators of $Der(R)$ is at most the order of $D_{n,q}$, which is $4q(n - q)$.

Publications:

1. Arindam Dey and Surjeet Kour *On the Module of Derivations of Rings of Invariants of $K[X, Y]$ Under the Action of Certain Dihedral Groups,* Journal of Algebra and its Applications. (under review)

Arindam Jana

Research Summary:

I am working on modular representation theory of groups. A representation of a group G is a group homomorphism $\rho : G \to \mathrm{Aut}(V)$, where V is a vector space over a field F and $\mathrm{Aut}(V)$ denotes the set of all automorphisms on V.

The representations of G can be studied in two different ways depending on characteristic of the field F over which V is defined. If characteristic of F is zero, then the theory is apparently same as it is over the field of complex numbers. However, the treatment is completely different in the case when F is of positive characteristic which is known as modular representation theory.

Currently I am working on a problem which shows that how modular representation theory can be applied to answer a question in the theory of complex representation. This is a joint work with U. K. Anandavardhanan.

Let G be a finite group. Let π be an irreducible complex representation of G. Then there is always the standard G-invariant inner product $\langle , \rangle_\pi$ on π. Let H and K be two subgroups of G such that the space of H-invariant vectors as well as the space of K-invariant vectors are one dimensional, *i.e*, $\dim \pi^H = 1 = \dim \pi^K$. Let v_H and v_K denote an H-invariant and K-invariant vector respectively. We are interested in computing the square of the absolute value of $\langle v_H, v_K \rangle_\pi$. This is called the correlation constant $c(\pi; H, K)$ defined by Benedict Gross.

We take $G = \mathrm{GL}_2(F_q)$, where F_q is the field with $q = p^f$ elements of odd characteristic p and H is its split torus and K is a non-split torus. We give a sufficient condition for $\langle v_H, v_K \rangle_\pi$ to be zero and a sufficient condition for it to be non-zero.

Our main idea is to attach a number ϵ_π (which is either $+1$ or -1) to an irreducible representation π of $\mathrm{GL}_2(F_q)$ which admits H-fixed vectors and K-fixed vectors. This is actually finite field analogue of the epsilon factor in automorphic representation theory. We show that if $\epsilon_\pi = -1$, then $\langle v_H, v_K \rangle_\pi = 0$. For the case $\epsilon_\pi = 1$, the key idea is to analyze the reduction mod-p of the complex representation π, of $\mathrm{GL}_2(F_q)$, using the results of Diamond. A crucial observation is that there is precisely one irreducible Jordan-Hölder component in reduction mod-p which produces H-fixed vectors and K-fixed vectors. We first exhibit v_H and v_K for this mod-p representation of $\mathrm{GL}_2(F_q)$. Then we give formula for $\langle v_H, v_K \rangle_\pi$ modulo p explicitly.

Finally we study the behaviour of $\langle v_H, v_K \rangle_\pi$ under the Shintani base change and give a sufficient condition for $\langle v_H, v_K \rangle_\pi$ to vanish for any irreducible representation $\pi = BC(\tau)$ of $\mathrm{PGL}_2(E)$ in terms of epsilon factor of the base change representation τ of $\mathrm{PGL}_2(F)$, where E/F is a finite extension of finite fields.

Preprints:

1. U. K. Anandavardhanan and Arindam Jana, *Orthogonality of invariant vectors*, https://arxiv.org/abs/2106.01929v2.

Conference/Workshops Attended:

1. *Mumbai-Pune Number Theory seminar (online)*, India, April, 2021.

Invited Lectures/Seminars:

1. *Mod-p representations of* $\mathrm{GL}(2, F)$, PDF joining seminar, Harish-Chandra Research Institute, India, March, 2021.

Suraj Singh Khurana

Research Summary:

I have joined the institute on December 28, 2020. Below is the brief summary of the research work done.

It is well known that the Euler's constant γ occurs as the constant term in the Laurent series expansion of the Riemann zeta function $\zeta(s)$ at $s = 1$. In particular, we have

$$\zeta(s) = \frac{1}{s-1} + \sum_{k=0}^{\infty} \frac{(-1)^k}{k!} \gamma_k (s-1)^k$$

where γ_k is the classical k-th Euler-Stieltjes constant and is given by the limit

$$\gamma_k := \lim_{N \to \infty} \left(\sum_{n=1}^{N} \frac{\log^k n}{n} - \frac{\log^{k+1} N}{k+1} \right).$$

In our research (joint work with Tapas Chatterjee), we derive a series representation of the generalized Stieltjes constants which arise in the Laurent series expansion of partial zeta function at the point $s = 1$. In the process, we introduce a generalized gamma function and deduce its properties such as functional equation, Weierstrass product and reflection formulas along the lines of the study of a generalized gamma function introduced by Dilcher in 1994. These properties are used to obtain a series representation for the k-th derivative of Dirichlet series with periodic coefficients at the point $s = 1$. Another application involves evaluation of a class of infinite products whose special case includes an identity of Ramanujan.

Publications:

1. Tapas Chatterjee, Suraj Singh Khurana, *A series representation of Euler-Stieltjes constants and an identity of Ramanujan,* Rocky Mountain Journal. (accepted)

Conference/Workshops Attended:

1. *Balu Fest (On the occasion of 60th Birthday of Prof. Ramachandran Balasubramanian)*, The Institute of Mathematical Sciences Chennai, India, March, 2021.

Invited Lectures/Seminars:

1. *On some expressions for derivatives of L-functions*, HRI Joining Seminar, Harish-Chandra Research Institute, Prayagraj, India, Janurary, 2021.

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, when the product of these ideals satisfies unital set condition (USC), 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 when the product of these ideals satisfies USC. We prove an analogous result for symplectic groups.. 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 USC. We extend the surjectivity result in the second context to certain congruence ideals subgroups of special linear groups and symplectic groups. The articles that are relevant that I have written are MR3887364 & Zbl 1425.11176, MR4166711 & Zbl 1455.11149, arXiv:1902.09311, arXiv:2007.10132.

Number Theory and Geometry - Elliptic Curves and Rational Distance Sets in the Euclidean spaces and Spheres: For a positive rational l, we define the concept of an l-elliptic and an l-hyperbolic rational set in a metric space. We examine the existence of (i) dense and (ii) infinite l-hyperbolic and l-ellitpic rationals subsets of the real line and unit circle. For the case of a circle, we prove that the existence of such sets depends on the positivity of ranks of certain associated elliptic curves. We also determine the closures of such sets which are maximal in case they are not dense. In higher dimensions, we show the existence of l-ellitpic and l-hyperbolic rational infinite sets, in general position, on unit spheres and in Euclidean spaces, for those values of l which satisfy a weaker condition regarding the existence of elements of order more than two, than the positivity of the ranks of the same associated elliptic curves. We also determine their closures. A subset T of the k-dimensional unit sphere S^k has an antipodal pair if both $x, -x \in T$ for some $x \in S^k$. In this article, we prove that there does not exist a dense rational set $T \subseteq S^2$ which has an antipodal pair by assuming Bombieri-Lang Conjecture for surfaces of general type. For any $k \in \mathbb{N}$, we actually show that the existence of such a dense rational set in S^k is equivalent to the existence of a dense 2-hyperbolic rational set in S^k which is further equivalent to the existence of a dense 1-elliptic rational set in the Euclidean space $\mathbb{R}^k$. The article that is relevant that I have written is arXiv:1612.02171.

Combinatorics of Finite Abelian p-Groups: Positivity Conjecture: For a partition $\underline{\lambda} = (\lambda_1^{\rho_1} > \lambda_2^{\rho_2} > \lambda_3^{\rho_3} > \ldots > \lambda_k^{\rho_k})$ and its associated finite $\mathcal{R}$-module $\mathcal{A}_{\underline{\lambda}} = \bigoplus_{i=1}^{k} (\mathcal{R}/\pi^{\lambda_i}\mathcal{R})^{\rho_i}$, where $\mathcal{R}$ is a discrete valuation ring, with maximal ideal generated by a uniformizing element π, having finite residue field $\mathbf{k} = \mathcal{R}/\pi\mathcal{R} \cong \mathbb{F}_q$, the number of orbits of pairs $n_{\underline{\lambda}}(q) = \mid \mathcal{G}_{\underline{\lambda}} \backslash \left(\mathcal{A}_{\underline{\lambda}} \times \mathcal{A}_{\underline{\lambda}}\right) \mid$ for the diagonal action of the automorphism group $\mathcal{G}_{\underline{\lambda}} = Aut(\mathcal{A}_{\underline{\lambda}})$, is a polynomial in q with non-negative coefficients. It has been conjectured that these coefficients are in fact non-negative. We consider the case of

partitions $\underline{\lambda}$ with $\rho_{i_0} \geq 2$ for some $1 \leq i_0 \leq k$, that is, the part λ_{i_0} of $\underline{\lambda}$ (repeats) appears more than once. If $\underline{\mu} = \left(\lambda_1^{\rho_1} > \lambda_2^{\rho_2} > \ldots > \lambda_{i_0-1}^{\rho_{i_0-1}} > \lambda_{i_0}^{1} > \lambda_{i_0+1}^{\rho_{i_0+1}} > \ldots > \lambda_{k-1}^{\rho_{k-1}} > \lambda_k^{\rho_k}\right)$ and $\underline{\nu} = \left((\lambda_1 - 2)^{\rho_1} > (\lambda_2 - 2)^{\rho_2} > \ldots > (\lambda_{i_0-1} - 2)^{\rho_{i_0-1}} \geq (\lambda_{i_0} - 1)^2 \geq \lambda_{i_0+1}^{\rho_{i_0+1}} > \ldots > \lambda_{k-1}^{\rho_{k-1}} > \lambda_k^{\rho_k}\right)$ then we prove that the orbit polynomial $n_{\underline{\lambda}}(q) = n_{\underline{\mu}}(q) + n_{\underline{\nu}}(q)$, that is, the orbit polynomial splits as the sum of two orbit polynomials. So $n_{\underline{\lambda}}(q)$ has nonnegative coefficients if both $n_{\mu}(q), n_{\underline{\nu}}(q)$ has nonnegative coefficients. As a consequence we prove that the positivity conjecture for partitions which has all parts distinct implies the positivity conjecture for all partitions in general. Currently I am working on proving the positivity conjecture for partitions which has all its parts distinct. The article that is relevant that I have written is arXiv:2001.02523.

Combinatorics - On Coherent Edge-Labelling of a Polyhedron in Three Dimensions: We consider the problem of coherently labelling edges of a convex polyhedron in three dimensions. We exhibit all the forty eight possible coherent labellings of the edges of a tetrahedron. We also exhibit that some simplicial polyhedra like bipyramids, Kleetopes, gyroelongated bipyramids are coherently edge-labellable. Also we prove that pyramids and antiprisms over n-gons for $n \geq 4$, which are not simplicial polyhedra, are coherently edge-labellable. We prove that among platonic solids, the cube and the dodecahedron are not coherently edge-labellable, even though, the tetrahedron, the octahedron and the icosahedron are coherently labellable. Unlike the case of a tetrahedron, in general for a polyhedron, we show that a coherent labelling need not induce a coherent labelling of edges incident at a vertex. We also give an obstruction criterion for a polyhedron not to be coherently edge-labellable and consequentially show that any polyhedron obtained from a pyramid with its apex chopped off is not coherently edge-labellable. Finally with the suggestion of the affirmative results we prove the main theorem that any simplicial polyhedron is coherently edge-labellable. The article that I have written that is relevant is arXiv:1801.08685.

Combinatorics - Hyperplane Arrangements and Point Arrangements: For positive integers $n \geq m \geq 1$, the parameter spaces for the isomorphism classes of the generic point arrangements of cardinality n, and the antipodal point arrangements of cardinality $2n$ in the Eulidean space $\mathbb{R}^m$, (that is, Normal systems in $\mathbb{R}^m$ of cardinality n) are described using the space of totally nonzero Grassmannian $Gr_{mn}^{tnz}(\mathbb{R})$. A stratification $\mathcal{S}_{mn}^{tnz}(\mathbb{R})$ of the totally nonzero Grassmannian $Gr_{mn}^{tnz}(\mathbb{R})$ is mentioned and the parameter spaces are respectively expressed as quotients of the space $\mathcal{S}_{mn}^{tnz}(\mathbb{R})$ of strata under suitable actions of the symmetric group S_n and the semidirect product group $S_n \ltimes (\mathbb{R}^*)^n$. The cardinalities of the space $\mathcal{S}_{mn}^{tnz}(\mathbb{R})$ of strata and of the parameter spaces $S_n \backslash \mathcal{S}_{mn}^{tnz}(\mathbb{R}), (S_n \ltimes (\mathbb{R}^*)^n) \backslash \mathcal{S}_{mn}^{tnz}(\mathbb{R})$ are enumerated in dimension $m = 2$. Interestingly enough, the enumerated value of the isomorphism classes of the generic point arrangements in the Euclidean plane is expressed in terms of the number theoretic Euler-totient function. The analogous enumeration questions are still open in higher dimensions for $m \geq 3$. The article that I have written that is relevant is arXiv:2102.10609.

Combinatorics - Discriminantal Arrangements: In the area of discriminantal arrangements I have done the following. Firstly it is shown that any six-line arrangement, consisting of three pairs of mutually perpendicular lines, does not give rise to a "very generic or sufficiently general" discriminantal arrangement in the sense of C. A. Athanasiadis. The second result is as follows. The codimension-one boundary faces of (a region) a convex cone of a very generic discriminantal arrangement has not been characterised and is not known even though the intersection lattice of a very

generic discriminantal arrangement is known. So secondly, we show that the number of simplex cells of the very generic hyperplane arrangement $\mathcal{H}_n^m = \{H_i : \sum_{j=1}^{m} a_{ij}x_j = c_i, 1 \leq i \leq n\}$ may not be not precisely equal to the number of codimension-one boundary hyperplanes of $\mathbb{R}^n$ of the convex cone C containing $(c_1, c_2, \ldots, c_n)$ in the associated very generic discriminantal arrangement. That is, for $1 \leq i_1 < i_2 < \ldots < i_m < i_{m+1} \leq n$, if $\Delta^m H_{i_1} H_{i_2} \ldots H_{i_m} H_{i_{m+1}}$ is a simplex cell of the hyperplane arrangement $\mathcal{H}_n^m$ then it need not give rise to a codimension-one boundary hyperplane of the convex cone C containing $(c_1, c_2, \ldots, c_n)$ in the associated very generic discriminantal arrangement. The article that I have written that is relevant is arXiv:2011.05327.

Publications:

1. C P Anil Kumar, *On the Factorization of Two Adjacent Numbers in Multiplicatively Closed Sets Generated by Two Elements,* Proceedings Mathematical Sciences: Indian Academy of Sciences **130**, Art. ID. 37, 16 Pages, (2020). https://doi.org/10.1007/s12044-020-00566-8

2. C P Anil Kumar, *On the surjectivity of certain maps II: for generalized projective spaces,* Journal of Ramanujan Mathematical Society, Vol. **35**, Issue 3, pp. 241-262, (2020). http://www.mathjournals.org/jrms/2020-035-003/2020-035-003-004.pdf

3. C P Anil Kumar, *On the triangles in certain types of line arrangements,* Discrete Mathematics, Algorithms and Applications **13**, No. 3, Art. ID. 2150031, 23 Pages, (2021). https://doi.org/10.1142/S1793830921500312

4. C P Anil Kumar, *A combinatorial identity for the p-binomial coefficient based on abelian groups,* Moscow Journal of Combinatorics and Number Theory **10**, No. 1, pp. 13-24, (2021). https://doi.org/10.2140/moscow.2021.10.13, Zbl 1459.05008

5. C P Anil Kumar, *A Weighted Inequality,* Mathematics Newsletter, Ramanujan Mathematical Society **31**, Issue 3, pp. 101-104, (2021). https://drive.google.com/file/d/19yaDG6ngE0CQJLOxjn52UevXHQR3bv-u/preview

6. C P Anil Kumar, *On the Enumeration of Certain Type of Hyperplane Arrangements,* Proceedings Mathematical Sciences: Indian Academy of Sciences, (2020). (accepted)

Preprints:

1. C P Anil Kumar, *On the Surjectivity of Certain Maps IV: For Congruence Ideal Subgroups of Type A_k and C_k,* July 2020, Submitted to a Journal, arXiv: 2007.10132, https://arxiv.org/pdf/2007.10132.pdf

2. C P Anil Kumar, *On Rational sets in Euclidean Spaces and Spheres,* September 2020, Submitted to a Journal, arXiv: 1612.02171, https://arxiv.org/pdf/1612.02171.pdf.

3. C P Anil Kumar, *On the Coherent Edge-Labelling of a Polyhedron in Three Dimensions.,* October 2020, Submitted to a Journal, arXiv: 1801.08685, https://arxiv.org/pdf/1801.08685.pdf.

4. C P Anil Kumar, *On the Generic Point Arrangements in Euclidean Space and Stratification of the Totally Nonzero Grassmannian,* February 2021, Submitted to a Journal, arXiv: 2102.10609,

   https://arxiv.org/pdf/2102.10609.pdf

5. C P Anil Kumar, *On the Reduciblity of a Certain Type of Rank 3 Uniform Oriented Matroid by a Point,* April 2021, Submitted to a Journal, arXiv: 1904.04065, https://arxiv.org/pdf/1904.04065.pdf

6. C P Anil Kumar, *On Very Generic Discriminantal Arrangements,* June 2020, Submitted to a Journal, arXiv: 2011.05327,

   https://arxiv.org/pdf/2011.05327.pdf

7. C P Anil Kumar, *On the Positivity Conjecture for Finite Abelian p-Groups,* June 2021, arXiv: 2001.02523, https://arxiv.org/pdf/2001.02523.pdf

8. C P Anil Kumar, *On the Intersection Lattice of Very Generic Discriminantal Arrangements: A New Geometric Description,* Preprint Just Prepared.

Invited Lectures/Seminars:

1. *On the Triangles in Certain Type of Line Arrangements*, Post Doctoral Fellow Seminars, Harish-Chandra Research Institute, Prayagraj, INDIA, October 2020.

Other Activities:

1. I have sent solutions to Problems 4531, 4540, 4547, 4548, 4549, 4550, OC476, OC477, OC478, OC479, OC480, OC481, OC482, OC483, OC485 in Crux Mathematicorum Journal Volume 46, 2020. I am in the list of problem solvers in Crux Mathematicorum Journal Volume 46, (SP)-Solvers and Proposers.

   https://cms.math.ca/wp-content/uploads/2020/01/crux_SP_v46_b.pdf

2. I am a reviewer for **Zentralblatt MATH**. I have written **Zentralblatt MATH Reviews** for the following articles.

   (a) Zbl 07167802: On congruence half-factorial Krull monoids with cyclic class group.

   (b) Zbl 1450:11101: Counting subrings of the ring $\mathbb{Z}_m \times \mathbb{Z}_n$.

   (c) Zbl 1453:11145: Filtrations of units in Viète field.

   (d) Zbl 1445:13018: On existence of Euclidean ideal classes in real cubic and quadratic fields with cyclic class group.

   (e) Zbl 07220063: The charm of units I, On the Kummer-Vandiver conjecture. Extended abstract.

   (f) Zbl 1455:11130: On the error term concerning the number of subgroups of the groups $\mathbb{Z}_m \times \mathbb{Z}_n$ with $mn \leq x$.

   (g) Zbl 07110008: The unit structure in a quotient ring of a quadratic number field.

(h) Zbl 07303532: Hirzebruch-type inequalities viewed as tools in combinatorics.

Animesh Lahiri

Research Summary:

In the previous year I have worked in the following two directions:

1. **On Residual and Stable Coordinates:** Let R be ring, $A = R[X_1, \ldots, X_n]$ and $F \in A$. F is said to be a *coordinate in* A if there exist $F_2, \ldots, F_n \in A$ such that $A = R[F, F_2, \ldots, F_n]$. For some positive integer m, we will say that F is an *m-stable coordinate in* A if F is a coordinate in $A^{[m]}$. F will be called a *residual coordinate in* A if, for each prime ideal P of R, F is a coordinate in $k(P)[X_1, \ldots, X_n]$, where $k(P)$ is the residue field of R at P.

   We have proved the following results:

   Theorem: Let k be an algebraically closed field and R a one-dimensional affine k-algebra. Let a be a non-zerodivisor in R and $P(Z_1, \ldots, Z_n) \in R[Z_1, \ldots, Z_n]$ $(= R^{[n]})$ be such that the image of P is a coordinate in $(R/aR)[Z_1, \ldots, Z_n]$. If R_{red} is seminormal or if the characteristic of k is zero then the polynomial F defined by $F := aW + P$ is a coordinate in $R[Z_1, \ldots, Z_n, W]$ $(= R^{[n+1]})$.

   Theorem: Let k be an algebraically closed field, R a one-dimensional affine k-algebra such that either the characteristic of k is zero or R_{red} is seminormal. Then, every residual coordinate in $A := R[Z_1, \ldots, Z_n]$ $(= R^{[n]}), n \geq 3$, is a 1-stable coordinate.

   Theorem: Let R be a Noetherian d-dimensional ring. Then every residual coordinate in $R[Z_1, \ldots, Z_n]$ $(= R^{[n]})$ is a $(2^d - 1)n$-stable coordinate.

   Theorem: Let k be an algebraically closed field of characteristic zero and R a finitely generated k-algebra of dimension d. Then every residual coordinate in $R[Z_1, \ldots, Z_n]$ $(= R^{[n]})$ is an r-stable coordinate, where $r = (2^d - 1)n - 2^{d-1}(n-1) = 2^{d-1}(n+1) - n$.

2. **On Image Ideals of Locally Nilpotent Derivations:** Let B be an affine k-domain containing Q, $D \in LND(B)$ and $A := \mathrm{Ker}\ D$.

   The **image ideals** of D are the ideals of A defined by : $I_n = A \cap D^n B$ for $n \geq 0$ and $I_\infty = \bigcap_{n=0}^{\infty} I_n$.
   I_1 is called the **plinth ideal** of D and I_∞ the **core ideal** of D. Also $I_n \supseteq I_{n+1}$ for all $n \geq 0$.

   Let R be a ring containing Q, $B = R[X_1, X_2, X_3]$, $D \in LND(B)$ and $A := Ker\ D$. D. Daigle have proved: if R is a field, then for each $n \in N$, I_n is a principal ideal of A.

   We have calculated the image ideals of $R[X_1, X_2, X_3]$ when R is a PID and $D^2 X_i = 0$ for all i. More generally, we have proved the following theorem:

   Theorem: Let R be a UFD containing Q and $B = R[V, W]$ $(= R^{[2]})$. Let D be an irreducible locally nilpotent R-derivation on B such that $D^2 V = D^2 W = 0$. Let $A = \mathrm{Ker}\ D$. If $DV = f$ and $DW = g$, then for each $n \geq 1$ the following hold:

(a) $I_n = (f, g)^n A$.

(b) If D is fixed point free, then $I_n = A$, otherwise $ht(I_n) = 2$. In the former case $I_\infty = A$ while in the latter case $I_\infty = (0)$.

We have also proved the following theorem:

Theorem: Let R be a UFD containing Q and $B = R[X, Y]$. Let D be an irreducible locally nilpotent R-derivation on B such that $D^2X = 0$ and $D^2Y \neq 0$. Then $\exists\, b \in R$ and $f \in R[X]$ such that $DX = b$ and $DY = -f'(X)$. If b is irreducible in R, then $I_1 = bA$.

Publications:

1. A. K. Dutta and A. Lahiri, *Residual and Stable Coordinates,* J. Pure Appl. Algebra **225**, (2021).

Preprints:

1. A. Lahiri, N. Dasgupta, *On image ideals of locally nilpotent derivations. (in preparation)*

Invited Lectures/Seminars:

1. *On Zariski Topology*, Ramakrishna Mission Vidyamandira, Belur Math, Howrah, West Bengal, on 6th December 2020.

Anwoy Maitra

Research Summary:

After joining in December 2020, I worked mainly on two projects:

Firstly, with Anindya Biswas (IISc, Bangalore) on a project that dealt with characterizing the bidisc $\mathbb{D}^2$ (the Cartesian product of the unit disc $\mathbb{D} \subset \mathbb{C}$ with itself). Specifically, we picked out the bidisc from among all 2-dimensional Kobayashi-hyperbolic manifolds by making some assumptions on the holomorphic automorphism group of such a manifold and about its action on the manifold. This work was completed in April 2021.

Secondly, with fellow postdocs Amar Deep Sarkar and Vikramjeet Singh Chandel on a project that deals with the recently introduced notion of visibility with respect to the Kobayashi distance. This notion is inspired by, and reminiscent of, some notions in Riemannian geometry and the theory of Gromov hyperbolic distance spaces. Therefore, techniques in metric geometry may be applied in investigating this notion. While such techniques have not been widely used in *S*everal *C*omplex *V*ariables (SCV) heretofore, recent results indicate that they may be fruitfully applied to investigate some questions in SCV, particularly those dealing with extension to the boundary of holomorphic maps. We have some new results in this direction and we are in the process of preparing a manuscript.

Preprints:

1. Anindya Biswas and Anwoy Maitra, *A characterization of the bidisc by a subgroup of its automorphism group,* arXiv:2104.05001. (accepted in J. Math. Anal. Appl)

Other Activities:

1. Helped supervise the project of a masters student from the Indian Association for the Cultivation of Science (IACS), Kolkata, Dec 2020 - Jan 2021.

Muna Naik

Research Summary:

Let S be a Damek–Ricci space and Δ be the Laplace–Beltrami operator of S. We explore the behaviour of heat propagator in S in large time to illustrate the differences with the corresponding results in R^n. In particular we study the relation between the limiting behaviour of the ball-averages as radius tends to ∞ and that of the the heat propagator as time goes to ∞ and use this relation for characterization of eigenfunctions of Δ.

Publications:

1. M. Naik, S. K. Ray, R. P. Sarkar: *Large time behaviour of heat propagator,* Bulletin des Sciences Mathematiques **167**, 102955, (2021).

Preprints:

1. M. Naik, R. P. Sarkar: *Asymptotic mean value property for eigenfunctions of the Laplace–Beltrami operator on Damek–Ricci spaces.*

Conference/Workshops Attended:

1. *NCM workshop on Harmonic Analysis*, India, December, 2020.

Invited Lectures/Seminars:

1. *Characterization of eigenfunctions of the Laplace-Beltrami operator using Fourier multipliers* , APRG Seminar, Indian Institute of Science, Bangalore, 07 October 2020.

Academic recognition/Awards:

- NBHM post-doctoral fellowship, 2020.

Soham Swadhin Padhan

Research Summary:

My research work is focused broadly on representations of finite groups over arbitrary fields of characteristic 0.

Frobenius developed representations of finite groups over the field of complex numbers. Schur extended that to representations of finite groups over subfields of the field of complex numbers, especially the field of rational numbers. Schur observed that certain irreducible representations over the complex numbers could not be realized over the field of rational numbers, but that a finite multiple of the certain irreducible representations could always be realized. The number associated with this multiplicity is called the *Schur index*, which was introduced by Schur in 1906.

Quasi-Permutation Representations of Holomorph of Cyclic p-Groups: For a finite group G, let $p(G)$ denote the minimal degree of a faithful permutation representation of G. The minimal degree of a faithful representation of G by quasi-permutation matrices over the fields $\mathbb{C}$ and $\mathbb{Q}$ are denoted by $c(G)$ and $q(G)$ respectively. In general $c(G) \leq q(G) \leq p(G)$ and either inequality may be strict. We study the representation theory of the group $G = \mathrm{Hol}(C_{p^n})$, which is the holomorph of a cyclic group of order p^n, p a prime. This group is metacyclic when p is odd and metabelian but not metacyclic when $p = 2$ and $n \geq 3$. We explicitly describe the set of all isomorphism types of irreducible representations of G over the field of complex numbers $\mathbb{C}$ as well as the isomorphism types over the field of rational numbers $\mathbb{Q}$. We compute the Wedderburn decomposition of the rational group algebra of G. Using the descriptions of the irreducible representations of G over $\mathbb{C}$ and over $\mathbb{Q}$, we show that $c(G) = q(G) = p(G) = p^n$ for any prime p. This is a joint work with B. Sury.

Faithful Irreducible Representations of Certain Metabelian Groups: Let F be any field of characteristic 0 and $\overline{F}$ be its algebraic closure. We prove that for a finite group having a prime power order maximal abelian normal subgroup containing the derived subgroup, all the faithful irreducible representations over F have the same degree and the Schur index of any faithful irreducible $\overline{F}$-representation with respect to F is always 1 or 2. We explicitly obtain the Wedderburn component corresponding to any faithful irreducible $\overline{F}$-representation in the group algebra of this group over F. Further, we also prove that for a normally monomial group with a prime power order maximal abelian normal subgroup, the Schur index of any faithful irreducible $\overline{F}$-representation with respect to F equals 1 or 2. This is a joint work with B. Sury.

Roquette's Theorem and Representations of Metacyclic p-groups: In 1958, Roquette proved an important result on Schur indices for p-groups, which is as follows: let G be a p-group, F a field of characteristic 0 and ρ an irreducible F-representation of G. If p is odd, or $p = 2$, and F contains $\sqrt{-1}$, then the Schur index of ρ equals to 1. If $p = 2$, and F does not contain $\sqrt{-1}$, then the Schur index of ρ equals to 1 or 2. We give an elementary proof of Roquette's theorem. We describe the set of all isomorphism types of irreducible representations of a metacyclic p-group over $\mathbb{Q}$. We also determine the Wedderburn decomposition $\mathbb{Q}[G]$, when G is a metacyclic p-group. In addition, we give a simple direct proof of the result: generalized quaternion groups are the only metacyclic 2-groups which have a faithful irreducible $\mathbb{Q}$-representation of Schur index 2. Moreover, we give a construction of producing faithful irreducible

$\mathbb{Q}$-representations, with Schur index 2. This is a joint work with Ravindra Shripad Kulkarni.

Preprints:

1. Soham Swadhin Pradhan and B. Sury, *Rational and Quasi-Permutation Representations of Holomorph of Cyclic p-Groups.* (submitted)

2. Soham Swadhin Pradhan and B. Sury, *Degrees of Faithful Irreducible Representations of Certain Metabelian Groups and a Question of Sim.* (submitted)

3. Ravindra Shripad Kulkarni and Soham Swadhin Pradhan, *An Elementary Proof of Roquette's Theorem and Representations of Metacyclic p-groups.* (in preparation)

Conference/Workshops Attended:

1. *Group Theory Sangam Seminar Series*, India, January - March, 2021.

Invited Lectures/Seminars:

1. *Schur Indices of p-Groups and Metacyclic Groups*, Post Doctoral Fellow Seminars, Harish-Chandra Research Institute (HRI), Prayagraj, India, November, 2020.

Chiranjit Ray

Research Summary:

In the academic year 2020-2021, my research focused on studying the relation between Siegel modular forms, t-core partitions and the class number of imaginary quadratic fields, and finding infinite families of arithmetic identities, congruences and distributions of several partition functions. Now we give a brief description of two of my projects during the academic year.

In a joint project with M. Roy and S. Yi, we have obtained some congruences between dimensions of the spaces of Siegel cusp forms of degree 2 and the class number $h(-p)$ of $\mathbb{Q}(\sqrt{-p})$. Then obtain connection between the 4-core partition function $c_4(n)$ and dimensions of spaces of Siegel cusp forms of degree 2. Let $\Gamma_0^{(1)}(N) = \left[\begin{smallmatrix} \mathbb{Z} & \mathbb{Z} \\ N\mathbb{Z} & \mathbb{Z} \end{smallmatrix}\right] \cap \mathrm{SL}(2,\mathbb{Z})$. Suppose $8n+5$ is a prime number and k is a positive integer. Then we proved that

$$c_4(n) \equiv \dim_{\mathbb{C}} S_{4k}^{\text{new}}\left(\Gamma_0^{(1)}(8n+5)\right) \pmod 2.$$

In another work, we have studied the divisibility and distribution of the minimal excludant or "mex" function introduced by Andrews and Newman. The minimal excludant of a partition π of n, $mex(\pi)$, is the smallest positive integer which is not a part of π. By restricting to the part of π, Andrews and Newman introduced $moex(\pi)$ to be the smallest odd integer that is not a part of π and $\sigma moex(n)$ to be the sum of $moex(\pi)$ taken over all partitions π of n. We proved that for every positive integer n,

$$\{1 \leq n \leq X : \sigma moex(n) \text{ is even (or odd) integer}\} \geq \alpha \log\log X,$$

where α is positive constant.

Publications:

1. Chiranjit Ray and Rupam Barman, *Arithmetic properties of Andrews' integer partitions with even parts below odd parts*, Journal of Number Theory, **215**, 321-338, (2020).

2. Chiranjit Ray and Kalyan Chakraborty, *Certain eta-quotients and ℓ-regular overpartitions*, The Ramanujan Journal. (accepted) https://doi.org/10.1007/s11139-020-00322-6.

3. D. S. Gireesh, Chiranjit Ray and C. Shivashankar, *A new analogue of t-core partitions*, Acta Arithmetica **199.1**, 1-22, (2021).

4. Kalyan Chakraborty and Chiranjit Ray, *Distribution of generalized mex-related integer partitions*, Hardy-Ramanujan Journal, **43**, 122-128, (2021).

5. Chiranjit Ray, *Divisibility and distribution of 2ℓ-regular overpartitions*, Special Issue - Proceedings of the International Conference on Number Theory and Discrete Mathematics–2020, Journal of Ramanujan Mathematical Society. (accepted)

Preprints:

1. Chiranjit Ray, Manami Roy and Shaoyun Yi, *Congruence relations for dimension of Siegel cusp forms and 4-core partitions*, The Ramanujan Journal (submitted with minor revisions), (arXiv: 2104.09710).

2. Chiranjit Ray, *Divisibility and distribution of mex related integer partitions of Andrews and Newman.* (under review)

3. Chiranjit Ray, *Arithmetic properties and Distribution of ℓ-regular partitions with distinct odd parts.* (under review)

4. Chiranjit Ray, *Arithmetic properties of the Fourier coefficients of Hauptmoduln.* (in preparation)

Conference/Workshops Attended:

1. *Online Conference in Automorphic Forms* (Zoom platform, Time zone: CEST), June 01–05, 2020.

2. *Combinatorial and Additive Number Theory* (Zoom platform, Time zone: EDT), June 01–05, 2020.

3. *Alumni Symposium on Mathematics and Computing–2020*, IIT Guwahati, September 19–20, 2020.

4. *International Conference on Number Theory and Discrete Mathematics–2020*, organized by Ramanujan Mathematical Society and Rajagiri School Of Engineering & Technology, December 11–12, 2020.

Invited Lectures/Seminars:

1. "*Certain eta-quotients and ℓ-regular overpartitions*", Alumni Symposium on Mathematics and Computing–2020, IIT Guwahati, September 19–20, 2020.

2. "*Divisibility and distribution of 2ℓ-regular overpartitions*", International Conference on Number Theory and Discrete Mathematics–2020, organized by Ramanujan Mathematical Society and Rajagiri School Of Engineering & Technology, December 11–12, 2020.

Academic recognition/Awards:

1. Seleceted for NBHM Post Doctoral Fellowship, 2020–21.

Other Activities:

1. Act as a reviewer for Research in Number Theory – Springer.
2. Act as a reviewer for Annals of Combinatorics – Springer.
3. Reviewed several articles for American Mathematical Society- MathSciNet - Mathematical Reviews with reviewer number: 151354.
   Reviewed article number: MR4107768, MR4120750, MR4028985, MR4229493.

Amar Deep Sarkar

Research Summary:

Transformation formula for the reduced Bergman kernel and its application:

First, recall that the Bergman space associated with a domain $D \subset \mathbb{C}$ consists of square integrable holomorphic functions on it. Another important space that has a close relationship with this space is the space of all holomorphic functions whose derivatives are square-integrable with respect to the area measure. This space can be associated with a closed subspace of the Bergman space, which we call the reduced Bergman space. The reduced Bergman space is a reproducing kernel Hilbert space with its reproducing kernel called the reduced Bergman kernel, defined below.

Let D be a domain in $\mathbb{C}$ and ν be a positive measurable function on D such that $1/\nu \in L^{\infty}_{loc}(D)$. The ν-weighted reduced Bergman space and reduced Bergman space of D are defined as

$$\mathcal{D}^{\nu}(D) = \left\{ f \in \mathcal{O}(D) : f = g' \text{ for some } g \in \mathcal{O}(D) \text{ and } \int_D |f(z)|^2 \nu(z) dA(z) < \infty \right\}.$$

and

$$\mathcal{D}(D) = \left\{ f \in \mathcal{O}(D) : f = g' \text{ for some } g \in \mathcal{O}(D) \text{ and } \int_D |f(z)|^2 dA(z) < \infty \right\}$$

respectively. These spaces are reproducing kernel Hilbert spaces. The reproducing kernel of $\mathcal{D}^{\nu}(D)$, denoted by $\tilde{K}^{\nu}_D(\cdot,\cdot)$, is called the weighted reduced Bergman kernel of D with weight ν and reproducing kernel of $\mathcal{D}(D)$, denoted by $\tilde{K}_D(\cdot,\cdot)$, is called the reduced Bergman kernel of D. They satisfy the reproducing property:

$$f(\zeta) = \int_D f(z) \, \overline{\tilde{K}^{\nu}_D(z,\zeta)} \, \nu(z) \, dA(z),$$

for all $f \in \mathcal{D}^{\nu}(D)$ and $\zeta \in D$, and

$$f(\zeta) = \int_D f(z) \overline{\tilde{K}_D(z,\zeta)} dA(z),$$

for all $f \in \mathcal{D}(D)$ and $\zeta \in D$.

Before we state our results, we recall the definition of a proper holomorphic maps and proper holomorphic correspondences. Let D_1 and D_2 be domains in the complex plane $\mathbb{C}$. A holomorphic map $f : D_1 \to D_2$ is called proper if $f^{-1}(K)$ is compact in D_1 whenever K is compact in D_2. Let $V \subset D_2$ denote the set of all critical values of f and $\tilde{V} = f^{-1}(V) \subset D_1$. Note that both V and $\tilde{V}$ are discrete sets. It is well known that $f : D_1 \setminus \tilde{V} \longrightarrow D_2 \setminus V$ is an m-to-1 holomorphic covering map for some $m \in \mathbb{N}$, where m is called the multiplicity of f. We will denote the m local inverses of f on $D_2 \setminus V$ by $\{F_k\}_{k=1}^m$.

Holomorphic correspondences are generalizations of proper holomorphic maps. It is defined as follows. Let $\pi_1 : D_1 \times D_2 \longrightarrow D_1$, $\pi_2 : D_1 \times D_2 \longrightarrow D_2$ be the projections. If V is a complex sub-variety of $D_1 \times D_2$, then consider the associated multi-valued function $f : D_1 \longrightarrow D_2$ given by $f(z) = \pi_2 \pi_1^{-1}(z) = \{w : (z,w) \in V\}$. The map f is

called a holomorphic correspondence and V is called the graph of f. The correspondence f is said to be proper if the projection maps $\pi_1 : V \longrightarrow D_1$ and $\pi_2 : V \longrightarrow D_2$ are proper.

We remark that there exist sub-varieties V_1 and V_2 of D_1 and D_2 respectively, and positive integers p and q such that $\pi_2\pi_1^{-1}$ is locally given by p holomorphic maps on $D_1 \setminus V_1$ which we will denote by $\{f_i\}_{i=1}^p$, and $\pi_1\pi_2^{-1}$ is locally given by q holomorphic maps on $D_2 \setminus V_2$ which we will denote by $\{F_i\}_{i=1}^q$. Note that the sub-varieties V_1 and V_2 are discrete subsets of D_1 and D_2 respectively.

We prove the transformation formula for the reduced Bergman kernels under proper holomorphic correspondences between bounded planar domains. The transformation formula under proper mappings will follow as a corollary. We also show that the transformation formula for the weighted reduced Bergman kernels under proper holomorphic mappings between bounded planar domains. We give an application of this transformation formula; any proper holomorphic map from a bounded planar domain to the unit disc is rational if the reduced Bergman kernel of the domain is rational. The statements of these results are given below.

Result 1. Let D_1 and D_2 be bounded domains in $\mathbb{C}$. If $f : D_1 \longrightarrow D_2$ is a proper holomorphic correspondence, then the reduced Bergman kernels $\tilde{K}_j$'s associated with D_j's, $j = 1, 2$, transform according to

$$\sum_{i=1}^{p} f_i'(z)\tilde{K}_2(f_i(z), w) = \sum_{j=1}^{q} \tilde{K}_1(z, F_j(w))\overline{F_j'(w)},$$

for all $z \in D_1$ and $w \in D_2$, where f_i's and F_j's, and the positive integers p, q are as above.

Result 2. Let D_1 and D_2 be bounded domains in $\mathbb{C}$. If $f : D_1 \longrightarrow D_2$ is a proper holomorphic map, then the reduced Bergman kernels $\tilde{K}_1$ and $\tilde{K}_2$ associated with D_1 and D_2 respectively, transform according to

$$f'(z)\tilde{K}_2(f(z), w) = \sum_{k=1}^{m} \tilde{K}_1(z, F_k(w))\overline{F_k'(w)},$$

for all $z \in D_1$ and $w \in D_2$, where m is the multiplicity of f and F_k's are the local inverses of f.

Result 3. Let D_1 and D_2 be bounded domains in $\mathbb{C}$ and ν be a positive measurable function on D_2 such that $1/\nu \in L^\infty_{loc}(D_2)$. If $f : D_1 \longrightarrow D_2$ is a proper holomorphic map, then the weighted reduced Bergman kernels $\tilde{K}_1^{\nu\circ f}$ and $\tilde{K}_2^{\nu}$ associated with D_1 and D_2 respectively, transform according to

$$f'(z)\tilde{K}_2^{\nu}(f(z), w) = \sum_{k=1}^{m} \tilde{K}_1^{\nu\circ f}(z, F_k(w))\overline{F_k'(w)},$$

for all $z \in D_1$ and $w \in D_2$, where m is the multiplicity of f and F_k's are the local inverses of f.

Result 4. *Suppose D is a bounded domain in $\mathbb{C}$ whose associated reduced Bergman kernel is a rational function, then any proper holomorphic mapping $f : D \to \mathbb{D}$ must be rational.*

Publications:

1. Amar Deep Sarkar, Kaushal Verma, *On the Hurwitz metric,* Kodai Mathematical Journal **44(1)**, 126-136, (2021).

Preprints:

1. Sahil Gehlawat, Aakanksha Jain and Amar Deep Sarkar, *Transformation formula for the reduced Bergman kernel and its application,* https://arxiv.org/abs/2106.07295.

Conference/Workshops Attended:

1. *Virtual Math Fest 2020*, Online, July 2020.

Invited Lectures/Seminars:

1. *A Study of some Conformal Metrics and Invariants on Planar Domains*, Postdoctoral extension talk, Harish-Chandra Research Institute (HRI), Prayagraj (Allahabad), July 2020.

2. *A submultiplicative property of the Carathéodory metric on planar domains*, Virtual Math Fest 2020, Online, July 2020.

Subham sarkar

Research Summary:

In *An equisingular specalisation of an irreducible nodal curves*, We showed that the compactified jacobian an irreducible nodal curve has an equisingular specialsation to the product of the jacobian variety of the normalisation of the given nodal curve and k-many product of rational nodal curve. *A variant oif Ceresa cycle* , We studied the abel -Jacobi image of a null homologus cycle in the moduli space of rank one Generalised parabolic bundle on a nonsingular curve in terms of iterated integrals.

Preprints:

1. Subham Sarkar, A. J. Parameswaran and Sourav Das, *An equisingular specalisation of an irreducible nodal curves.*
2. Subham Sarkar, *A variant oif Ceresa cycle.* (in preparation)

Sourav Sen

Research Summary:

1. *Tame degree functions in arbitrary characteristic:*

   Daniel Daigle had proved a few results on *tameness* of a degree function on an integral domain B containing the field of rationals, which ensures that, under certain hypotheses, a derivation on B gives rise to a homogeneous derivation on an associated graded ring of B induced by the degree function. In this papaer, we have extended Daigle's results to arbitrary integral domains not necessarily containing the field of rationals.

2. *On double Asanuma threefolds: A counter-example to the cancellation problem:*

   Let k be a field.
   T. Asanuma constructed the following family of threefolds given by the equation

   $$\{x^m y + z^{p^e} + t + t^{sp} = 0\},$$

   where characteristic of k is $p > 0$, m, e, s are natural numbers with p^e does not divide sp and sp does not divide p^e. N. Gupta showed that this family of threefolds is not isomorphic to affine three space when $m \geq 2$, thereby providing a counter-example to the Zariski Cancellation Problem in positive characteristic.

   We have considered a family of affine threefolds $T_{d,e}$ defined by a pair of equations

   $$\{x^d y - F(x, z, t) = 0, x^e w - G(x, y, z, t) = 0\},$$

   where d, e are natural numbers, $F(X, Z, T) \in k[X, Z, T]$ is monic in Z and $G(X, Y, Z, T) \in k[X, Y, Z, T]$ is monic in Y.

   Let $F(0, Z, T) = f(Z, T)$ and $G(0, Y, Z, T) = g(Y, Z, T)$. We have named them "double Asanuma threefolds".

   We plan to investigate some important algebro-geometric properties and classify the isomorphism classes of the family of double Asanuma threefolds. Furthermore, we strongly suspect that this family would provide a new counter-example to the Zariski Cancellation problem and hence I am also trying to prove that. Until now we found results regarding the factoriality of this family of threefolds. We have also calculated certain invariants (namely Makar-Limanov invariant and Derksen invariant) regarding the additive group actions on this family of threefolds.

3. *Nijenhuis operators on Hom-Lie algebras:*

   In this joint work with Apurba Das, we have studied Nijenhuis operators on Hom-Lie algebras. We have constructed a graded Lie algebra (via the Hom-analog of the Frölicher-Nijenhuis bracket) whose Maurer-Cartan elements are given by Nijenhuis operators. This allows us to define a cohomology associated to a Nijenhuis operator. As an application, we study formal deformations of Nijenhuis operators that are generated by the above defined cohomology. Finally, we have introduced Hom-NS-Lie algebras as an algebraic structure behind Nijenhuis operators on Hom-Lie algebras.

Publications:

1. Neena Gupta, Sourav Sen, *Tame degree functions in arbitrary characteristic,* J. Pure Appl. Algebra **225**, 15 pp, (2021).

Preprints:

1. Apurba Das, Sourav Sen, *Nijenhuis operators on hom-Lie algebras.*
2. Apurba Das, Sourav Sen, *Weighted covariant bialgebras and related structures.* (in preparation)
3. Sourav Sen, *On double Asanuma threefolds: A counter-example to the Zariski Cancellation Problem.* (in preparation)

Conference/Workshops Attended:

1. *Motivic, Eqivariant and Non-commutative Homotopy Theory*, France, July, 2020.
2. *Virtual Geometric Group Theory*, France, June, 2020.

Academic recognition/Awards:

- Post-doctoral position (1+1 year) offered by IMSc Chennai on 5th January, 2021. Name of the Award, year.

Other Activities:

1. Member of the Core Organizing Committee of 'Virtual Math Fest 2020' from 20th July to 26th July, 2020,
(https://sites.google.com/view/virtualmathfest).
2. Member of the Organizing Committee of 'Motivic Homotopy Theory Seminar',
(https://sites.google.com/view/motivichomotopytheory/home).
3. Member of the Organizing Committee of 'Minicourse on Stable Homotopy Groups of Spheres' by Prof. Dan Isaksen, Dates: April 27, 28 & 29, 2021.

Pramath Anamby

Research Summary:

Theta components of Jacobi forms with level and Fourier coefficients of Siegel cusp forms: The decomposition of a Jacobi form into *theta components* act as a bridge between different type of modular forms. For example, through Fourier–Jacobi coefficients and the Eichler–Zagier map, they give an important map between the Siegel modular forms of degree 2 and the half integral weight modular forms.

In this research work we study the non–vanishing of theta components of Jacobi forms for congruence subgroup $\Gamma_0(N)$. As an application we prove that a non–zero Siegel cusp form F of degree 2 and an odd level N in the Atkin–Lehner type newspace is determined by fundamental Fourier coefficients up to a divisor of N.

Publications:

1. P. Anamby, S. Das and R. Pal *Large Hecke eigenvalues and an Omega result for non-Saito–Kurokawa lifts,* The Ramanujan Journal, 1-13, (2020).

Preprints:

1. P. Anamby, *Theta components of Jacobi forms with level and an application,* (in preparation)

Conference/Workshops Attended:

1. *2020 Quebec-Maine Number Theory Conference*, (virtual), Laval University, Canada, September, 2020.
2. *Online workshop on Algebraic Number Theory*, (virtual), Department of Mathematics, Assam University, Silchar, India, September, 2020.
3. *Chicago Number Theory Day 2020*, virtual number theory conference, June, 2020.

Invited Lectures/Seminars:

1. *Hecke eigenvalues of non Saito–Kurokawa lifts*, International conference on Number Theory and Algebra, IIT-BHU, online, December, 2020.

Rishabh Agnihotri

Research Summary:

In the academic year 2020-21, I have worked on some properties of Fourier coefficients of Hilbert modular form. More specifically, In a joint work with Prof. Kalyan chakraborty, We prove that given any $\epsilon > 0$, a non zero adelic Hilbert cusp form $\mathbf{f}$ of weight $k = (k_1, k_2, \cdots, k_n) \in (\mathbb{Z}_+)^n$ and square-free level $\mathfrak{n}$ with Fourier coefficients $C_{\mathbf{f}}(\mathfrak{m})$, there exists a square-free integral ideal $\mathfrak{m}$ with $N(\mathfrak{m}) \ll k_0^{3n+\epsilon} N(\mathfrak{n})^{\frac{6n^2+1}{2}+\epsilon}$ such that $C_{\mathbf{f}}(\mathfrak{m}) \neq 0$. The implied constant depend on ϵ, F.

In a joint work with Prof. Kalyan Chakraborty and Mr. K. Krishnarjun, we study the sign changes in Fourier coefficients of adelic Hilbert modular form when restricted to square-free integral ideals, integral ideals in an "arithmetic progression". In all these cases, analytic properties of the associated Dirichlet series are derived by comparing them with the L- series of Hilbert modular forms twisted with suitable Hecke characters.

In the following year, I would like to study representation theocratic approach in the the theory of classical modular form as well as for Hilbert modular form.

Publications:

1. Rishabh Agnihotri, K. Chakraborty, *Fourier coefficients of certain Hilbert modular forms*, The Ramanujan Journal (2021). (to appear).
2. Rishabh Agnihotri, K. Chakraborty, *Sign Changes of certain Arithmetical Function at Prime Powers*, Czechoslovak Mathematical Journal (2021). (to appear).
3. Rishabh Agnihotri, Debasish Karmakar, Veekesh Kumar, *A note on some applications of the subspace theorem*, Research In Number Theory, 7, Article No. 14, (2021).

Preprints:

1. Lalit Vaishya, and Rishabh Agnihotri, *A Note on Holomorphic genralized eta quotient*. (submitted)

Conference/Workshops Attended:

1. Online workshop on Modular Form, IIT Guwahati, Dec 14 - Dec 19, 2020.
2. Online International conference on Number Theory and Algebra, IIT BHU, Varanasi, December 2020.
3. Online A.I.S on Commutative Algebra, IIT Gandhinagar, Jan-May, 2021.
4. Online A.I.S on Local Fields, HRI Prayagraj, Jan - May, 2021.

Invited Lectures/Seminars:

1. *Fourier coefficients of certain Hilbert modular forms,* International conference on Number Theory and Algebra, IIT BHU, Varanasi, December 2020.

Kushal Bhowmick

Research Summary:

In the academic year 2020-21, I focused on the arithmetic aspects of elliptic curves. Understanding the structure of the set of rational points on an elliptic curve has been an aim in number theory for over a century. It has connections to open problems buried in antiquity, such as the congruent number problem. The famous Mordell-Weil theorem established an analogy between the rational points on an elliptic curve and the unit group of algebraic integers in an number field. I learnt basic aspects of modular forms, L-series and the Hasse-Weil L-fuction associated to an elliptic curve. The Birch and Swinnerton-Dyer (BSD) conjecture which predicts the interrelation between the rank of an elliptic curve and the associated Hasse-Weil L-fuction , is analogous to the class number formula. For an elliptic curve over Q, one can associate a weight two modular form (Modularity conjecture by Wiles). Now one can also construct a Drinfeld modular form over function field. In the following year, I would like to continue my project on Drinfeld modular form over function field.

Conference/Workshops Attended:

1. *Virtual Math Fest*, India, July, 2020.
2. *Advanced Instructional Course on Commutative Algebra*, India, Jan-May, 2021.

Academic recognition/Awards:

- Harish-Chandra Memorial Award, 2021.

Priyanshu Chakraborty

Research Summary:

In the academic year 2020-2021, I have studied some papers related to toroidal Lie algebras, Virasoro Lie algebras, Witt algebras and loop algebras related to some well known Lie algebras. I have completed two work, one of which is related to loop of toroidal Lie algebras (partially done in this academic year) and other related to loop of Witt algebras.

Preprints:

1. Priyanshu Chakraborty, Punita Batra, *Classification of irreducible integrable representations of loop toroidal Lie algebras,* arXiv:2007.06415.

2. Priyanshu Chakraborty, S. Eswara Rao, *Partial classification of irreducible modules for loop-Witt algebras,* arXiv:2105.03722.

Srijonee Shabnam Chaudhury

Research Summary:

I am working on quadratic forms, specially on sum of squares and Pythagorus numbers in number fields. The study of particular quadratic forms dates back many centuries. It ranges from Lagrange's four square theorem in seventeenth century to Hilbert's twelfth problem in twentieth century. In my papers I have tried to show that every algebraic integer satisfying some special properties, can be written as sum of integral squares. Also in some cases I gave an upper bound of Pythagorus number of the ring of integers of that field. I have worked on some non-totally real number fields and on totally real multi-quadratic fields.

I am giving precisely the extract of my work below.

1. Let K be any non-totally real number field and $\mathcal{O}_K$ be its ring of integer. Let us define m_K to be the smallest positive integer such that every element of $m_K\mathcal{O}_K$ can be written as sum of integral squares. I have given an upper bound of m_K for complex bi-quadratic, complex multi-quadratic and cyclotomic fields. Furthermore, l have given the Pythagoras number of $m_K\mathcal{O}_K$ of the above mentioned number fields, depending on the minimal number of squares required to represent -1 in $\mathcal{O}_K$.

2. Let $K = \mathbf{Q}(\sqrt{m}, \sqrt{n})$ be a real bi-quadratic field, where m and n are two distinct, positive, square-free integers and $\mathcal{O}_K^+$ be the set of all totally positive integers in K. I have shown that for every real bi-quadratic field K there exist an integer s_0 depending on m, n such that for all $s \leq s_0$ every element of $s\mathcal{O}_K^+$ can not be written as sum of integral squares. I have also proved that, there exist an integer s_0 depending on m and n such that every element of $s\mathcal{O}_K^+$, for any $s \geq s_0$, can be written as diagonal quadratic form with co-efficients 1 or -1. Furthermore, I have given a necessary and sufficient condition under which a totally positive integer of K can be written as a product of two totally positive integers of its quadratic sub-fields. Using this, I obtain a positive integer s_0 depending on m, n such that for any $\{s_1, s_2\} \geq s_0$, and for any α satisfying the condition, $s_1 s_2 \alpha$ can be written as sum of six integer squares.

Preprints:

1. Srijonee Shabnam Chaudhury, *Sum of Integral Squares in Some Non-Totally Real Number Fields.* (in preparation)

2. Srijonee Shabnam Chaudhury, *Sums of Squares and Diagonal Quadratic form on Real Bi-quadratic Fields.* (in preparation)

Conference/Workshops Attended:

1. *Virtual Math Fest* , India , July 20-26, 2020. (Virtual)

2. *3rd Chennai-Tirupati Number Theory Conference*, India, August 26-28, 2020. (Virtual)

3. *International Conference of Number Theory and Discrete Mathematics*, India, December 11-14, 2020. (Virtual)

4. *International Conference of Number Theory and Algebra*, India, December 22-23, 2020. (Virtual)

Shubham Gupta

Research Summary:

Let R be a commutative ring with unity and $n \in R$. A set $\{a_1, a_2, \cdots, a_n\}$ is called Diophantine $m-$tuples in R with the property $D(n)$ if $a_i a_j + n = \alpha_{ij}^2$, for all $1 \leq i < j \leq n$, where $a_i, a_j \in R \setminus \{0\}$ and $\alpha_{ij} \in R$. A conjecture states that there exist a quadruple with the property $D(n)$ if and only if n can be written as the difference of two squares in R, up to finitely many exceptions. Many authors have checked the validity of this conjecture in certain commutative rings. But, if we take a commutative ring $Z[\sqrt{4r+2}]$ with equations $x^2 - (4r+2)y^2 = -1$ and $x_1^2 - (4r+2)y_1^2 = 6$ are solvable in integers, then for this type of rings, above conjecture fails. This is the joint work with Prof. K. Chakraborty and Dr. A. Hoque.

The arithmetic of elliptic curves is a very useful tool for analyzing Diophantine m-tuples. Motivated by this, I have read the theory of elliptic curves from J. H. Silverman's two books. I have also studied some papers related to rank, torsion point, twists of an elliptic curve. As an application of the elliptic curve, I have looked at some papers related to congruent numbers and Diophantine m-tuples.

Publications:

1. S. Gupta, *S. Gupta, D(-1) tuples in imaginary quadratic fields,* Acta Math. Hungar. (to appear)

Preprints:

1. K. Chakraborty, S. Gupta, A. Hoque, *Existence Of Infinitely Many $D(n)$-Quadruples in $Z[\sqrt{4r+2}]$.* (in preparation)

2. S. Gupta, M. Mishra, *On the Proportion of Positive Rank Twists of Elliptic Curves.* (submitted)

Conference/Workshops Attended:

1. *Modular Forms (2020)*, India, December, 2020.

2. *International Conference of Number Theory and Discrete Mathematics*, India, December, 2020.

Debasish Karmakar

Research Summary:

During the academic year, the following problems have been worked out.

1. Let $f(z) = \sum_{n=0}^{\infty} a_n z^n$ be a power series with integer coefficients and converging in the disc $D = \{z : |z| < R\}$ for some $R > 0$. In 1985, Laohakosol proved, using Ridout theorem, that the largest prime factors of partial sums of $f(b)$ for a rational number $0 < |b| < R$ is unbounded, if $f(b)$ is a non-zero algebraic number.

   In this work, we prove similar results for other approximation of $f(b)$ using the subspace theorem. We have also provided the number field analogue of Laohakosol's result.

2. Let $\beta > 1$ be a real algebraic integer such that all its other conjugates have absolute value less than or equal to 1. For any positive integers $a_1 < a_2 < \ldots < a_m$, we have proved that the numbers

$$1, \quad \sum_{n=1}^{\infty} \frac{1}{\beta^{a_1 n^2}}, \quad \sum_{n=1}^{\infty} \frac{1}{\beta^{a_2 n^2}}, \quad \ldots, \quad \sum_{n=1}^{\infty} \frac{1}{\beta^{a_m n^2}}$$

   are $\mathbb{Q}(\beta)$-linearly independent. As a consequence, we observe that for every integer $n \geq 1$, the m- Jacobi theta values

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

   are $\mathbb{Q}(\beta)$-linearly independent with 1, where $\tau_n = \frac{i \log \beta}{\pi} + 2n$.

3. A set $A \subseteq \mathbb{N}$ is called syndetic if there exists $l \in \mathbb{N}$ such that A intersects every set of l consecutive natural numbers. In 2006, Beiglböck et al. raised a question of whether a syndetic set contains arbitrarily long geometric progressions. In 2019, Glasscock et al. investigated an infinite family of syndetic sets containing arbitrarily long geometric progressions.

   In this work, we describe some new families of syndetic sets containing geometric progressions of arbitrary length. Moreover, we have deduced some combinatorial properties of a syndetic set A from the ratio set $R(A)$.

Ongoing Work:

4. For a finite group G, the Davenport constant $D(G)$ is defined to be the smallest natural number k such that any sequence in G of length k has a non-empty product-one subsequence. We also denote by $s(G)$ (or $E(G)$ respectively) the smallest integer k such that every sequence in G of length k has a product-one subsequence of length $\exp(G)$ (or $|G|$ respectively). For a finite abelian group, the exact values of these constants are known in many cases.

   The study of sequences and associated invariants for non-abelian groups is a recent topic. The exact values of the constants are known only for few non-abelian groups, for example, Dihedral groups and Dicyclic groups.

The Harborth constant $g(G)$ of a finite group G is the smallest integer k such that any subset of G of size k contains a product-one set of length $\exp(G)$. Recently, for a particular subclass of Metacyclic groups, the exact value of the Harborth constant is established.

We wish to study the Davenport constant and the Harborth constant for a certain class of Metacyclic groups. It is a joint work with Subha Sarkar.

Publications:

1. Rishabh Agnihotri, Debasish Karmakar, Veekesh Kumar, *A note on some applications of the subspace theorem*, Research In Number Theory, 7, Article No. 14, (2021).

Preprints:

1. Debasish Karmakar, Veekesh Kumar, R. Thangadurai, *Linear independence of special values of Jacobi-theta constants*. (submitted)
2. Debasish Karmakar, Bhuwanesh Rao Patil, *Multiplicative patterns in syndetic sets*. (submitted)
3. Debasish Karmakar, Subha Sarkar, *Davenport constant and the Harborth constant for a certain class of Metacyclic groups*. (in preparation)
4. Debasish Karmakar, Veekesh Kumar, *A transcendence criterion on sum of two infinite products*. (in preparation)

Conference/Workshops Attended:

1. *TMC-IITB-ICTS Distinguished Lecture Series on Mathematics*, India, October, 2020 - February, 2021.
2. *International Conference on Special Functions & Applications*, India, December 22 - 23, 2020.
3. *35th Annual Conference of the Ramanujan Mathematical Society*, India, December 28 - 30, 2020.
4. *Online SageMath Workshop*, IIT Jodhpur, February 15 - 18, 2021.
5. *Balu Fest (Conference on Number Theory)*, IMSc, Chennai, March 12 - 18, 2021.
6. *Name of the symposium or workshop*, Country, month, year.

Invited Lectures/Seminars:

1. *A note on some applications of the subspace theorem*, 35th Annual Conference of the Ramanujan Mathematical Society, Central University of Rajasthan, India, December, 2020.

2. *A note on some applications of the subspace theorem*, International Conference on Special Functions & Applications, Babu Banarsi Das University, India, December, 2020.

Academic recognition/Awards:

- Infosys Scholarship, 2020 - 2021.

Other Activities:

1. Tutor at Advanced Instructional Course in Local Arithmetic, January 18 - May 21, 2021.
2. Took several online classes for undergraduate students.
3. Taught a few post-graduate students for National Eligibility Test.

Rahul Kaushik

Research Summary:

Let G be a finite group and $K(G) := \{[a, b] \mid a, b \in G\}$. It is well known that the commutator subgroup $\gamma_2(G)$ of G is generated by $K(G)$. A natural question that has attracted the attention of many mathematicians over last many many decades is whether $\gamma_2(G)$ is equal to $K(G)$ or not for groups G in a given class of groups. It has been proved that $K(G) = \gamma_2(G)$ for all alternating groups $G = A_n$, $n \geq 5$. Later it was proved that, it holds for all finite simple groups as well. There exist groups of order 96, for which $K(G) \neq \gamma_2(G)$, and these are smallest such groups.

This problem has been studied for finite p-groups also. If we take order of group G in consideration, then it has been established that $K(G) = \gamma_2(G)$ for all groups of order atmost p^5, where p is an odd prime, and for groups of order upto 2^6. There exists groups of order p^6 and 2^7, for which $K(G) \neq \gamma_2(G)$. Now if we take rank of $\gamma_2(G)$ in consideration, then it is proved that if rank of $\gamma_2(G)$ is atmost 3, then $K(G) = \gamma_2(G)$. No more generalisation is possible in terms of the rank of the commutator subgroup of finite p-groups. In literature there exist groups G of order p^6, p odd, such that $\gamma_2(G)$ is elementary of order p^4, and groups of order 2^8, with $\gamma_2(G)$ is elementary abelian of order 16, but $K(G) \neq \gamma_2(G)$. Earlier, in 2020, in joint work with my supervisor Prof. Manoj Kumar Yadav, I gave classification of finite p-groups G (upto isoclinism) with $\gamma_2(G)$ of order p^4 and exponent p such that $K(G) \neq \gamma_2(G)$. As a result, a clear characterisation of groups G of order p^6 such that every element of $\gamma_2(G)$ is not a commutator. The theory developed so far seems revealing no patterns. So it is highly desirable to investigate more classes of finite p-groups. Thus, in 2021, in joint work with my supervisor Prof. Manoj Kumar Yadav, I gave the classification of groups G of order p^7, p prime, in which $K(G) \neq \gamma_2(G)$.

Publications:

1. R. Kaushik and M. K. Yadav, *Commutators and commutator subgroup of finite p-groups*, J. Algebra **568** (2021), 314-348.

Preprints:

1. Rahul Kaushik and Manoj K. Yadav, *Commutators in groups of order p^7*, preprint, arXiv:2106.07205.

Conference/Workshops Attended:

1. $86th$ Annual Conference of The Indian Maths Society, December 17-20, 2020.
2. International conference on Number Theory and Algebra, IIT BHU, December 22-23, 2020.
3. 35th Annual Conference of the Ramanujan Mathematical Society, Central University of Rajasthan, December 28-30, 2020.
4. Group Theory Sangam Seminar Series, January-May, 2021.

5. Group Theory Sangam Conference, June 1-4, 2021.

Other Activities:

1. Delivered a contributed talk, *Commutators and commutator subgroup of finite p-groups*, in $86th$ Annual Conference Of The Indian Maths Society, VIT Vellore, December 17-20, 2020.

2. Delivered a contributed talk, *Commutators and commutator subgroup of finite p-groups*, International conference on Number Theory and Algebra, IIT BHU, December 22-23, 2020.

3. Delivered a contributed talk, *Commutators and commutator subgroup of finite p-groups*, 35th Annual Conference of the Ramanujan Mathematical Society, Central University of Rajasthan, December 28-30, 2020.

Parul Keshari

Research Summary:

The main focus of these semesters was to understand fundamentals of Quiver representations, notions of Tannakian categories, and its relation to the algebraic groups. Along the way, we have been trying to extend some results by M. V. Nori, on the representations of fundamental group, to vector bundles with extra structures.

We also studied the abelian category of (twisted) quiver sheaves and notions of stability in some particular cases of these categories.

Other Activities:

1. Attended English language course for scientific writing organised by HBNI, March-April, 2021.

Krishnarjun K

Research Summary:

Modular forms are classical objects whose Fourier coefficients carry important arithmetic information. Furthermore, their study has been a centerpiece of number theory for over a century. There are many conjectures which are still open. Research into the behaviour of these Fourier coefficients has been carried out. More precisely we investigated the 'sign change' of these Fourier coefficients of Hilbert modular new forms and the generalized divisor problem for classical modular forms of higher level.

Furthermore, Hecke characters are $GL(1)$ analogues of modular forms and the associated L functions have important representation theoretic interpretations. These avenues were also explored and new results were obtained.

Currently, we are investigating the intricate connection between the Fourier coefficients of half integral weight modular forms and the class numbers of imaginary quadratic number fields. Furthermore, from the work of Waldspurger it follows that these coefficients also carry information regarding the conjecturally finite Tate-Shafarevic groups. We hope to extend some classical non divisibility results in this area.

Publications:

1. Krishnarjun K, *Generalized divisor problem for new forms of higher level,* Czechoslovak Mathematical Journal. (to appear)

Preprints:

1. Rishabh Agnihotri, Kalyan Chakraborty, Krishnarjun K, *Sign Changes in Restricted coefficients of Hilbert Modular Forms*

2. Kalyan Chakraborty, Krishnarjun K, *On Moments of Non-Normal number fields,* arXiv : https://arxiv.org/abs/2104.04752v1

Conference/Workshops Attended:

1. *NCM Workshop on Modular Forms (Online) organized by IIT Guwahati*, India, December, 2020.

2. *Recent advances in Mathematics and related areas, International conference commemorating Srinivasa Ramanujan organized by Kerala School of Mathematics in assication with NBHM*, India, December, 2020.

Visits to other Institutes:

1. Kerala School of Mathematics, Kozhikode, India, December, 2020.

Arup Kumar Maity

Research Summary:

Let m be a measurable function. m is said to be a multiplier if the corresponding operator T is defined by

$$\widehat{Tf} = m\widehat{f}, f \in \mathcal{S}(\mathbb{R}^n)$$

is L^p to L^q bounded for some p and q. In this case we say $m \in M_p^q$. Our main aim is to classify the space M_p^q. We have started to work in this direction. Hahn has shown that if $f \in L^p$ and $g \in L^{p'}$ (p and p' are conjugate exponent) then convolution of f and g are multiplier belongs to space M_r^r where $\frac{1}{p} + \frac{1}{r} = \frac{3}{2}$. We are showing that what happens when convolution is replaced by twisted convolution. Note that here dimension is always even. In this case we get example of new multiplier belongs to some other multiplier space. They are not in general functions they are tempered distribution. We have done similar kind of results for Weyl multiplier.

Preprints:

1. A. Maity, P.K. Ratnakumar; *A note on L^p-L^q multiplier.* (tentative)

Conference/Workshops Attended:

1. *Workshop on Harmonic Analysis*, India, December, 2020. (online)
2. *Advances in Applied Probability 2*, India, January, 2021. (online)

Mohit Mishra

Research Summary:

In the academic year 2020-2021, I worked on the structure of the class group of real cyclotomic fields. The class group of real cyclotomic fields are quite small as compared to the class group of cyclotomic fields and very less is known about them. In a joint work with Prof. Lawrence Washington and Prof. Rene Schoof, we proved that: every finite abelian group occurs as a subgroup of the class group of infinitely many cyclotomic fields.

I also worked on the Hilbert class field tower problem and showed the existence of infinitely many number fields of higher degree admitting an infinite Hilbert class field tower and ramified at certain number of primes.

I also read elliptic curves and some papers related to congruent numbers, rank, torsion points and twists of elliptic curves. In the following academic year, I am planning to study the advance topics in elliptic curves.

Publications:

1. Mohit Mishra, Lawrence Washington and Rene Schoof, *Class group of real cyclotomic fields,* Monatsh. Math. **195**, 489-496, (2021).

Preprints:

1. Mohit Mishra, *Infinite Hilbert class field tower,* submitted for publication 2020.
2. Mohit Mishra, *Lower bound for class number of certain real quadratic fields,* submitted for publication 2020.

Conference/Workshops Attended:

1. Online workshop on Modular forms, IIT Guwahati, 14 – 19 December, 2020.
2. Online international conference on Number theory and Algebra, IIT BHU, Varanasi, December, 2020.
3. Online A.I.S on Local Fields, HRI Prayagraj, January - May, 2021.

Nishant

Research Summary:

In the academic year 2020-2021, I worked on the extensions of skew braces. Skew-braces corresponds to the non-degenerate solution of Yang-Baxter equation. More precisely we worked on the extension of skew brace by a trivial brace. We developed the full cohomology for extensions which splits at the level of " $+$ ". and second cohomology and well's type exact sequence for non-split case .

I also worked on the general extensions of skew braces and classify all the split extensions of skew braces in terms a semi-direct product defined by us. We also establish a bijection between between $Ext(H, I)$ and $Ext(H, soc(I))$ When I is trivial skew brace(need not abelian).

I also read the cohomology theory of linear cycle sets and which are particular case of skew braces. In the following academic year , I am planning to study the module theory over braces and try to develop its representation theory.

Preprints:

1. Nishant, Manoj K Yadav *Cohomology, Extension and Automorphism of Skew-braces,* arXiv:2102.12235.

Conference/Workshops Attended:

1. Online Group Theory Sangam seminar series April - May, 2021

Souvik Pal

Research Summary:

In the academic year 2020-2021, I mainly worked on two projects, which are based on classifying irreducible $quasi\text{-}finite$ modules (quasi-finite modules mean modules with $finite\text{-}dimensional$ weight spaces) for the untwisted as well as for the twisted full toroidal Lie algebras. A brief summary of my projects are given below.

In 2018, S. Eswara Rao and P. Batra classified all possible irreducible $integrable$ quasi-finite representations of $non\text{-}zero\ level$ of the $twisted$ full toroidal Lie algebras. In a joint work with S. Eswara Rao, we addressed the mutually exclusive problem and henceforth classified all the $level\ zero$ irreducible $integrable$ quasi-finite modules over the $twisted$ full toroidal Lie algebras. This ultimately gives us all the $simple\ objects$ in the category of integrable quasi-finite representations of the twisted full toroidal Lie algebras.

In a current ongoing project, I am trying to classify all the irreducible quasi-finite (but not necessarily integrable) modules over the $untwisted$ full toroidal Lie algebras.

Publications:

1. Souvik Pal, *Integrable modules for graded Lie tori with finite-dimensional weight spaces*, Journal of Pure and Applied Algebra **225**, (2021).

2. Souvik Pal, S. Eswara Rao, *Classification of level zero irreducible integrable modules for twisted full toroidal Lie algebras*, Journal of Algebra **578**, 1-29, (2021).

Conference/Workshops Attended:

1. *6th Biennial International Group Theory Conference–2021 (6BIGTC-2021)*, India, March 04–06, 2021.

2. *Workshop on Macdonald polynomials*, India, April 5 - May 20, 2021.

3. *Springfest in honour of Vera Serganova*, Israel, Apr 25 - May 6, 2021.

Invited Lectures/Seminars:

1. *Level zero integrable modules for twisted full toroidal Lie algebras*, 6th Biennial International Group Theory Conference–2021 (6BIGTC-2021),
organized (online) by Vellore Institute of Technology (Vellore), India,
March 04–06, 2021.

2. *Level zero integrable modules with finite-dimensional weight spaces for the graded Lie tori*, ARCSIN (Algebra, Representations, Combinatorics and Symmetric functions in India) Seminar Series, jointly organized (online) by Indian Institute of Science (Bangalore), Indian Institute of Technology (Kanpur), Institute of Mathematical Sciences (Chennai), India, March 26, 2021.

3. *Level zero integrable modules for the graded Lie tori with finite-dimensional weight spaces*, Séminaire d'algébre, organized (online) by Université Laval, Canada, May 28, 2021.

Academic recognition/Awards:

- Harish-Chandra Memorial Award, 2020.

Gopinath Sahoo

Research Summary:

We have been trying to classify compactly generated t-structures of the derived category of sheaves of modules of a quasi compact quasi separated scheme - along the lines of eariler works of Hopkins-Neeman, Thomason and Alonso-Jeremías-Saorín.

Hopkins-Neeman classification provides a bijection between thick triangulated subcategories of the derived category of perfect complexes of a commutative Noetherian ring R and the specialization closed subsets of the spectrum of R. Later, Thomason extended this classification to the case of quasi-compact quasi-separated schemes. He made a crucial observation that in the situation of schemes one has to take the thick triangulated subcategories that are tensor compatible for the classification to hold.

In 2010, Alonso-Jeremías-Saorín, considered the classification of compactly generated t-structures of the unbounded derived category of complexes of R-modules of a commutative Noetherian ring. A t-structure is determined by its aisle, and aisles are suitable coreflective subcategories which are close to triangulated subcategories but in general not triangulated.

Our goal is to extend the work of Alonso-Jeremías-Saorín to the case of quasi-compact quasi-separted schemes. Keeping the observation of Thomason in mind, we have been able to find the correct tensor compatibilitly condition for t-structures, and have made some progess in getting the classification.

Santanu Tantubay

Research Summary:

In the academic year 2020-2021, I studied the structure of Extended Affine Lie Algebras. In a joint work with my supervisor Prof. Punita Batra, I classified irreducible integrable modules for twisted toroidal extended affine Lie algebras with finite dimensional weight spaces where the zero degree center acting trivially.

I am reading the modules for the derivations of rational quantum torus and working on a problem related to that.

Preprints:

1. Santanu Tantubay, Punita Batra *Classification of irreducible integrable modules for Extended Affine Lie Algebras with center acting trivially,* arXiv:2105.02000.

Lalit Vaishya

Research Summary:

1. *Estimate for the shifted convolution sums involving Fourier coefficients of half-integral weight cusp forms* (Joint work with Abhash Kumar Jha):

   In this work, we obtain the estimate for the following shifted convolution sum:

   $$S(f,g,b) := \sum_{n\geq 1} a_f(n+b)a_g(n)G(n)$$

   where f and g both are half-integral weight cusp forms with the Fourier coefficients $a_f(n)$ and $a_g(n)$ respectively of distinct weight for the congruence group $\Gamma_0(4N)$ and G is a smooth function with the support in $[\frac{X}{2}, \frac{5X}{2}]$ satisfying $G^{(p)}(x) \ll (\frac{X}{P})^{-p}$ for all integer $p \geq 0$, where $1 \leq P \leq X$. by using Poincaré method. Precisely, we obtain the following estimate:

   $$S(f,g,b) \quad = \quad \sum_{n\geq 1} a_f(n+b)a_g(n)G(n) \quad \ll_{\epsilon,f,g,b,G} \quad X^{\frac{3}{4}+\epsilon}P^{\frac{3}{2}}. \tag{2}$$

2. *Average estimates and sign change of Fourier coefficients of Hecke eigenforms at integers represented by binary quadratic forms of fixed discriminant*:

   In this work, we generalise the work of S. Zhai to the case where the sum of two squares is replaced by integers represented by a primitive integral positive definite binary quadratic form of fixed negative discriminant D with the class number $h(D) = 1$. We also give an estimate when $r = 1$. Precisely, we prove an estimate for the following sums: for $1 \leq r \leq 8 \quad \text{and} \quad x \geq 1$,

   $$\sum_{\substack{\underline{x}\in\mathbb{Z}^2 \\ Q(\underline{x})\leq x}} (\lambda_f(Q(\underline{x})))^r, \tag{3}$$

   where $\lambda_f(n)$ is the n^{th} normalised Fourier coefficients of a Hecke eigenform $f \in S_k(SL_2(\mathbb{Z}))$ and $Q(\underline{x})$ is a primitive integral positive definite binary quadratic form (reduced form) of fixed negative discriminant D with the class number $h(D) = 1$ given by $Q(\underline{x}) = ax_1^2 + bx_1x_2 + cx_2^2$, where $\underline{x} = (x_1, x_2) \in \mathbb{Z}^2$, $a, b, c \in \mathbb{Z}$ with $\gcd(a, b, c) = 1$, with fixed discriminant $D = b^2 - 4ac < 0$.

   Moreover, we use these estimates to obtain a result on sign change of sequence of the Fourier coefficients of the Hecke eigenforms supported at integers represented by a primitive integral binary quadratic form of fixed discriminant $D < 0$ with class number $h(D) = 1$. In this work, we improved our previous result on sign change.

3. *A note on generalised eta quotient* (Joint work with Rishabh Agnihotri):

   For fixed positive integers k and N, there are only finitely many holomorphic eta quotients of weight k for the congruence subgroup $\Gamma_0(N)$. In this article, we obtain finiteness result for holomorphic generalized eta quotients of weight k on

$\Gamma_1(p)$ where k is a positive integer and p is a prime number and the generalized Dedekind eta function is defined by

$$\eta_{\delta,g}(\tau) := e^{\pi i P_2(\frac{g}{\delta})\delta\tau} \prod_{\substack{m>0 \\ m\equiv g \pmod{\delta}}} (1-q^m) \prod_{\substack{m>0 \\ m\equiv -g \pmod{\delta}}} (1-q^m)$$

where δ and g be positive integers, $q = e^{2\pi i\tau}$, $\tau \in \mathbb{H}$ and $P_2(t) = \{t\}^2 - \{t\} + \frac{1}{6}$ is the second Bernoulli polynomial and $\{t\}$ denotes the fractional part of a real number t. We also obtain a criterion for two holomorphic generalised eta quotients which represent the same one.

Publications:

1. Abhash Kumar Jha and Lalit Vaishya, *Estimates of shifted convolution sums involving Fourier coefficients of Hecke Maass eigenform*, Int. J. Number Theory, (2021). (to appear) https://doi.org/10.1142/S1793042121500524

2. Lalit Vaishya, *Signs of Fourier coefficients of cusp forms at integers represented by an integral binary quadratic form*, Proc. of Indian Acad. Sci. (Math. Sci.), (2021). (accepted)

Preprints:

1. Abhash Kumar Jha and Lalit Vaishya, *Estimate for the shifted convolution sums involving Fourier coefficients of half-integral weight cusp forms.* (submitted)

2. Lalit Vaishya, *Average estimates and sign change of Fourier coefficients of Hecke eigenforms at integers represented by binary quadratic forms of fixed discriminant.*

3. Rishabh Agnihotri and Lalit Vaishya, *A note on generalised eta quotient,* (submitted)

Conference/Workshops Attended:

1. Conference on Number Theory (Balu Fest- 2021), March 12-18, 2021, Institute of Mathematical Sciences Chennai, India.

2. International Conference on Number Theory and Algebra, December 22-23, 2020, Dept of Mathematical Sciences, IIT (BHU) Varanasi, India.

3. Conference on Recent Advances in Mathematics, December 18-22, 2020, Kerala School of Mathematics, Kozhikode, India.

4. Workshop on Algebraic Number Theory, Aug 31- Sept 5, 2020, Dept. of Mathematics, Assam University, Silchar, India.

5. Virtual Math Fest-2020 (online), July 20-26, 2020, Institute of Mathematical Sciences, Chennai, India.

Invited Lectures/Seminars:

1. *Signs of Fourier coefficients of cusp forms at integers represented by an integral binary quadratic form.* Virtal Math Fest 2020 (online), Institute of Mathematical Sciences, Chennai, India, July 20-26, 2020.

2. *Signs of Fourier coefficients of cusp forms at integers represented by an integral binary quadratic form.* International conference on Number Theory and Algebra (online), IIT (BHU), Varanasi, India, Dec 22-23, 2020.

Academic Report - Physics

Anirban Basu

Research Summary:

My research has focussed on analyzing properties of string invariants that arise at genus one and two in the low momentum expansion of string amplitudes in the effective action of superstring theory. This has yielded eigenvalue equations satisfied by these string invariants, as well as relations between them. I have also studied contributions from worldsheet (anti)instantons to BPS interactions in the effective action of type II string theory in eight dimensions.

Publications:

1. Anirban Basu, *Integrating simple genus two string invariants over moduli space,* JHEP 03 **03**, 158, (2021).

2. Anirban Basu, *Relations between elliptic modular graphs,* JHEP **12**, 195, (2020), JHEP **03**, 061 (erratum), (2021).

3. Anirban Basu, *Poisson equations for elliptic modular graph functions,* Phys.Lett.B **814**, 136086, (2021).

4. Anirban Basu, *Zero mode of the Fourier series of some modular graphs from Poincare series,* Phys.Lett.B **809**, 135715, (2020).

5. Anirban Basu, *Worldsheet (anti)instanton bound states in type II on T^2,* JHEP **04**, 168, (2020).

Preprints:

1. Anirban Basu, *Poisson equation for genus two string invariants: a conjecture,* arXiv:2101.04597.

Invited Lectures/Seminars:

1. *String Theory and Quantum Gravity*, Dr. Subhash Science College, Junagadh, June, 2020.

Tapas Kumar Das

Research Summary:

I have been working on various aspects of black hole astrophysics and on emergent spacetime.

Publications:

1. Pratik Tarafdar, Susovan Maity, and Tapas K. Das, *Influence of flow thickness on general relativistic low angular momentum accretion around spinning black holes,* Physical Review D **103**, 023023, (2021).

Preprints:

1. Susovan Maity, Md. Arif Shaikh, Pratik Tarafdar, and Tapas K. Das, *Carter-Penrose diagrams for emergent spacetime in axisymmetrically accreting black hole systems,* arXiv:2106.07598.

2. Karan Fernandes, Susovan Maity, and Tapas K. Das, *Dynamical analogue spacetimes in non-relativistic flows,* arXiv:2106.07618.

Visits to other Institutes:

1. Visited Prof. Sankhasubhra Nag from Sarojni Naidu College, Kolkata, and Prof. Subir Ghosh from Indian Statistical Institute, Kolkata, during January - February, 2021.

Other Activities:

1. Ph.D. Thesis Supervision

   (a) Mr. Praik Tarafdar completed (in 2021) his Ph.D. thesis (and received his degree) under the joint supervision of myself and Prof. Amitava Lahiri of S. N. Bose National Centre for Basic Sciences, Kolkata, India.

Aditi Sen De

Research Summary:

During 2020-21, the main directions of quantum technologies that I have worked on include designing efficient quantum network for information transmission which is robust against noise, characterization of quantumness in multipartite states, investigations of quantum features in the dynamics of quantum many-body systems, understanding multimode correlation in continuous-variable systems.

Towards establishing the quantum network, we design a global and optimal local measurement-based protocol in one- and two-dimensional lattices by which any two or more prefix sites can be connected via entanglement from several copies of bipartite noisy entangled states. In this respect, complete characterization of a noisy multipartite quantum state in terms of entanglement requires full knowledge of how the entanglement content in the state is affected by the spatial distribution of noise in the state. Specifically, we find that if the measurement basis in the protocol of computing localizable entanglement and the basis of the Kraus operator representing the local noisy channel do not commute, the information regarding the noise is retained in the system even after the qubit is traced out after measurement.

To design quantum technologies in physical systems like cold atoms, ion traps, it is important to characterize the many-body system. We study quantum correlations of the dynamical state of the alternating field transverse XY spin chain with Dzyaloshinskii-Moriya interaction. We report that multipartite entanglement of the evolved state has the potential to detect interesting phenomena like a dynamical quantum phase transition in this system. Moreover, we seek suitable information-theoretic quantities, which during dynamics can give prominent response to the quantum critical region in the transverse field quantum XY model.

Although quantum information protocols were originally proposed for discrete variable systems and they have been implemented, e.g., by using the polarization degree of freedom of photons, there are some shortcomings. It turns out that continuous-variable (CV) systems can overcome certain difficulties and hence implementing quantum information processing tasks by using CV states in infinite-dimensional systems can be important. Recently, we propose an efficient way to quantify entanglement in multimode CV states, both for Gaussian as well as non-Gaussian states.

Publications:

1. R. Gupta, S. Gupta, S. Mal and A. Sen(De), *Performance of Dense Coding and Teleportation for Random States –Augmentation via Pre-processing*, Phys. Rev. A **103**, 032608 (2021).

2. K. Sen, C. Srivastava, S. Mal, A. Sen(De), and U. Sen, *Detection loophole in measurement-device-independent entanglement witness* , Phys. Rev. A **103**, 032415 (2021).

3. C. Srivastava, S. Mal, A. Sen(De), and U. Sen, *Sequential measurement-device-independent entanglement detection by multiple observers*, Phys. Rev. A **103**, 032408 (2021).

4. R. Banerjee, S. Ghosh, S. Mal, and A. Sen(De), *Spreading Nonlocality in Quantum Network*, Phys. Rev. Research **2**, 043355 (2020).

5. S. Haldar, S. Roy, T. Chanda, and A. Sen (De), *Response of macroscopic and microscopic dynamical quantifiers to the quantum critical region*, Phys. Rev. Research **2**, 033249 (2020).

6. S. Roy, T. Das, and A. Sen(De), *Computable genuine multimode entanglement measure: Gaussian vs. non-Gaussian*, Phys. Rev. A **102**, 012421 (2020).

7. S. Roy, A. Bera, S. Mal, A. Sen(De), and U. Sen, *Recycling the resource: Sequential usage of shared state in quantum teleportation with weak measurements*, Phys. Lett. A **392**, 127143 (2021).

8. S. Das, A. Kumar, A. Sen(De), and U. Sen, *Quantum Process Randomness*, Phys. Lett. A **387**, 127024 (2020).

9. S. Roy, T. Das, D. Das, A. Sen(De), and U. Sen, *How efficient is transport of quantum cargo through multiple highways?*, Ann. of Phys. **422**, 168281 (2020).

10. S. Haldar, S. Roy, T. Chanda, A. Sen(De), and U. Sen, *Multipartite entanglement at dynamical quantum phase transitions with non-uniformly spaced criticalities*, Phys. Rev. B **101**, 224304 (2020).

11. C. Srivastava, S. Das, A. Sen (De) and U. Sen, *Signaling versus distinguishing different superpositions of same pure quantum state*, J. Phys. A: Math. Theor. **53**, 275302 (2020).

12. A. Ghoshal, S. Das, A. Sen(De), and U. Sen, *Population inversion and entanglement in single and double glassy Jaynes-Cummings models*, Phys. Rev. A **101**, 053805 (2020).

13. R. Banerjee, A.K. Pal, and A. Sen(De), Uniform Decoherence Effect on Localizable Entanglement in Random Multi-qubit Pure State, Phys. Rev A **101**, 042339 (2020).

Preprints:

1. R. Banerjee, S. Roy, T. Das, and A. Sen (De), *Localizing genuine multimode entanglement: Asymmetric gains via non-Gaussianity*, arXiv:2103.10388.

2. L.G.C.Lakkaraju, S. Mal, and A. Sen (De), *Randomness Amplification under Simulated PT-symmetric Evolution*, arXiv:2102.13630.

3. R. Gupta, S. Roy, S. Mal, and A. Sen (De), *Emergence of Monogamy under Static and Dynamic Scenarios*, arXiv:2102.04940.

4. L.G.C.Lakkaraju, S. Ghosh, A. Sen (De), *Decoherence-free mechanism to protect long-range entanglement against decoherence*, arXiv:2012.12882.

5. S. Roy, A. Kumari, S. Mal, A. Sen (De), *Robustness of Higher Dimensional Nonlocality against dual noise and sequential measurements*, arXiv:2012.12200.

6. K. Sen, C. Srivastava, S. Mal, A. Sen (De), and U. Sen, *Noisy quantum input loophole in measurement-device-independent entanglement witnesses*, arXiv:2012.09089.

7. A. Ghoshal, S. Das, A.K. Pal, A. Sen (De), and U. Sen, *Three cooling off in two baths: Beyond two-body system-bath interactions in quantum refrigerators*, arXiv:2012.08399.

8. S. Roy, S. Mal and A. Sen(De), *Gain in Performance of Teleportation with Uniformity-breaking Distributions*, arXiv:2010.14552.

9. S. Mal and A. Sen(De), *Unifying Two Notions of Nonlocality in Quantum Theory*, arXiv:2009.04245.

10. L. G. C. Lakkaraju, S. Ghosh, S. Roy and A. Sen(De), *Distribution of entanglement with variable range interactions*, arXiv:2006.09257.

11. S. Ghosh, T. Chanda, S. Mal and A. Sen(De), *Fast charging of quantum battery assisted by noise*, arXiv:2005.12859.

12. R. Gupta, S. Gupta, S. Mal and A. Sen(De), *Constructive Feedback of Non-Markovianity on Resources in Random Quantum States*, arXiv:2005.04009.

Conference/Workshops Attended:

1. *Online Symposium on Quantum information and Computation (Quantum Talks)*, IIIT Hyderabad, June 2020.

2. *Indo-Japan webinar on quantum technologies*, July 2020.

3. *Quantum Foundations, Technology and Applications 2020*, IISER Mohali, December 2020.

4. *IPA50 Webinar series*, India, November 2020- March 2021.

Invited Lectures/Seminars:

1. *Quantum Technologies*, Vigyan Vidushi programme, Tata Institute for fundamental research, June, 2020.

2. *Aspects of Quantum Technologies: Research at HRI*, Indo-Japan webinar on "Quantum Technologies", Science and Technology Wing, Embassy of India in Tokyo, July, 2020.

3. *Recent developments in Quantum Technologies* , inauguration of the Center for Atomic, Molecular, and Optical Sciences and Technologies (CAMOST), IIT Tirupati and IISER Tirupati, August, 2020.

4. *Quantum Technologies*, Vigyan Jyoti Programme(DST), Jawahar Navodaya Vidyalaya , Bangalore, August, 2020.

5. *Quantum communication Network*, Qiskit YouTube Quantum Seminar series, IBM, September, 2020.

6. *Quantum info processing with many-body physics*, Lakshmi Raman Memorial Lecture 2020, IIT Madras, September, 2020.

7. *Quantum Technologies*, National Webinar on "Harnessing Quantum Weirdness: Towards New-Age Technologies", Susil Kar College, Kolkata, September, 2020.

8. *Aspects of Quantum Technologies*, Indo-Russia webinar on "Quantum Technologies", SEmbassy of India in Russia, September, 2020.

9. *Quantum Technologies*, Faculty Development Program on Quantum Information and Computation, NIT Sikkim, October, 2020.

10. Quantum technologies with many-body physics, DPS Seminar, IISER Mohali, October, 2020.

11. *Quantum Technologies*, Faculty Development Program on Quantum Information and Computation, University of Goa, November, 2020.

12. *Quantum Technologies*, S N Bose Memorial Lecture at IWCEAMMS-2020, Calcutta Mathematical Society, December, 2020.

13. *Quantum Technologies*, Conference on "Recent advances in Mathematics and related areas, KSCSTE-Kerala School of Mathematics, December, 2020.

14. *Quantum Technologies*, 1st International Conference on Applied Analysis, Computation and Mathematical Modelling in Engineering, National Institute of Technology Rourkela, February, 2020.

15. *Quantum Technologies*, Webinar series for celebrating 50 years of Indian Physics Association, IPA, March, 2021.

16. *Recent Trends in Communication*, NASI organized webinar on Quantum Technologies, Christ Church College, March, 2021.

17. *Quantum Technologies*, Prof. R. Ananthakrishnan' Colloquium, Indian Institute of Tropical Meteorology, March, 2021.

18. *Recent developments in Quantum Technologies*, Colloquium, Defence Research and Development Organisation, March, 2021.

Academic recognition/Awards:

- Awarded Rupa Chakravarty Memorial Silver Medal as a distinguished ex-Bethunite from Bethune College, 2021.

Other Activities:

1. Served as a Thematic group member (TG-Research) in the process of formulating India's new Science, Technology, and Innovation Policy (STIP 2020).

2. Serving as a Member of the Gender in Physics Working Group of Indian Physics Association.

3. Taught classical mechanics course during Jan-May semester. Taught partially quantum information and computation -I and II courses.

4. Served as a member of Q-Turn 2020 Program Committee.

5. Served as a member of the advisory committee in YouQu-2020.

6. Serving as the convenors of the medical committee, Covid monitoring committee, Internal complaint committee (ICC) and women's grievances at HRI.

7. Serving as referees in national and international journals.

8. Serving as members of the physics graduate committee, and Guest House/Pantry/ Student Mess/housing.

AseshKrishna Datta

Research Summary:

During the academic year 2020-2021, I had to confine my research activities within the broad area of search for Supersymmetry (SUSY) at the Large Hadron Collider (LHC) and its connection to Cosmology, in particular, to dark matter (DM) phenomenology, vacuum stability, electroweak phase transitions (EWPT) in the early Universe and electroweak baryogenesis (EWBG).

In a work that got accepted in *JHEP* earlier this year, I, along with my graduate student and a postdoctoral fellow from our Institute, presented a detailed study on the viability of a relatively light, highly bino-like neutralino dark matter in the Z_3-symmetric Next-to-Minimal SUSY Standard Model (NMSSM). We demonstrated that, in contrary to the existing notion, such a neutralino can be as light as a few tens of a GeV and can still be consistent with all pertinent constraints.

Viability of such a light electrowino, which is the Lightest SUSY Particle (LSP), paves the way for the possible presence of other such light states which might escape detection at the LHC under diverse circumstances that warrant thorough studies. I, along with the same graduate student and a faculty member from an Indian institute, am finishing a work where we are looking into such a possibility within the NMSSM, in the presence of light singlet-like scalars of the scenario. Such a scenario is rather congenial to a triggering of a first order EWPT in the early Universe leading to EWBG that can explain the observed baryon asymmetry in the Universe. The connection to gravitational waves originating during the process is also in the context.

In two different collaborations, with faculty members from institutes abroad and my other graduate student, I have been studying the novel phenomenology of relatively light electrowinos of the $B - L$ SUSY Standard Model (BLSSM) that could have evaded the latest LHC searches. Another project that is nearing completion studies the novel LHC phenomenology of a rather fat Z'-like resonance in the said framework.

In another collaboration, with a faculty members from an Indian institute and two postdoctoral fellows from two different institutes, I have been exploring the interesting dependencies of the bottom and the tau Yukawa couplings on the parameters of a SUSY scenario like the Non-Holomorphic SUSY Standard Model (NHSSM), over and above their well-known dependencies on a parameter like $\tan\beta$ and their implications for the LHC.

Publications:

1. AseshKrishna Datta, with Waleed Abdallah and Subhojit Roy, *A relatively light, highly bino-like dark matter in the Z_3-symmetric NMSSM and recent LHC searches,* arXiv:2012.04026 [hep-ph] (accepted for publication in Journal of High Energy Physics (JHEP)).

Preprints:

1. AseshKrishna Datta, with Waleed Abdallah and Stefano Moretti, *A fat Z' in the $B - L$ supersymmetric Standard Model,* (in preparation).

2. AseshKrishna Datta, with Utpal Chattopadhyay, Samadrita Mukherjee and Abhaya Kumar Swain, *Production of heavier Higgs bosons in association with bottom quark(s) at the LHC as a probe to Nonholomorphic MSSM,* (in preparation).

3. AseshKrishna Datta, with Arindam Chatterjee and Subhojit Roy, *Light scalars and electrowinos of the NMSSM: Implications for Electroweak Baryogenesis and LHC searches,* (in preparation).

4. AseshKrishna Datta, with Waleed Abdallah and Afsar Reja, *Light electrowinos of the $B - L$ supersymmetric Standard Model at the LHC,* (in preparation).

Conference/Workshops Attended:

1. *Anomalies 2020*, IIT, Hyderabad, India, September, 2020 (online workshop).

2. *Tools 2020*, IP2I, Lyon, France, November, 2020 (online workshop).

3. *Less Travelled Path of Dark Matter*, ICTS, Bangalore, India, November, 2020 (online workshop).

Visits to other Institutes:

None; due to the prevailing COVID-19 pandemic.

Invited Lectures/Seminars:

None. *Had to decline several opportunities as I have been dealing with major harassments (that I am facing at my workplace) at the highest level.*

Other Activities:

1. Supervising two graduate students towards their Ph.D. theses.

2. Mentored a student in two mandatory projects during his graduate course work.

3. Serving doctoral committees of several graduate students.

4. In the panel of referees of various international journals.

5. Served as a member of the Physics Outreach Programme Committee and the Sports and Entertainment Committees at HRI.

Raj Gandhi

Research Summary:

My work over the past year has focussed on understanding the anomalous signals observed at the Liquid Scintillator Neutrino Detector (LSND) and at MiniBooNE, both of which have reported an excess of electron-like events in their signal. Over the past decade, empirical evidence has mounted against what was assumed to be the most likely solution, $i.e$, oscillations between active and sterile neutrinos with masses in the $1 - 10$ eV range. This has led to a large number of efforts to find non-oscillation new physics solutions to these anomalies. We have worked on finding a solution which would also explain the observed anomalous muon $g - 2$ value measured at both Brookhaven earlier and Fermilab recently. The papers listed below are a result of these efforts.

Publications:

1. W. Abdallah, R. Gandhi and S. Roy, *Understanding the MiniBooNE and the muon and electron $g - 2$ anomalies with a light Z' and a second Higgs doublet,* JHEP **12**, 188 (2020), doi:10.1007/JHEP12(2020)188 [arXiv:2006.01948 [hep-ph]].

Collaboration Publications:

1. B. Abi *et* al. [DUNE], *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume III: DUNE Far Detector Technical Coordination,* JINST **15**, no.08, T08009 (2020) doi:10.1088/1748-0221/15/08/ T08009, [arXiv:2002.03008 [physics.ins-det]].

2. B. Abi *et al.* [DUNE], *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV: Far Detector Single-phase Technology,* JINST **15**, no.08, T08010 (2020), doi:10.1088/1748-0221/15/08/T08010, [arXiv:2002.03010 [physics.ins-det]].

3. B. Abi *et al.* [DUNE], *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I Introduction to DUNE,* JINST **15**, no.08, T08008 (2020), doi:10.1088/1748-0221/15/08/T08008, [arXiv:2002.02967 [physics.ins-det]].

Collaboration Preprints:

1. A. Abed Abud *et al.* [DUNE], *Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report,* [arXiv:2103.13910 [physics.ins-det]].

2. B. Abi *et al.* [DUNE], *Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics,* [arXiv:2002.03005 [hep-ex]].

Conference/Workshops Attended:

1. NEUTRINO 2020, June 22 to July 3 2020 (Virtual Meeting).

Invited Lectures/Seminars:

1. Theory Seminar, IIT Mumbai, November 2020.

Other Activities:

1. Member, DUNE International Collaboration.
2. Member, Institutional Board, DUNE International Collaboration.
3. Member, Analysis Review Committee, DUNE International Collaboration.
4. Taught Particle Physics, Spring 2020, HRI Graduate Program.
5. Taught Particle Physics, Spring 2021, HRI Graduate Program.

Dileep P. Jatkar

Research Summary:

I worked on three disparate topics last year.

First one, in collaboration with Sujay Ashok and Madhusudhan Raman, I studied the relations governing the ring of quasiautomorphic forms associated to triangle groups with a single cusp, thereby extending our earlier results on Hecke groups. The Eisenstein series associated to these triangle groups were shown to satisfy Ramanujan-like identities. These identities in turn allowed us to associate a nonlinear differential equation to each triangle group. We showed that they are solved by the quasiautomorphic weight-2 Eisenstein series associated to the triangle group and its orbit under the group action. We concluded by discussing the Painlevé property of these nonlinear differential equations.

In the second work, in collaboration with Md. Abhishek, Subramanya Hegde, and Arnab Priya Saha, I studied double soft theorem for the generalised biadjoint scalar field theory whose amplitudes are computed in terms of punctures on CP^{k-1}. We found that whenever the double soft limit does not decouple into a product of single soft factors, the leading contributions to the double soft theorems come from the degenerate solutions, otherwise the non degenerate solutions dominate. Our analysis used the regular solutions to the scattering equations. Most of the results are presented for $k = 3$ but we show how they generalise to arbitrary k. We have explicit analytic results, for any k, in the case when soft external states are adjacent.

Finally, in collaboration with Subramanya Hegde, I studied topological defect lines in two character rational conformal field theories. Among them one set of two character theories are commutant pairs in $E_{8,1}$ conformal field theory. Using these defect lines we constructed defect partition function in the E_8 theory. We found that the defects preserve only a part of the E_8 current algebra symmetry. We also determined the defect partition function in $c = 24$ CFT using these defects lines of 2 character theories and we showed that these defects preserve all current algebra symmetries of $c = 24$ CFT.

Publications:

1. Sujay K. Ashok, Dileep P. Jatkar, Madhusudhan Raman, *Triangle Groups: Automorphic Forms and Nonlinear Differential Equations,* SIGMA 16 **16**, 102, (2020).

2. Md. Abhishek, Subramanya Hegde, Dileep P. Jatkar, Arnab Priya Saha, *Double Soft Theorem for Generalised Biadjoint Scalar Amplitudes,* SciPost Phys. **10**, 036, (2021).

Preprints:

1. Subramanya Hegde, Dileep P. Jatkar, *Defect Partition Function from TDLs in Commutant Pairs,* 2101.12189.

Anshuman Maharana

Research Summary:

My Research in the last year has been focused in two directions, string phenomenology and cosmology.

In string phenomenology: i) The statistics of the supersymmetry breaking scale in the string landscape has been extensively studied in the past finding either a power-law behaviour induced by uniform distributions of F-terms or a logarithmic distribution motivated by dynamical supersymmetry breaking. These studies focused mainly on type IIB flux compactifications but did not systematically incorporate the Kähler moduli. We have pointed out that the inclusion of the Kähler moduli is crucial to understand the distribution of the supersymmetry breaking scale in the landscape since in general one obtains unstable vacua when the F-terms of the dilaton and the complex structure moduli are larger than the F-terms of the Kähler moduli. After taking Kähler moduli stabilisation into account, we find that the distribution of the gravitino mass and the soft terms is power-law only in KKLT and perturbatively stabilised vacua which therefore favour high scale supersymmetry. On the other hand, LVS vacua feature a logarithmic distribution of soft terms and thus a preference for lower scales of supersymmetry breaking. Whether the landscape of type IIB flux vacua predicts a logarithmic or power-law distribution of the supersymmetry breaking scale thus depends on the relative preponderance of LVS and KKLT vacua.

ii) Generic features of models of inflation obtained from string compactifications are the correlations between the model parameters and the postinflationary evolution of the universe. Thus, the postinflationary evolution depends on the inflationary model parameters and accurate inflationary predictions require that this be incorporated in the evolution of the primordial spectrum. The fibre inflation model is a promising model of inflation constructed in type IIB string theory. This model has two interesting features in its postinflationary evolution. The reheating temperature of the model is directly correlated with the model parameters. The model also necessarily predicts some dark radiation, which can be sizable for certain choices of discrete parameters in the model. We have analyzed this model in detail using publicly available codes - ModeChord and CosmoMC with the latest Planck+BICEP2/Keck array data to constrain the model parameters and N-pivot (the number of e-foldings between horizon exit of the CMB pivot mode and the end of inflation). We have also carried out the same analysis using the publicly available code Cobaya. We found the results of both the analysis to be in agreement. Our analysis provides the basic methods necessary to extract precise inflationary prediction in string models incorporating correlations between model parameters and postinflationary evolution.

In cosmology: Decay of the inflaton or moduli which dominated the energy density of the universe at early times leads to a matter to radiation transition epoch. We have studied non-thermal sterile dark matter particles produced as decay product during such transitions. The particles have a characteristic energy distribution - that associated with decays taking place in a matter dominated universe evolving to radiation domination. Focusing primarily on the case when the particles are hot dark matter, and study their effects on the Cosmic Microwave Background (CMB) and Large Scale Structure (LSS), explicitly taking into account their non-thermal momentum distri-

bution. Our results for CMB angular power and linear matter power spectra reveal interesting features - such as an order of magnitude higher values of hot dark matter mass in comparison to the thermal case being consistent with the present data. We have observed that this is related to the fact that $\Delta N_{\rm eff}$ and the hot DM energy density can be independent of each other unlike the case of thermal or non-resonantly produced sterile hot DM. We have also found features in the CMB at low ℓ angular power potentially related to supersonic transmission of hot dark matter through the photon-baryon plasma.

Publications:

1. I. Broeckel, M. Cicoli, A. Maharana, K. Singh and K. Sinha
   Moduli Stabilisation and the Statistics of SUSY Breaking in the Landscape , JHEP **10** (2020), 015.

2. S. Bhattacharya, K. Dutta, M. R. Gangopadhyay, A. Maharana and K. Singh, *Fibre Inflation and Precision CMB Data*
   Phys. Rev. D **102** (2020).

3. S. Bhattacharya, S. Das, K. Dutta, M. R. Gangopadhyay, R. Mahanta and A. Maharana, *Nonthermal hot dark matter from inflaton or moduli decay: Momentum distribution and relaxation of the cosmological mass bound* Phys. Rev. D **103** (2021) no.6, 063503.

Preprints:

1. Koushik Dutta and Anshuman Maharana
   Models of Accelerating Universe in Supergravity and String theory
   Invited Review for European Physical Journal Special Topics: Accelerating Universe, accepted for publication, in press

Other Activities:

1. Member HBNI Board of Studies for Physical Sciences

2. Chief Vigilance Officer, HRI

3. Chief Patent Officer, HRI

Pinaki Majumdar

Research Summary:

I have been working on mainly two aspects of correlated systems. These are (i) the effect of geometric frustration on the dynamics of these systems, and (ii) the nonequilibrium response, to strong voltage bias, temperature difference, etc. The primary tool for this is the Langevin dynamics approach, which retains the advantages of the earlier static path based Monte Carlo and additionally is free of any "cluster" approximation. Much of the focus has been on magnetic and phonon modes. We are working to understand the effect of the slow dynamics of these modes on the electronic spectrum.

Publications:

1. Arijit Dutta and Pinaki Majumdar, *Spatial behavior in a Mott insulator near the voltage-driven resistive transition,* Phys. Rev. B **101**,245155 (2020).

Preprints:

1. Arijit Dutta and Pinaki Majumdar, *Thermal fluctuation driven nonequilibrium resistive and magnetic transitions in a voltage biased Mott insulator,* arXiv:2009.04533v1

2. Sauri Bhattacharyya and Pinaki Majumdar, *Dynamics of magnetic collective modes in the square and triangular lattice Mott insulators at finite temperature,* arXiv:2009.01833v1

3. Dheeraj Kumar Singh, Samrat Kadge, Yunkyu Bang, and Pinaki Majumdar, *Fermi arcs and pseudogap phase in a minimal microscopic model of d-wave superconductivity*, Submitted.

Other Activities:

1. Taught Statistical Mechanics, Condensed Matter Physics 2, and parts of Quantum Mechanics 3 and Advanced Statistical Mechanics.

2. Participated in the Vaibhav Summit organised by the Govt of India.

Arun Kumar Pati

Research Summary:

Estimating quantum coherence by noncommutativity of any observable and its incoherent part: We establish an inequality involving the quantum coherence of an arbitrary quantum state, possibly nonpure, in arbitrary dimension and a noncommutativity estimator of an arbitrary observable. The noncommutativity estimator uses the commutator of the observable and its incoherent or classical part. The relation provides a direct method of obtaining an estimate of the quantum coherence of an arbitrary quantum state, without resorting to quantum state tomography or the existing witness operators

Creation of quantum coherence with general measurement process: Quantum measurement usually destroys the coherence of a quantum system. On the contrary, we show that a complete measurement process with an arbitrary measurement basis can also create coherence. Thus, quantum measurement which is thought to be hindrance for quantumness can also be used to create the quantum resource. Based on this observation, we characterize the measurements into two categories, namely, the measurements with the ability to induce coherence and the ones without this ability. We also find a trade-off relation between the coherence creation, entanglement (between system and apparatus), and the mixedness of the system in a general measurement setup.

Classical Communications with Indefinite Causal Order for N completely depolarizing channels: If two identical copies of a completely depolarizing channel are put into a superposition of their possible causal orders, they can transmit non-zero classical information. Here, we study how well we can transmit classical information with N depolarizing channels put in superposition of M causal orders via quantum SWITCH. We calculate Holevo quantity if the superposition uses only cyclic permutations of channels and find that it increases with M and it is independent of N. For a qubit it never reaches 1 if we are increasing M. On the other hand, the classical capacity decreases with the dimension d of the message system. Further, for $N = 3$ and $N = 4$ we studied superposition of all causal orders and uniformly superposed causal orders belonging to different cosets created by cyclic permutation subgroup.

Reverse Quantum Speed Limit: How Slow Quantum Battery can Discharge?: We introduce the notion of reverse quantum speed limit for arbitrary quantum evolution, which answers a fundamental question: "how slow a quantum system can evolve in time?" Using the geometrical approach to quantum mechanics the fundamental reverse speed limit follows from the fact that the gauge invariant length of the reference section is always greater than the Fubini-Study distance on the projective Hilbert space of the quantum system. We illustrate the reverse speed limit for two-level quantum systems with an external driving Hamiltonian and show that our results hold well. We find one practical application of the reverse speed limit in discharging process of quantum batteries which answers the question: "how slow quantum batteries can discharge?" Also, this provides the lower bound on the discharging power of quantum batteries

Dismantling Wave-Particle Duality with Quantum Cheshire Cat: The quantum Chesire

cat has drawn quite a deal of attention over the past few years, challenging the common sense perception that a physical system is inseparable from its physical properties. In this work we propose a thought experiment based on the quantum Chesire cat, which shows that suitable pre- and post-selections can not only separate a physical system from its properties, but also even separate the wave and particle attributes of a physical system. The enduring view about the wave-particle duality has suggested that a quantum entity behaves like both a wave and a particle. However, the wave-particle duality can be spatially separated under such pre- and post-selection conditions, thus allowing us to dismantle these two fundamental attributes of nature.

Remote Creation of Quantum Coherence via Indefinite Causal Order: Quantum coherence is a prime resource in quantum computing and quantum communication. Quantum coherence of an arbitrary qubit state can be created at a remote location using maximally entangled state, local operation and classical communication. However, if there is a noisy channel acting on one side of the shared resource, then, it is not possible to create perfect quantum coherence remotely. Here, we present a method for the creation of quantum coherence at a remote location via the use of entangled state and indefinite causal order. We show this specifically for the superposition of two completely depolarizing channels, two partially depolarizing channels and one completely depolarizing channel along with a unitary operator. We find that when the indefinite causal order of channels act on one-half of the entangled pair, then the shared state looses entanglement, but can retain non-zero quantum discord. This finding may have some interesting applications on its own where discord can be consumed as a resource. Our results suggest that the indefinite causal order along with a tiny amount of quantum discord can act as a resource in creating non-zero quantum coherence in the absence of entanglement.

Publications:

1. Arun K. Pati, C. Mukhopadhyay, S. Chakraborty, S. Ghosh, *Quantum precision thermometry with weak measurement,* Phys. Rev. A **102**, 012204 (2020).

2. Surya Narayan Sahoo, Sanchari Chakraborti, Arun K. Pati, Urbasi Sinha, *Quantum State Interferography* , Phys. Rev. Lett. **125**, 123601 (2020).

3. C. Mukhopadhyay, Arun K. Pati, *Superposition of causal order enables perfect quantum teleportation with very noisy singlets,* J. Phys. Commun. **4**, 105003 (2000).

4. C. Mukhopadhyay, Arun K. Pati, S. Sazim, *Quantum addition imparts less disorder than mixing and commutes with incoherent channels,* IOP SciNotes **1**, 025212 (2020).

Preprints:

1. Tanaya Ray, Arun K. Pati, Ujjwal Sen, *Estimating quantum coherence by noncommutativity of any observable and its incoherent part*, arXiv:2004.07729

2. Sanuja D. Mohanty, Sk Sazim, Biswajit Pradhan, Arun K. Pati, *Creation of quantum coherence with general measurement processes,* arXiv:2004.10875 .

3. Sk Sazim, Michal Sedlak, Kratveer Singh, Arun K Pati, *Classical Communications with Indefinite Causal Order for N completely depolarizing channels,* arXiv:2004.14339 .

4. Brij Mohan, Arun K Pati, *Reverse Quantum Speed Limit: How Slow Quantum Battery can Discharge?,* arXiv:2006.14523 .

5. Pratyusha Chowdhury, Arun K Pati, Jing-Ling Chen, *Dismantling Wave-Particle Duality with Quantum Cheshire Cat,* arXiv:2009.00545

6. Jasleen Kaur, Shrobona Bagchi, Arun K Pati, *Remote Creation of Quantum Coherence via Indefinite Causal Order,* arXiv:2103.04894 .

Invited Lectures/Seminars:

1. Delivered a Seminar on five day Online Symposium on Quantum information and Computation during June 29- July 3, 2020 at IIIT, Hyderabad.

2. Delivered a Keynote talk in the International Webinar on Fundamental Sciences and Quantum Technologies using Atomic Systems (FSQT 2020), held at PRL, Ahmedabad from 28th September to 1st October, 2020.

3. Delivered a popular talk to motivate College students in Hinjilicut College, Odisha on October 3, 2020.

4. Delieverd two talks at Faculty Development Program on Quantum Information and Computation, held at NIT, Sikkim during 5th to 17th October 2020.

5. Delivered physics online colloquium at IIT Gandhinagar on 21st October, 2020 4:30 PM (IST) on " Conservation of Quantum Information".

6. Delivered a special Webinar at Department of Physics, University of Kerala on "Quantum Information Technology" on 14th Dec 2020 at 3:30pm, as a part of the Webinar series to celebrate the 50th anniversary of the Department.

7. Delivered a Plenary talk in Young Scientists' Conference(YSC), IISF on Dec 23, 2020 held at NPL, Delhi from 22-24 Dec 2020. Plenary session was on Frontier Areas of Basic and Applied Sciences-Physical Science.

8. Delivered an online Seminar on "Mysteries in Quantum Physics" to motivate College students at Gunupur College, Odisha on 15 Jan 2021 at 4.00 pm.

Academic recognition/Awards:

- Ranks in top 1% Scientists in the world in General Physics and in top 2% Scientists in the world from all branches of Science– a study conducted by the Stanford University in 2020.

- Received "Distingushed Alumni Award" from Berhampur University, Berhampur, Odisha in January 2021.

- Research work has been included in a Book “Nobel Dreams of India” published by juggernaut publications. One can find it free at https://www.juggernaut.in/books/nobel-dreams-india-inspiring-budding-scientists-1

  The book highlights the research work of Nobel Prize winners and a similar significant contribution in the same area of research by Indian scientists over the past 21 years of Nobel Prize awarded in Physics.

- Our work on ”Quantum State Interferography” has been included as top 20 Discoveries of DST, India in 2020 where I have proposed the theoretical idea how to determine quantum states using quantum interference and RRI, Bangalore Group (Prof. U. Sinha and team) carried out the experiment.

  This work has been highlighted by PSA to Priminister of India office.

Other Activities:

1. Mentored several M. Sc. students over online.
2. 6 students are doing PhD in Quantum Information.
3. Gave an interview and explained What is Quantum Computing for general students in a podcast created by High School students.

Santosh Kumar Rai

Research Summary:

My research has continued to focus on models beyond the Standard Model (SM) of particle physics and their phenomenology. We looked at extended gauge and discrete symmetries and new scalars with vector-like fermions. In a more specific and technical analysis we looked at the effect of large width of an exotic coloured gauge boson on the collider signal of its decay products. In another work we analysed using machine learning methods to reveal kinematic novelties in boosted decay products in a supersymmetric model with compressed mass spectrum and studied its LHC signal.

The search for compressed supersymmetry at multi-TeV scale, in the presence of a light gravitino dark matter, can get sizable uplift while looking into the associated fat-jets with missing transverse momenta as a signature of the boson produced in the decay process of much heavier next-to-lightest sparticle. We considered the hadronic decay of the ensuing Higgs and/or Z boson giving rise to at least two fat-jets in the final state. We perform a detailed study adopting a multivariate analysis using a boosted decision tree to provide a robust investigation to explore the discovery potential for such signal at 14 TeV LHC considering different benchmark points satisfying all the theoretical and experimental constraints. Kinematic observables were investigated in order to distinguish between compressed and uncompressed spectra having similar event yields.

In other relevant work still under preparation, we studied the phenomenology of an S_3-symmetric two Higgs doublet model by adding two generations of vector like leptons (VLL) which are odd under a discrete Z_2 symmetry. The lightest neutral component of the vector like leptons act as a dark matter (DM) whereas the full VLL set belongs to a dark sector with no mixings allowed with the standard model fermions. A detailed collider analysis of multi-lepton signal along with missing transverse energy in the final state was done using both the cut-based analysis and multivariate analysis respectively at the high luminosity 14 TeV LHC run.

Publications:

1. S. Dasgupta, Santosh Kumar Rai, T. S. Ray, *Impact of a colored vector resonance on the collider constraints for top-like top partner,* Physical Review **D 102**, 115014, (2020).

2. Mariana Frank, Benjamin Fuks, Katri Huitu, Subhadeep Mondal, Santosh Kumar Rai, Harri Waltari, *Left-right supersymmetric option at a high-energy upgrade of the LHC,* Physical Review **D 101**, 115014, (2020).

3. Akanksha Bhardwaj, Juhi Dutta, Partha Konar, Biswarup Mukhopadhyaya and Santosh Kumar Rai, *Boosted jet techniques for a supersymmetric scenario with gravitino LSP,* Journal of High Energy Physics **10**, 083, (2020).

4. Baradhwaj Coleppa, Santosh Kumar Rai and Agnivo Sarkar, *Charged Higgs Discovery Prospects,* Springer Proc. Phys. **248**, 199, (2020).

5. A. K. Nayak, Santosh Kumar Rai and T. Samui, *Improving Heavy Dijet Resonance Searches Using Jet Substructure at the LHC,* European Physics Journal **C 81 2**, 130, (2021).

Preprints:

1. Indrani Chakraborty, Dilip Kumar Ghosh, Nivedita Ghosh, Santosh Kumar Rai, *Dark Matter and Collider Searches in S_3-Symmetric 2HDM with Vector Like Leptons,* (in preparation).

Conference/Workshops Attended:

1. *Anomalies 2020*, India, September, 2020.

Other Activities:

1. Taught M.Sc. course (shared) titled *Numerical Methods*, April-May, 2020.
2. Taught M.Sc. course titled *Mathematical Methods-II*, August 2020-January, 2021.
3. Supervising Ph.d. of Mr. Anjan Kr. Barik and Mr. Shyamashish Dey.
4. Stand-in Supervisor (for Prof. B. Mukhopadhyay) of Ph.d. students Mr. Avirup Ghosh, Mr. Arpan Kar and Ms. Atri Dey.
5. Stand-in Supervisor (for Prof. S. Choubey) of INO Ph.d. student Mr. Deepak Raikwal.
6. Supervised Theory project for Afsar Reza.
7. Member of Thesis Committee for around 6-8 students.
8. Referee for journals Physical Review D, EPJC.
9. Co-ordinator, Regional Centre for Accelerator-based Particle Physics (RECAPP).
10. Member, Local Works & Estate (LW&E), HPC Cluster, Computer Committee, Faculty Appointment Committee, Endowment Committee.
11. Convener, Security Committee.

Sumathi Rao

Research Summary:

We continued our work on topological quantum matter, focussing this year on edge states, Weyl semimetals and also on quasiparticles that occur in these materials as excitations - abelian anyons, non-abelian excitations like Majorana modes and their even more exotic cousins, parafermions.

The work on shining light on bilayer graphene to obtain chiral co-propagating Luttinger liquids at the interface of two polarisations was published. We are now studying the chiral edge states obtained by gating bilayer graphene. In particular, we are looking for reconstruction of these edge states in the presence of electron-electron interactions. We have also been studying the interacting electron system in domain walls in silicene and other spin-orbit coupled materials and in particular, have been trying to see whether we can tune the Kondo effect in the helical Luttinger liquid that is obtained at the domain wall, via gates.

Our work on multicritical points in topological phase transitions was published, as also our work on the interface between $\nu = 3$ and $\nu = 4$ quantum Hall systems. We have continued our work on edge modes and have studied a circuit where the path from the source of electric current to the drain necessarily passes through a segment consisting solely of neutral modes. We find that the neutral modes carry information using which it is possible to reconstruct the DC charge current at the drain. We show that our protocol can be used as a detector of all kinds of neutral modes.

We have also given a new formalism to study anyons in terms of the Kohn-Sham density functional theory, and shown by comparing the theory with exact results from few anyon systems, that it can both qualitatively and quantitatively capture the relevant physics, and may turn out to be a new tool for studying anyons in other contexts as well. We have also been studying parafermion excitations, which can be constructed by the proximity of chiral edge states of quantum Hall systems with superconductors. Our aim is to study detection of parafermions using an Aharonov-Bohm ring setup.

We have studied Fermi arc reconstruction at a junction of two Weyl semi-metals (WSM) twisted by an angle with respect to each other, and shown that there exists regions in the parameter space where the Fermi arcs disconnect from the projections of the Weyl nodes and become normal Fermi loops. These surface states are true surface states and decay exponentially into the bulk. We are also currently studying Weyl semi-metals in a magnetic field in the Hofstader regime, where the lattice length is comparable to the magnetic length, where we have found not only found new WSM phases we have also found new insulating phases which do not occur in the absence of a magnetic field. Finally, we have also been working on a normal metal - insulator - WSM junction in the thin and thick barrier limits to study electrical conductances and thermal conductances through such junctions.

We have also working on a hybrid setup involving a superconductivity-proximitised quantum spin Hall insulator and a quantum anomalous Hall insulator for chiral injection of electrons. Our aim is to show how to engineer a phase space where the Majorana mode will be stable to disorder and amenable to detection.

Publications:

1. Sourav Biswas, Tridev Mishra, Sumathi Rao and Arijit Kundu, *Chiral Luttinger liquids in graphene tuned by irradiation,* PRB **102**, 235129, (2020).

2. Faruk Abdulla, Priyanka Mohan and Sumathi Rao, *Curvature function renormalisation, topological phase transitions and multicriticality,* PRB **103**, 155428, (2020).

3. Amartya Saha, Suman Jyoti De, Sumathi Rao, Yuval Gefen and Ganpathy Murthy, *Emergence of spin-active channels at a quantum hall interface* PRB **102**, L081401, (2021).

4. Yayun Hu, Ganpathy Murthy, Sumathi Rao and Jainendra Jain, *Kohn-Sham density functional theory of abelian anyons,* PRB**103**, 035124, (2021).

Preprints:

1. Faruk Abdulla, Sumathi Rao and Ganpathy Murthy, *Fermi arc reconstruction at the interface of twisted Weyl semimetals,* cond-mat/2101.09907.

2. Ankur Das, Sumathi Rao, Yuval Gefen and Ganpathy Murthy, *Dc electrical current generated by upstream neutral modes,* cond-mat/2103.06200

3. Vivekananda Adak, Aabir Mukhopadyay, Suman Jyoti De, Udit Khanna, Sumathi Rao and Sourin Das, *Chiral detection of Majorana bound states at the edge of a quantum spin Hall insulator*, in preparation.

4. Faruk Abdulla, Ankur Das, Sumathi Rao and Ganpathy Murthy, *Lattice Weyl semi-metal in the Hofstader regime*, in preparation.

5. Sourav Biswas, Allesandro de Martino, Sumathi Rao and Arijit Kundu, *Tunable Kondo effect at domain walls in silicene*, in preparation.

Conference/Workshops Attended:

1. *WEB conference, QMAT3 2020, S.N. Bose national centre for basic sciences, Kolkata, India, September 6-11, 2020*

2. *WEB conference, Emerging trends in quantum matters, statistical and biological physics, Bhubaneswar, India, November 23-24, 2020*

Invited Lectures/Seminars:

1. *Edge dynamics of topological phases*, QMAT3 2020, S.N. Bose National centre for basic sciences, Kolkata, 9 September, 2020.

2. *Topological phases of quantum matter*, Online Short term course on current trends in condensed matter physics, NIT, Jallandar, 28 September, 2020.

3. *Topological phases of quantum matter*, Guru Jambeshwar University of Science and Technology, Hisar, Haryana, 16 October, 2020.

4. *Exotic quastiparticles in condensed matter systems*, Emerging trends in quantum matters, statistical and biological physics, Bhubaneswar, India, Institute of Physics, Bhubaneswar, 23 November, 2020.

Other Activities:

1. Divisional Associate Editor, Physical Review Letters, American Physical Society, 2018 -2020, 2021 - .

2. Convenor, Endowment committee (HRI) till December 31, 2020.

Ashoke Sen

Research Summary:

My work during April 2020 - March 2021 has been mainly on the analysis of D-instanton contribution to string amplitudes. I developed a general procedure for dealing with the infrared divergences that appear in the computation of D-instanton amplitudes in string theory and showed how we can use string field theory to extract unambiguous results for these apparently divergent quantities. I used this to discuss unitarity of the D-instanton amplitudes and possible failure of unitarity when tachyonic modes are present on the D-instanton. I also used open string field theory to compute the overall normalization of the D-instanton amplitudes – a task not attempted earlier due to the infrared divergences that plague this computation.

In a separate work with Nabamita Banerjee, Ajit Bhand, Suvankar Dutta and Ranveer Singh, I showed how Bhargava's cube can be used to classify the duality orbits of the STU model.

Publications:

1. A. P. Saha, B. Sahoo and A. Sen, *Proof of the classical soft graviton theorem in $D = 4$*, JHEP **06** (2020), 153 doi:10.1007/JHEP06(2020)153 [arXiv:1912.06413 [hep-th]].
2. A. Sen, *D-instanton Perturbation Theory*, JHEP **08** (2020), 075, doi:10.1007/JHEP08(2020)075 [arXiv:2002.04043 [hep-th]].
3. A. Sen, *Divergent $\Longrightarrow$ complex amplitudes in two dimensional string theory*, JHEP **02** (2021), 086 doi:10.1007/JHEP02(2021)086 [arXiv:2003. 12076 [hep-th]].

Preprints:

1. N. Banerjee, A. Bhand, S. Dutta, A. Sen and R. K. Singh, *Bhargava's Cube and Black Hole Charges*, [arXiv:2006.02494 [hep-th]].
2. A. Sen, *Cutkosky Rules and Unitarity (Violation) in D-instanton Amplitudes*, [arXiv: 2012.00041 [hep-th]].
3. A. Sen, *D-instantons, String Field Theory and Two Dimensional String Theory*, [arXiv: 2012.11624 [hep-th]].
4. A. Sen, *Normalization of D-instanton Amplitudes*, [arXiv:2101.08566 [hep-th]].

Invited zoom talks at Conferences / Workshops / Schools

1. *Divergent to Complex Amplitudes in Two Dimensional String Theory*, at 'String field theory and related topics', Sao Paolo, June 2020
2. *D-instanton Perturbation Theory*, Strings 2020, Cape Town, June 2020
3. *Soft Theorem and its Classical Limit, at 'Recent Developments in S-matrix theory'*, ICTS, Bangalore, July 2020

4. *Classical radiation and soft graviton theorem, at the workshop on 'Rethinking the Relativistic Two-Body Problem'*, AEI Potsdam, August 2020

5. *Cutting Rules and Unitarity (Violation) in D-instanton Amplitudes*, at 'The dual mysteries of gauge theories and gravity', IIT Madras, October 2020

6. *Soft theorem and classical radiation*, Mini review at the DAE Symposium on High Energy Physics, NISER, Bhubaneswar, December 2020

7. *Bhargava's cube and black hole charges*, at 'Recent advances in Mathematics and Related areas 2020, Kerala school of Mathematics, Kozhikode, December 2020

8. *How to compute string amplitudes*, at the Kavli Asian Winter School (KAWS) on Strings, Particles and Cosmology, Beijing, January 2021

9. *Unitarity and Analyticity in String Field Theory*, 'Workshop Quantum Gravity, Higher Derivatives & Nonlocality', Tokyo Institute of Technology, March 2021

10. *Classical gravitational radiation and soft theorem*, CAmplitudes 2021, California, March 2021

Invited zoom talks at other institutes

1. *D-instanton Perturbation Theory*, Italian String Webinars, May 2020

2. *Gravitational Waves from Soft Theorem*, University of Groningen, May 2020

3. *D-instanton Perturbation Theory*, Israel string theory seminar, June 2020

4. *Four lectures on D-instanton Perturbation Theory*, SAIFR, Sao Paolo, June 2020

5. *Cutting Rules and Unitarity (Violation) in D-instanton Amplitudes*, AEI Potsdam, November 2020.

6. *Cutting Rules and Unitarity (Violation) in D-instanton Amplitudes*, Queen Mary University, London, November 2020.

7. *D-instanton Amplitudes*, Harvard University, February 2021

8. *D-instanton Amplitudes*, ICTS, Bangalore, February 2021

9. *D-instanton Amplitudes*, University of Wurzburg, February 2021

10. *D-instanton Amplitudes in String Theory*, ETH Zurich, February 2021

11. *D-instanton Amplitudes in String Theory*, Paris area seminar, February 2021

12. *D-instanton Amplitudes in String Theory*, Oxford University, March 2021

13. *D-instanton Amplitudes in String Theory*, Nordic string seminar, Helsinki, March 2021

14. *D-instanton Amplitudes in String Theory*, London area seminar, March 2021

15. *Three lectures on D-instanton Amplitudes in String Theory*, KIAS, Seoul, March 2021

Courses given at HRI

1. *Quantum field theory 1*, September 2020 - January 2021
2. *Cosmology*, February 2021 - May 2021

Prasenjit Sen

Research Summary:

In this period we focussed on two major themes: materials for alternative energy; fundamental understanding of magnetic materials.

We explored a class of ternary transition metal tri-chalcogenide compounds for their efficiency as electrocatalysts in hydrogen evolution reaction. We identified 10 new stable compounds with this property. We also developed new insights into how catalytic efficiency of some of the known compounds can be increased further.

We collaborated with the experimental group of Dr. T. N. Narayanan of TIFR, Hyderabad to develop microscopic understanding of how cobalt decorated nitrogenated graphitic carbon spheres (Co-NGC) work as good bi-functional catalyst for oxygen evolution and oxygen reduction reactions (OER/ORR). This property makes Co-NGC a promising cathode material in rechargeable Zn-air batteries. We also developed a theoretical understanding of how a mixed (KOH+LiOH) electrolyte enhances cyclability of rechargeable Zn-air batteries.

In fundamental studies, we developed new theoretical understanding into magnetic properties of Co_2C nano-particles in collaboration with the experimental group of Prof. S. Banerjee at IIT-Kanpur, who had found nano-particles of this material to show complex magnetic behavior including large magnetic anisotropy energy. We also developed new insights into electronic and magnetic properties of the tri-chalcogenide compounds.

Publications:

1. K. Alam, N. Seriani and P. Sen, *Catalytic properties of α-MnO_2 for Li-air battery cathodes: a density functional investigation,* Phys. Chem. Chem. Phys. **22**, 9233, (2020).

2. P. Sen and R. Chouhan, *Electronic structure of MPX_3 tri-chalcogenide monolayers in density functional theory: A case study with four compounds (M=Mn, Fe; X=S, Se),* Elec. Str. **2**, 025003, (2020).

3. P. Sen, K. Alam, T. Das, R. Banerjee and S. Chakraborty, *Combinatorial design and computational screening of 2D transition metal tri-chalcogenide monolayers: Toward efficient catalysts for hydrogen evolution reaction,* J Phys. Chem. Lett. **11**, 3192, (2020).

4. P. Thakur, M. Yeddala, K. Alam, S. Pal, P. Sen, and T. N. Narayanan, *Cobalt Nanoparticles Dispersed Nitrogen-Doped Graphitic Carbon Nanospheres-Based Rechargable High Performance Zinc-Air Batteries,* ACS Appl. Energy Mater. **3**, 7813, (2020).

Preprints:

1. K. Alam, T. Das, S. Chakraborty and P. Sen, *Finding the catalytically active sites on the layered tri-chalcogenide compounds $CoPS_3$ and $NiPS_3$ for hydrogen evolution reaction,* (submitted).

2. T. Das, K. Alam, S. Chakraborty and P. Sen, *Probing active sites on $MnPSe_3$ and $FePSe_3$ tri-chalcogenides as a design strategy for better hydrogen evolution reaction catalysts*, (submitted).

3. P. Thakur, K. Alam, P. Sen and T. N. Narayanan, *Extending the Cyclability of Alkaline Zinc-Air Batteries: Synergistic Roles of Li^+ and K^+ Ions in Electrodics*, (submitted).

4. N. Roy, M. A. Ali, A. Sen, P. Sen and S. Banerjee, *Evidence of Exchange Bias effect in pure Co_2C nanoparticles*, arxiv.org/abs/2005.04904 (submitted).

Conference/Workshops Attended:

1. *Webinar Series on Materials Simulation: A Virtual Guided Tour*, India, May, 2020.

2. *Conference on Quantum Condensed Matter Physics (QMAT-2020)*, India, July, 2020.

Invited Lectures/Seminars:

1. *Layered ternary tri-chalcogenides and Co-based clusters: Energy applications and new insights*, Webinar Series on Materials Simulation: A Virtual Guided Tour, IIT, Delhi, online, May, 2020.

2. *Screening layered ternary transition metal tri-chalcogenides as electrocatalysts*, Conference on Quantum Condensed Matter Physics (QMAT-2020), S. N. Bose National Centre for Basic Sciences, Kolkata, online, July, 2020.

Other Activities:

1. Participated in the Vaibhav Summit in the Computational Materials Science horizontal, October, 2020.

2. Editorial Board Member of *Physica Scripta*.

3. Convener Cluster Committee, member Colloquium Committee, Physics Academic Committee.

4. Dean Academic since March 2020.

5. Teaching courses: Condensed Matter Physics 1, Spectroscopic Methods.

Ujjwal Sen

Research Summary:

In the last academic year, I have been working on different aspects of quantum devices, and at the interface of quantum information with other sciences.

In one of these works, I have collaborated with Ahana Ghoshal on heat current and entropy production rate in local non-Markovian quantum dynamics of a global Markovian evolution. We examined the elements of the balance equation of entropy in open quantum evolutions, and their response as we go over from a Markovian to a non-Markovian situation. In particular, we looked at the heat current and entropy production rate in the non-Markovian reduced evolution, and a Markovian limit of the same, experienced by one of two interacting systems immersed in a Markovian bath. The analysis naturally led us to define a heat current deficit and an entropy production rate deficit, being differences between the global and local versions of the corresponding quantities. The investigation brought us, in certain cases, to a complementarity of the time-integrated heat current deficit with the relative entropy of entanglement between the two systems.

In another work, I have collaborated with Kornikar Sen and Chirag Srivastava to provide measurement-device-independent nonlinear entanglement witnesses. Entanglement witnesses are one of the most effective methods to detect entanglement. It is known that nonlinear entanglement witnesses provide better entanglement detection than their linear counterparts, in that the former detect a strictly larger subset of entangled states than the latter. Whether linear or nonlinear, the method is measurement-device dependent, so that imperfect measurements may cause false certification of entanglement in a shared state. Measurement-device-independent entanglement witnesses provide an escape from such measurement dependence of the entanglement detection for linear entanglement witnesses. We presented measurement-device-independent nonlinear entanglement witnesses for non-positive partial transpose entangled states as well as for bound entangled states with positive partial transpose. The constructed measurement-device-independent nonlinear entanglement witnesses certified the entanglement of the same sets of entangled states as their device-dependent parents do, and therefore are better than the linear entanglement witnesses, device-independent or otherwise.

Publications:

1. Riddhi Ghosh, Ahana Ghoshal, and Ujjwal Sen, *Quantum thermal transistors: Operation characteristics in steady state versus transient regimes,* Phys. Rev. A **103**, 052613, (2021).

2. Chirag Srivastava, Sreetama Das, and Ujjwal Sen, *Resource theory of quantum coherence with probabilistically non-distinguishable pointers and corresponding wave-particle duality,* Phys. Rev. A **103**, 022417 (2021).

3. Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen De, and Ujjwal Sen, *Detection loophole in measurement-device-independent entanglement witness,* Phys. Rev. A **103**, 032415 (2021).

4. Debmalya Das and Ujjwal Sen, *Delayed choice of paths selected by grin and snarl of quantum Cheshire Cat,* Phys. Rev. A **103**, 012228 (2021).

5. Chirag Srivastava, Shiladitya Mal, Aditi Sen De, and Ujjwal Sen, *Sequential measur*
ement-device-independent entanglement detection by multiple observers, Phys. Rev. A **103**, 032408 (2021).

6. Sohail and Ujjwal Sen, *Witnessing nonseparability of bipartite quantum operations,* Phys. Lett. A **404**, 127411 (2021).

7. Sreetama Das, Asutosh Kumar, Aditi Sen De, and Ujjwal Sen, *Quantum Process Randomness,* Phys. Lett. A **387**, 127024 (2021).

8. Ahana Ghoshal, Sreetama Das, Aditi Sen De, and Ujjwal Sen, *Population inversion and entanglement in single and double glassy Jaynes-Cummings models,* Phys. Rev. A **101**, 053805 (2020).

9. Chirag Srivastava, Sreetama Das, Aditi Sen De, and Ujjwal Sen, *Signaling versus distinguishing different superpositions of same pure quantum state,* J. Phys. A: Math. Theor. **53**, 275302 (2020).

10. Stav Haldar, Saptarshi Roy, Titas Chanda, Aditi Sen De, and Ujjwal Sen, *Multipartite entanglement at dynamical quantum phase transitions with non-uniformly spaced criticalities,* Phys. Rev. B **101**, 224304 (2020).

11. Saptarshi Roy, Tamoghna Das, Debmalya Das, Aditi Sen De, and Ujjwal Sen, *How efficient is transport of quantum cargo through multiple highways?,* Annals of Physics **422**, 168281 (2020).

12. Sreetama Das, Chiranjib Mukhopadhyay, Sudipto Singha Roy, Samyadeb Bhattacharya, Aditi Sen De, and Ujjwal Sen, *Wave-particle duality employing quantum coherence in superposition with non-orthogonal pointers,* J. Phys. A: Math. Theor. **53**, 115301 (2020).

Preprints:

1. Kornikar Sen, Chirag Srivastava, and Ujjwal Sen, *Measurement-device-independent nonlinear entanglement witnesses,* arXiv:2106.05796.

2. George Biswas, Anindya Biswas, and Ujjwal Sen, *Inhibition of spread of typical bipartite and genuine multiparty entanglement in response to quenched disorder,* arXiv:2105.03384.

3. Brij Mohan, Sohail, Chirag Srivastava, Arun K. Pati, and Ujjwal Sen, *Quantum information can remain without physical body in volatile form,* arXiv:2105.03250.

4. Ujjwal Sen, *Quantum analog of resource theory of stinginess,* arXiv:2103.16799.

5. Saronath Halder and Ujjwal Sen, *Unextendible entangled bases and more nonlocality with less entanglement,* arXiv:2103.09140.

6. Ahana Ghoshal and Ujjwal Sen, *Heat current and entropy production rate in local non-Markovian quantum dynamics of global Markovian evolution,* arXiv:2102.06694.

7. Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen De, and Ujjwal Sen, *Noisy quantum input loophole in measurement-device-independent entanglement witnesses,* arXiv:2012.09089.

8. Ahana Ghoshal, Sreetama Das, Amit Kumar Pal, Aditi Sen(De), and Ujjwal Sen, *Three cooling off in two baths: Beyond two-body system-bath interactions in quantum refrigerators,* arXiv:2012.08399.

9. Chirag Srivastava and Ujjwal Sen, *Scaling of non-adiabaticity in disordered quench of quantum Rabi model close to phase transition,* arXiv:2012.04568.

10. Arun Sehrawat, Chirag Srivastava, and Ujjwal Sen, *Equilibrium and dynamical phase transitions in fully connected quantum Ising model: Approximate energy eigenstates and critical time,* arXiv:2012.00561.

11. Asmitha Mekala and Ujjwal Sen, *All entangled states are quantum coherent with locally distinguishable pointers,* arXiv:2008.11148.

12. Shashaank Khanna, Saronath Halder, and Ujjwal Sen, *Quantum entanglement percolation on monolayer honeycomb lattice,* arXiv:2008.09040.

13. Saronath Halder and Ujjwal Sen, *Local indistinguishability and incompleteness of entangled orthogonal bases: Method to generate two-element locally indistinguishable ensembles,* arXiv:2008.01620.

14. Asmita Kumari and Ujjwal Sen, *Local preservation of no-signaling in multiparty PT-symmetric evolutions,* arXiv:2007.13461.

15. C S Sudheer Kumar and Ujjwal Sen, *How many runs ensure quantum fidelity in teleportation experiment?,* arXiv:2004.14816.

16. Tanaya Ray, Arun Kumar Pati, and Ujjwal Sen, *Estimating quantum coherence by noncommutativity of any observable and its incoherent part,* arXiv:2004.07729.

17. Shubhalakshmi S and Ujjwal Sen, *Noncommutative coherence and quantum phase estimation algorithm,* arXiv:2004.01419.

Conference/Workshops Attended:

1. *QMAT-2020*, SN Bose National Center for Basic Sciences, Kolkata, India, 07-11 Sep, 2020. Online.

2. *Young Quantum 2020*, Harish-Chandra Research Institute, Allahabad, India, 12-15 Oct, 2020. Online.

Invited Lectures/Seminars:

1. *Quantum talks*, IIIT Hyderabad, India, June-July 2020. Online. Presented a talk on "Quantum devices using systems with impurities".

2. *International E-Conference on Recent Advances in Physics*, GPGC, Bazpur, India, 24-25 Jun, 2020. Online. Presented a talk on "Quantum devices using systems with impurities".

3. *Physics Colloquium*, IIT Gandhinagar, India, 03 July 2020. Online. Presented a talk on "Quantum devices using systems with impurities".

4. *QMAT-2020*, SN Bose National Center for Basic Sciences, Kolkata, India, 07-11 Sep, 2020. Online. Presented a talk on "Quantum devices in disordered systems".

5. *India-Russia Quantum Technologies Meet*, Embassy of India in Russia and the DST, GoI, 10 Sep, 2020. Online. Presented a talk on "Quantum information meets few- and many-body physics".

6. *Technical Education Quality Improvement Programme (TEQIP) - III sponsored Faculty development program (FDP) on Quantum Information and Computation*, NIT Sikkim, India, 03-17 Oct, 2020. Online. Presented two talks on "Interface of quantum information with few- and many-body physics".

Other Activities:

1. Current PhD students: Chirag Srivastava, Ahana Ghoshal, Kornikar Sen, Tanaya Ray. [Sreetama Das, another student, was awarded a PhD degree recently.]

2. Courses taken/ongoing: Research methodology and Numerical Methods, January-May 2020 (shared with Prof. Santosh K. Rai); Quantum information and computation 2, January-May 2020 (shared with Prof. Aditi Sen De); Quantum Information and Computation 1, August-December 2020 (shared with Profs. Arun Kumar Pati and Aditi Sen De); Quantum Information and Computation 2, January-May 2021 (shared with Prof. Aditi Sen De); Quantum mechanics 2, May-August 2021.

3. Committees: Convener of HRI computer committee, members of HRI cluster computing, HRI outreach program, HRI faculty appointment committees.

4. Mentored/mentoring projects of Aparajita Bhattacharyya, Priya Ghosh, Sayan Mondal, Tanay Konar, Anish Majumdar.

5. Mentored/mentoring the masters theses of Ingita Banerjee, IIT Dhanbad; Sheikh Parvez Mandal, IISER Pune; Soubhadra Maiti, IISER Pune. Online.

6. Visiting students (online): Sheikh Parvez Mandal, Ayushi Dubal, Riddhi Ghosh, Sayanwita Biswas, Ingita Banerjee, Kartikeya Arora, Soham Sau, Shilpa Mahato, Soubhadra Maiti, Adithi Ajith, Swati Choudhary, Arunava Majumdar, Sudheer Kumar.

7. Editorial/advisory boards of journals: Journal of Physics B, Quantum, IOP SciNotes.

8. Member of thesis committees of several students at HRI and outside HRI.

Jayanta Dutta

Research Summary:

Since my joining on November 1st, 2020, I have been working on the primordial star formation, especially their interaction with the surrounding gas medium within the disk and their survival possibility till present epoch. Technically, we have constructed an N-body code that can be implemented for an interacting primordial star-gas system that is highly complex and nonlinear in nature. We have verified the self-written code with the published work (Szebehely & Peters, 1967). We have also studied the individual and total gas accretion rate of protostars within the different gas clumps that have a wide range of rotation. We have also installed the Lagrangian based code Smoothed particle hydrodynamics (SPH) Gadget-2 in our HRI cluster in order to study the 3D gravitational collapse of primordial gas.

In addition, in collaboration with the various group around the world, we are in process of implementing the radiative feedback process for a multi-protostar scenario.

Preprints:

1. Jayanta Dutta, *Formation of primordial stars and their survival possibility - a basic overview for beginners,* (submitted in January, 2021)

2. Sukolpo Kundu and Jayanta Dutta *On the effect of rotation in the accretion rate of primordial protostars,* (in preparation)

3. Sukolpo Kundu, Jayanta Dutta, Sharanya Sur and Jasjeet Singh Bagla *Radiative feedback process of the first generation of star,* (in preparation)

Conference/Workshops Attended:

1. *The 9th KIAS Workshop on Cosmology and Structure Formation*, Korea, November, 2020.

Invited Lectures/Seminars:

1. *N-body simulation on survival possibility of Population III stars*, KIAS Cosmology Workshop 2020 Korea, November, 2020.

2. *Formation of primordial stars and their survival possibility - a brief overview for non-experts*, Popular talk, HRI, Prayagraj, March, 2021.

Other Activities:

1. Teaching Theoretical Astrophysics and Cosmology at HRI, since January, 2021.

2. Teaching Numerical Method at HRI, since February, 2021.

3. Supervising four students at HRI, since November, 2020.

Tisita Das

Research Summary:

During this period I have worked on following projects:

I have investigated the catalytic activity of two ternary transition metal (TMTC) $MPSe_3$ (M: Mn, Fe) nano-ribbons with selected edge sites using first-principles electronic structure calculations. We have elucidated the edge effect on the active sites, in experimentally observed bulk counterparts with low HER overpotential. The HER catalytic activity has been predicted through determination of the hydrogen adsorption free energy with and without solvation effect. During this activity prediction, we have also explored the hydrogen concentration dependency. Based on Nørskov's approach of reaction coordinate mapping, we have envisaged the HER active edges for these two compounds while successfully addressing the correspondence between the experimental observation and theoretical prediction. Our Density Functional Theory (DFT) calculations clearly establish that the edges of $MnPSe_3$ and $FePSe_3$ are the catalytically active regions in these materials. In fact, we have identified the specific active sites both in low and high H^+ concentrations. Since the calculations are performed both in vacuum as well as in aqueous environment, we succesfully capture the effect of electrochemical environment on the HER activity. The results conclude that the catalytic activities of these materials can be increased even further if they can be synthesized in structures that expose a large number of sulphide, selenium or phosphorus edge sites. This manuscript is under review.

The second project is done in collaboration with an experimental group. Using a facile microwave strategy they have synthesized $Ni_3Bi_2S_2$ nanocrystal which exhibits two closely related orthorhomic and monoclinic phases. Tuning the synthesis parameters the distribution of two phases has been controlled to optimize the best catalyst for efficient hydrogen evolution. It has been observed that the catalyst with highest percentage of monoclinic phase demonstrated a negligible onset potential of only 24 mV close to that of state-of-the-art Pt/C with an overpotential as low as 0.088 V. Using DFT calculation we determined that the monoclinic phase exhibits lowest hydrogen adsorption free energy (ΔG_{H^*}) and therefore the highest hydrogen evolution activity amonst the two phases. Adsorption of hydrogen atom on all the possible adsorption sites predicts Ni site as the most active site in both the phases. The value of ΔG_{H^*} is largest when H adsorbed on NiS-Ni surafce, a by-product during the systhsis procedure indicating this phase is not at all HER active. This manuscript is just accepted in ChemSusChem journal. Apart from this, I have also worked on a couple of other collaborative projects where I have theoretically validated the experiemental findings on exploring oxygen evolution and reduction reaction activity in perovosikte and alloy materials. In all these cases the primary descriptors for predicting the activity we used are the work fuction and the binding energy of the reaction intermediates on top of the catalyst surafce. This binding energy allows us to produce reaction coordinate which eventually helps determining the reaction kinetics as well as the active most sites involved in the reactions.

My current project focuses on another TMTC member where I am trying to activate the basal plane of $FePS_3$ monolayer for efficient hydrogen evolution. As per the previous experimental and theiretical works the basal of FePS3 monolayer exhibits

high overpotential and large ΔG_{H^*} value correspoding to hydrogen adsorption suggesting its poor catalyzing ability toward H_2 production. Efficient hydrogen evolution requires plenty of active sites on the catalyst surafce. Therefore in this project we are aiming to promote this efficiency by tuning the electronic properties of the catalyst surface through elemental functionalization and strain engineering. This is an ongoing work.

Publications:

1. Rahul Majee, Tisita Das, Sudip Chakraborty, and Sayan Bhattacharyya, *Shaping a Doped Perovskite Oxide with Measured Grain Boundary Defects to Catalyze Bifunctional Oxygen Activation for a Rechargeable Zn-Air Battery,* ACS Applied Materials and Interfaces **12**, 40355-40463, (2020).

2. Shreya Sarkar, S. D. Ramarao, Tisita Das, Risov Das, C. P. Vinod, Sudip Chakraborty, and Sebastian C. Peter *Unveiling the Roles of Lattice Strain and Descriptor Species on Pt-Like Oxygen Reduction Activity in Pd-Bi Catalysts,* ACS Catalysis **11**, 800-808, (2021).

3. Shreya Sarkar, Abhishek Rawat, Tisita Das, Mattia Gaboardi, Sudip Chakraborty, C. P. Vinod, and Sebastian C. Peter, *Structure-Tailored Non-Noble Metal-based Ternary Chalcogenide Nanocrystals for Pt-like Electrocatalytic Hydrogen Production,* ChemSusChem **14**, 1-11, (2021).

Preprints:

1. Tisita Das, Khorsed Alam, Sudip Chakraborty, and Prasenjit Sen, *Probing active sites on $MnPSe_3$ and $FePSe_3$ tri-chalcogenides as a design strategy for better hydrogen evolution reaction catalysts.* (in preparation)

2. Khorsed Alam, Tisita Das, Sudip Chakraborty, and Prasenjit Sen, *Identifying the catalytically active sites on the layered tri-chalcogenide compounds $CoPS_3$ and $NiPS_3$ for efficient hydrogen evolution reaction,* (in preparation).

Conference/Workshops Attended:

1. Oral presentation in *ACS supported Virtual Conference on "Materials for Energy Harvesting and Catalysis"*, organized jointly by TIFR, Mumbai and IISER, Kolkata in May 1-3, 2020.

2. Attended lectures and talks in *"Webinar Series on Materials Simulation: A Virtual Guided Tour"*, India, 21–31 May, 2020.

3. Attended *3rd Annual Conference of Quantum Condensed Matter (Q-MAT: 2020)*, organized by S. N. Bose National Centre for Basic Sciences in September 7-11, 2020.

4. Attended web seminar *"Vaibhav Summit: V5 – Computational Sciences"*, India, October 10, 2020.

5. Poster presentation in *"On-line Workshop on Excited Charge Dynamics in Semiconductors" SMR3516*, organized by The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, in September 28-30, 2020.

6. Oral presentation in *"Evolution of Electronic Structure Theory and Experimental Realization (EESTER 2020)"*, jointly organized by SRMIST KTR (India), IIT Madras (India) and Uppsala University (Sweden), in December 14-18, 2020 in webinar mode.

7. Attended *"Conference on Advances in Catalysis, Eneergy, and Environmental research Online Meet (CACEE 2020)"*, organized by TIFR, Hyderabad in December 16-18, 2020 in webinar mode.

Academic recognition/Awards:

- Best talk award for oral presentation in ACS supported Virtual Conference on "Materials for Energy Harvesting and Catalysis" organized jointly by TIFR, Mumbai and IISER, Kolkata in May 1-3, 2020.

Karan Fernandes

Research Summary:

My areas of research concern asymptotic symmetries on black hole spacetimes and dynamical effects in accretion flows

Two of my publications and a recent preprint involve investigations on infrared limits of massless fields on black hole spacetimes. These studies particularly address the implications of soft limits of gauge and gravitational fields on late time gravitational wave observables, soft hair on extremal black hole spacetimes and soft limits on AdS spacetimes. My planned research in in the coming year will cover holographic manifestations of soft limits and asymptotic symmetries on asymptotically flat and AdS spacetimes.

My most recent preprint, in collaboration with Prof. Tapas Das, concern dynamical effects in accretion flows and analogue spacetimes. We recently demonstrated that the paradigm for stationary analogue spacetimes realized in linear perturbations of transonic flows can be generalized to dynamical analogue spacetimes from nonlinear perturbations. We intend to apply our formalism to experimentally accessible transonic systems and accretion flows on curved spacetimes.

Publications:

1. K. Fernandes, D. Ghosh and A. Virmani, *Horizon Hair from Inversion Symmetry,* Class.Quant.Grav., **38**, 055006, (2021).

2. K. Fernandes and A. Mitra, *Soft factors from classical scattering on the Reissner-Nordström spacetime,* Phys.Rev.D, **102**, 105015, (2020).

3. K. Fernandes, K. S. Kolekar, K. Narayan and S. Roy, *Schwarzschild de Sitter and extremal surfaces,* Eur.Phys.J.C, **80**, 866, (2020).

Preprints:

1. K. Fernandes, S. Maity and T. K. Das, *Dynamical analogue spacetimes in non-relativistic flows,* arXiv: 2106.07618 [gr-qc].

2. N. Banerjee, K. Fernandes and A. Mitra, *Soft Photon theorem in the small negative cosmological constant limit,* arXiv: 2102.06165 [hep-th].

Conference/Workshops Attended:

1. *Island Hopping - 2020 workshop*, Swtizlerland, November, 2020.

2. *Hamilton School on Mathematical Physics*, Ireland, July, 2020.

3. *Recent Developments in S-matrix theory (ONLINE) workshop*, India, July, 2020.

4. *Strings 2020 conference*, South Africa, June, 2020.

5. *Black-Hole Microstructure conference*, France, June, 2020.

Visits to other Institutes:

1. International Center for Cosmology, CHARUSAT, Gujarat, India, December, 2020.

Invited Lectures/Seminars:

1. *Dynamical effects in accretion and memory effects in gravitational waves*, Invited Talk, International Center for Cosmology, Charotar University of Science and Technology (CHARUSAT), Gujarat, December, 2020.

Purusottam Ghosh

Research Summary:

I have been working as a post-doctoral fellow in Department of Physics at HRI since September, 2019. My area of research mostly focused on Dark Matter (DM) phenomenology, its multipartite aspect, connection to neutrino physics, vacuum stability and discovery potential at direct search and at LHC. Here I will briefly summerise the research work so far I have done during the academic year 2020-2021, *i.e*, 1st April 2020 to 31st March 2021.

Publications:

1. Subhaditya Bhattacharya, Manoranjan Dutta, Purusottam Ghosh and Narendra Sahu, . *Singlet-Doublet Majorana Dark Matter and Neutrino Mass in a minimal Type-I Seesaw Scenario,* JCAP 2103 (2021) 008 DOI: 10.1088/1475-7516/2021/03/008, (2021).

Preprints:

1. Basabendu Barman, Purusottam Ghosh, Farinaldo S. Queiroz, Abhijit Kumar Saha, *Scalar Multiplet Dark Matter in a Fast Expanding Universe: resurrection of the desert region,* arXiv:2101.10175.

2. Shyamashish Dey, Purusottam Ghosh, Santosh Kumar Rai, *Doubly charged scalar with Fermionic DM in the extended Left Right Symmetric Model,* (in preparation)

3. Purusottam Ghosh, Satyabrata Mahapatra, Nimmala Narendra and Narendra Sahu *Experimentally Verifiable U_{B-L} Symmetry Model with Type II Seesaw and Dark Matter* (in preparation)

Conference/Workshops Attended:

1. *Invisibles21 School*, Spain, 12 April to 7 May, 2021 (online mode).

2. *Beyond Standard Model: From Theory to Experiment (BSM- 2021)*,Egypt , 29 March to 2 April, 2021 (online mode).

Invited Lectures/Seminars:

1. *Features of Multipartite Scalar Dark Matter*, Beyond Standard Model: From Theory to Experiment (BSM- 2021), Zewail City of Science and Technology, Egypt, March, 2021.

Nivedita Ghosh

Research Summary:

In this academic year 2020-2021, *i.e*, 1st April 2020 to 31st March 2021, I have mainly taken into account extension of the Standard Model(SM) which can alleviate some of the drawbacks of the SM.

One of the main motivations to look beyond the SM is the discrepancy between the theoretical prediction and observation of anomalous magnetic moment of muon. Alleviating this tension between theory and experiment and satisfying the bounds from lepton flavor violation data simultaneously is a challenging task. In this paper, we consider generalised Two Higgs Doublet Model, with a Yukawa structure as a perturbation of Type X Two Higgs Doublet Model. In view of this model, we explore muon anomaly and lepton flavor violation along with constraints coming from B-physics, theoretical constraints, electroweak observables and collider data which can restrict the model parameter space significantly. We find that within the framework of this model it is possible to obtain regions allowed by all constraints, that can provide an explanation for the observed muon anomaly and at the same time predicts interesting signatures of lepton flavor violation. Furthermore, we consider the flavor violating decay of low-mass CP-odd scalar to probe the allowed parameter space at future runs of the LHC. With simple cut-based analysis we show that part of that parameter space can be probed with significance $> 5\sigma$. We also provide Artificial Neural Network analysis which definitely improves our cut-based results significantly. We then consider the "wrong − sign" lepton-Yukawa coupling which gives rise to interesting phenomenological consequences and can be probed at the LHC with lower luminosity, making the detection easier. [Nivedita Ghosh and Jayita Lahiri, Physical Review D **103**, 055009, (2021), and Arxiv:2103.10632.]

On a different note, we study the S_3-symmetric two Higgs doublet model by adding two generations of vector like leptons (VLL) which are odd under a discrete Z_2-symmetry. The lightest neutral component of the VLL acts as a dark matter (DM) whereas the full VLL set belongs to a dark sector with no mixings allowed with the standard model fermions. We analyse the model in light of dark matter and collider searches. We show that the DM is compatible with the current relic density data as well as satisfying all direct and indirect dark matter search constraints. We choose some representative points in the model parameter space allowed by all aforementioned dark matter constraints and present a detailed collider analysis of multi-lepton signals *viz.* the mono-lepton, di-lepton, tri-lepton and four-lepton along with missing transverse energy in the final state using both the cut-based analysis and multivariate analysis respectively at the high luminosity 14 TeV LHC run. [Nivedita Ghosh, Santosh Kumar Rai, Indrani Chakraborty, Dilip Kumar Ghosh, (in preparation)]

Publications:

1. Nivedita Ghosh and Jayita Lahiri, *Revisiting a generalized two-Higgs-doublet model in light of the muon anomaly and lepton flavor violating decays at the HL-LHC,* Physical Review D **103**, 055009, (2021).

Preprints:

1. Nivedita Ghosh and Jayita Lahiri, *Generalized 2HDM with wrong-sign lepton Yukawa coupling, in light of $g_\mu - 2$ and lepton flavor violation at the future LHC,* Arxiv:2103.10632.

2. Nivedita Ghosh, Santosh Kumar Rai, Indrani Chakraborty, Dilip Kumar Ghosh, *Dark Matter and Collider Searches in S_3-Symmetric 2HDM with Vector Like Leptons,* (in preparation)

Saronath Halder

Research Summary:

In the last academic year, I have worked on several items of quantum information theory, for example, unextendible product bases, bound entangled states, the range criterion, local indistinguishability and incompleteness of entangled orthogonal bases, entanglement percolation, multi-copy adaptive local discrimination, teleportation fidelity and its deviation, unextendible entangled bases and more nonlocality with less entanglement. All of the papers, which I have written in the last academic year, are collaborative works with several coauthors.

An unextendible product basis (UPB) is a set of orthogonal product states which span a subspace of a given Hilbert space while the complementary subspace contains no product state. These product bases are useful to produce bound entangled (BE) states. We have considered reducible and irreducible UPBs of maximum size, which can produce BE states of minimum rank. From a reducible UPB, it is possible to eliminate one or more states locally, keeping the post-measurement states orthogonal. On the other hand, for an irreducible UPB, the above is not possible. Particularly, the UPBs of this size are important as they might be useful to produce BE states, having ranks of the widest variety, which satisfy the range criterion. We have talked about such BE states. We have also provided other types of BE states and we have analyzed certain properties of the states. Some of the BE states have been associated with the tile structures. Furthermore, we have provided different UPBs corresponding to the BE states of minimum rank and we have discussed important properties of the UPBs.

We have related the phenomenon of local indistinguishability of orthogonal states with the properties of unextendibility and uncompletability of entangled bases for bipartite and multipartite quantum systems. We have proved that all two-qubit unextendible entangled bases are of size three and they cannot be perfectly distinguished by separable measurements. We have identified a method of constructing two-element orthogonal ensembles, based on the concept of unextendible entangled bases, that can potentially lead to information sharing applications. Two-element ensembles form the fundamental unit of ensembles, and yet does not offer locally indistinguishable ensembles for pure state elements. Going over to mixed states does open this possibility, but can be difficult to identify. The method provided using unextendible entangled bases can be used for their systematic generation. In multipartite systems, we have found a class of unextendible entangled bases for which the unextendibility property remains conserved across all bipartitions. We have also identified nonlocal operations, local implementation of which require entangled resource states from a higher-dimensional quantum system, i.e., from a higher dimensional Hilbert space.

The problem of establishing Bell and Greenberger-Horne-Zeilinger states between faraway places or distant nodes of a circuit is a difficult and an extremely important one, and a strategy which addresses it is entanglement percolation. We have provided a method for attaining the end through a quantum measurement strategy involving three-, two-, and single-qubit measurements on a single-layer honeycomb lattice of partially entangled bipartite entangled states.

Ensembles of composite quantum states can exhibit nonlocal behavior in the sense that their optimal discrimination may require global operations. Such an ensemble

containing N pairwise orthogonal pure states, however, can always be perfectly distinguished under adaptive local scheme if (N-1) copies of the state are available. However, we have provided examples of orthonormal bases in two-qubit Hilbert space whose adaptive discrimination require three copies of the state. For this composite system, we have analyzed multi-copy adaptive local distinguishability of orthogonal ensembles in full generality which in turn assigns varying nonlocal strength to different such ensembles. We have also come up with ensembles whose discrimination under adaptive separable scheme require less number of copies than adaptive local schemes. Our construction finds important application in multipartite secret sharing tasks and indicates towards an intriguing super-additivity phenomenon for locally accessible information.

We have considered the following teleportation protocol: There is an arbitrary two-qubit resource state, shared between two spatially separated parties, Alice and Bob. Applying local unitary operators, they transform the resource state into the canonical form. To teleport an unknown qubit, Alice now measures her qubits in the Bell basis. Then, the measurement outcome is communicated by Alice to Bob via noisy classical channel(s). Finally, after receiving the classical message, Bob applies the necessary unitary operator to his qubit. Under this protocol, we have found the exact formulae of teleportation fidelity and its deviation. We further have found conditions for non-classical fidelity within this protocol. If the classical communication is noiseless in the above protocol then there are resource states which can lead to zero fidelity deviation. However, we have showed that such states may not lead to zero fidelity deviation when the classical communication is noisy in the same protocol. We also have explored the opposite case, i.e., the states, which cannot lead to zero fidelity deviation in the above protocol when the classical communication is noiseless, may lead to zero fidelity deviation when the classical communication is noisy in the same protocol without compromising the non-classical fidelity. Moreover, we have exhibited scenarios within the present protocol, where the fidelity deviation increases if the entanglement of the resource state is increased.

We have considered a general version of the phenomenon of more nonlocality with less entanglement, within the framework of the conclusive quantum state discrimination problem under local quantum operations and classical communication. We have showed that although the phenomenon was obtained before for two qutrits, it can also be observed for two qubits, while still being at the single-copy level. We have established that the phenomenon is intrinsically connected to the concept of unextendible entangled bases, in the two-qubit case. In the process, we have demonstrated a hierarchy of nonlocality among sets of two-qubit orthogonal pure states, where the nonlocality is in the sense of a difference between global and local abilities of quantum state discrimination. We have presented a complete characterization of two-qubit pure orthogonal state sets of cardinality three with respect to their nonlocality in terms of conclusive local distinguishability, the status for other cardinalities being already known.

Publications:

1. P. Bej and S. Halder, *Unextendible product bases, bound entangled states, and the range criterion,* Physics Letters A **386**, 126992, (2021).

Preprints:

1. S. Halder and U. Sen, *Local indistinguishability and incompleteness of entangled orthogonal bases: Method to generate two-element locally indistinguishable ensembles,* arXiv:2008.01620.

2. S. Khanna, S. Halder, and U. Sen, *Quantum entanglement percolation on monolayer honeycomb lattice,* arXiv:2008.09040.

3. M. Banik, T. Guha, M. Alimuddin, G. Kar, S. Halder, and S. S. Bhattacharya, *Multi-copy adaptive local discrimination: Strongest possible two-qubit nonlocal bases,* arXiv:2011.09287.

4. P. Bej, S. Halder, and R. Sengupta, *Teleportation fidelity and its deviation for an arbitrary two-qubit state when the classical communication is noisy,* arXiv:2102.01022.

5. S. Halder and U. Sen, *Unextendible entangled bases and more nonlocality with less entanglement,* arXiv:2103.09140.

Conference/Workshops Attended:

1. *Young Quantum - 2020*, India, October, 2020.

2. *Quantum Foundations, Technology and Applications - 2020*, India, December, 2020.

Subramanya Hegde

Research Summary:

In the academic year 2020-2021, I worked on the following problems.

CEGM formalism was recently introduced as a generalisation of CHY formalism for scattering amplitudes. In CEGM formalism, an amplitude is given by integration over moduli space of n-puncture CP^{k-1}. They have an interesting connection with $Gr(k,n)$ cluster algebras. In a paper with Md. Abhishek, Arnab Priya Saha and Dileep P. Jatkar, we derived the double soft theorem for these amplitudes.

While CEGM amplitudes display interesting factorisation properties typical to scattering amplitudes, a physical interpretation of these amplitudes is lacking. In a paper with Md. Abhishek and Arnab Priya Saha, we gave a physical interpretation of the CEGM amplitude with $k = 3, n = 6$ by making use of its connection to D_4 cluster algebra.

Defects in two dimensional conformal field theories are important to study the behavior of theories under renormalisation group flow. In a recent work, defects were constructed in Monster CFT by using the commutant pairs inside the Monster CFT by relating the relation between their characters to fermionisation. In a preprint with Dileep P. Jatkar, we presented an approach to construct defects in theories with such a commutant pair structure, by focusing on$E_{8,1}$ WZW model CFT and $c = 24$ meromorphic CFTs.

Publications:

1. Md. Abhishek, Subramanya Hegde, Dileep P. Jarkar, Arnab Priya Saha, *Double Soft Theorem for Generalised Biadjoint Scalar Amplitudes,* Scipost **10**, 036, (2021).

2. Md. Abhishek, Subramanya Hegde, Arnab Priya Saha *One-loop integrand from generalised scattering equations,* JHEP **05**, 012, (2021).

Preprints:

1. Subramanya Hegde, Dileep P. Jatkar *Defect Partition Function from TDLs in Commutant Pairs,* arXiv: 2101.12189 [hep-th].

Conference/Workshops Attended:

1. *Recent developments in S matrix theory*, ICTS Bengaluru, India (Online), July 2020.

2. *Student Talks on Trending Topics in Theory 2020*, India (Online), July, 2020.

3. *Hamilton School on Mathematical Physics 2020*, Trinity College Dublin, Ireland (Online), August, 2020.

Invited Lectures/Seminars:

1. *Lecture course on Supergravity*, Delivered a nine hour lecture course on 'Supergravity' in Student Talks on Trending Topics in Theory 2020, Organised by Indian High Energy Theory students and post-docs, Online, 2020.

Asmita Kumari

Research Summary:

In the previous academic year, I have worked on aspects of quantum foundation, quantum information and PT-symmetric quantum theory.

Violation of the no-signaling principle may occur in PT-symmetric evolutions, that is, evolutions that stem from Hamiltonians that are symmetric with respect to parity and time-reversal, of bipartite entangled states. The violation can be avoided by using a non-conventional inner product. We show that even within the formalism that utilizes the conventional Dirac inner product between physical state vectors, it is possible to obtain instances of local preservation of the no-signaling principle for evolutions corresponding to PT-symmetric non-hermitian Hamiltonians with real eigenvalues, of multiparty entangled states, whose bipartite versions still violate the principle. The phenomenon can be witnessed already by using the Greenberger-Horne-Zeilinger state. Interestingly, the generalized W states do not support such a local preservation of no-signaling.

Robustness in the violation of Collins-Linden-Gisin-Masser-Popescu (CGLMP) inequality is investigated from the dual perspective of noise in measurements as well as in states. To quantify it, we introduce a quantity called area of nonlocal region which reveals a dimensional advantage. Specifically, we report that with the increase of dimension, the maximally violating states (MVS) show a greater enhancement in the area of nonlocal region in comparison to the maximally entangled states (MES) and the scaling of the increment, in this case, grows faster than visibility. Moreover, we examine the robustness in the sequential violation of CGLMP inequality using weak measurements, and find that even for higher dimensions, two observers showing a simultaneous violation of the CGLMP inequality as obtained for two-qubit states persists. We notice that the complementarity between information gain and disturbance by measurements is manifested by the decrease of the visibility in the first round and the increase of the same in the second round with dimensions. Furthermore, the amount of white noise that can be added to an MES so that it gives two rounds of the violation, decreases with the dimension, while the same does not appreciably change for the MVS.

In [PRL, 113, 050401 (2014)] the authors have shown that instead of Luder rule, if degeneracy breaking von Neumann projection rule is adopted for state reduction, the quantum value of three-time Leggett-Garg inequality can exceed it's Luders bound. Such violation of Luders bound may even approach algebraic maximum of the inequality in the asymptotic limit of system size. They also claim that for Clauser-Horne-Shimony-Holt (CHSH) inequality such violation of Luders bound (known as Cirelson's bound) cannot be obtained even when the measurement is performed sequentially first by Alice followed by Bob. In this paper, we have shown that if von Neumann projection rule is used, quantum bound of CHSH inequality exceeds it's Cirelson's bound and may also reach its algebraic maximum four. This thus provide a strong objection regarding the viability of von Neumann rule as a valid state reduction rule. Further, we pointed out that the violation of Cirelson's bound occurs due to the injection of additional quantum non-locality by the act of implementing von Neumann measurement rule.

Preprints:

1. Asmita Kumari and Ujjwal Sen, *Local preservation of no-signaling in multiparty PT-symmetric evolutions,* arXiv:2007.13461.

2. Saptarshi Roy, Asmita Kumari, Shiladitya Mal and Aditi Sen De, *Robustness of Higher Dimensional Nonlocality against dual noise and sequential measurements,* arXiv:2012.12200.

3. Asmita Kumari and A. K. Pan, *Luder rule, von Neumann rule and Cirelson's bound of Bell CHSH inequality,* arXiv:2012.13880.

Arpan Krishna Mitra

Research Summary:

1) Time evolution of modes of density contrast, in particular the growing modes, dictate the structure formation in Universe. In this project we explicitly show how behavior of the modes get modified if we consider the cosmological fluid to be non isentropic in nature, that is we compute the power law profiles of the density contrast modes those have received the modification . We define a generalised fluid Lagrangian which produce all the dynamical equations for nonisentropic fluids. The fluid equations, namely the Euler equation, receives explicit contribution. When mapped to comoving coordinates this, along with continuity and entropy convection equations, generate the extended versions of continuity and Friedmann equations for cosmology. Introducing cosmological perturbations yield the entropy corrected evolution of density contrast modes.

2)We are studying the transonic properties of general relativistic polytropic axisymmetric hydrodynamic accretion in the Schwirschild metric. We are studying all the existing models in this context. It comes out that the specefic energy, for such accretion phenomena, can be expressed as polynomial(of different order for different accretion flow types) of the critical point of the flow configuration. Onwards we are going to construct the corresponding Sturm's chain algorithm to calculate the number of real roots lying within the astrophysically relevant domain.

Preprints:

1. Satadal Datta, Arpan Krishna Mitra *Simulating gravity in roational flow,* arXiv:2011.05837

2. Arpan Krishna Mitra, Souvik Ghose, Angshika Mishra *Nonisentropic fluid and Growing Modes of Inhomogeneity in Cosmology,* (in preparation).

3. Arpan Krishna Mitra, Pratik Tarafdar, Tapas Das *Transonic properties of relativistic accretion in Schwarzschild black hole: an analytical study* (in preparation).

Other Activities:

1. Successfully defended my Doctoral thesis and received Ph.D degree from University of Calcutta, December, 2020.

Rafiqul Rahaman

Research Summary:

After joining HRI on 16th October 2020, I started working on the spin-spin correlation of a pair of spin-full particles in collaboration with Dr. Ritesh K. Singh. In this work, we discuss a formalism for the spin-spin correlations and polarizations in two-particle systems with spins half-half, half-one, and one-one, providing the connections between the polarizations and correlations with the double angular distributions of decay products by identifying the asymmetries for them. We demonstrate the formalism in partonic processes $e^-e^+ \to t\bar{t}$, $e^-e^+ \to ZZ$ and $gb \to tW^-$ in the standard model as examples. We investigate the effect of some anomalous couplings on the polarizations and correlations in the idealistic processes $e^+e^- \to t\bar{t}$, $u\bar{d} \to ZW^+$ and $gb \to tW^-$ and compare their strengths. The manuscript of this work is almost prepared, and we hope to communicate this work very soon.

I am also working on distinguishing various Beyond Standard Models (BSM) with the help of polarization observables and machine learning technique in collaboration with Dr. Santosh Kumar Rai and Mr. Anjan Kumar Barik. In this work, we look for $2jl^{\pm} + MET$ final state in $e^+e^- \to h^+h^-$ in the two-Higgs doublet model (2HDM), and in the process $e^+e^- \to \chi^+\chi^-$ in supersymmetry. These signal are contrasted with the background process $e^+e^- \to W^+W^-$. We look for lab frame kinematic quantities (observables) correlated with the polarization observables of $W^{\pm}$ as the $W^{\pm}$ rest frame is not reconstructable due to missing neutrinos. We find that $E(l^-)/E(W+)$ captures one of the polarization of W^- at a reasonable percentage. We aim to use this polarization motivated observable, other lab frame angular quantities, along with machine learning techniques to distinguish between 2HDM and supersymmetry models in the above signal processes.

I am also involved in of exploring dark-Z/Z_d boson in electron proton collision in collaboration with Prof. Ashok Kumar Goyal, Dr. Mukesh Kumar and Dr. Satendra Kumar. Here, we explore the Lorentz structure and the magnitude of parity violation of dark-Z coupling to the standard model (SM) fermions. We consider a generic structure,

$$\mathcal{L}_{Z_d f\bar{f}} = -\epsilon\, e\, \bar{f}\, (g_{f,v}\gamma_\mu + g_{f,a}\gamma_\mu\gamma_5)\, f Z_d^\mu, \tag{4}$$

for the Z_d interaction with the SM fermions. Since Z_d couples to SM particles via the interactions in Eq. (4), the production of Z_d in e^-p collider follows through charged (neutral (NC)) currents (CC): $e^-p \to \nu_e(e^-)Z_d\, j$. To probe the mass range of Z_d as a function of ϵ in this setup, we use cross section and asymmetries associated with polarisation observables of Z_d constructed from the decay of $Z_d \to \ell^+\ell^-$.

Beside these above works, I completed and communicated an work on "Probing non-standard $b\bar{b}h$ interaction at the LHC at $\sqrt{s} = 13$ TeV " in collaboration with Dr. Partha Konar, Prof. Biswarup Mukhopadhyaya and Dr. Ritesh K. Singh. In this work, we probe the non-standard $hb\bar{b}$ coupling parametrized in a model-independent standpoint, phenomenologically expressed in terms of a modification factor α_b, in $b\bar{b}$-associated production of Higgs. We use machine learning techniques with the XGBoost module to enhance signal significance over the cut based analysis in a detailed detector level simulations. We explore the QCD next-to-leading order (NLO) effect on the limit on α_b and find it slightly weaker than at leading-order (LO) result. We also

investigate the effect of (renormalization and factorization) scale variation on the results at NLO and observe a significant variation, with better results at relatively higher scale values. This work is published in Physics Letters B on 7th May 2021.

Preprints:

1. Partha Konar, Biswarup Mukhopadhyaya, Rafiqul Rahaman and Ritesh K. Singh *Probing non-standard $b\bar{b}h$ interaction at the LHC at $\sqrt{s} = 13$ TeV,* arXiv:2101.10683 [hep-ph].

2. Rafiqul Rahaman and Ritesh K. Singh, *Breaking down the entire spectrum of spin-spin correlations of a pair of particles with spin-$1/2$ and spin-1,* manuscript under preparation.

3. Ashok Kumar Goyal, Mukesh Kumar, Satendra Kumar, Rafiqul Rahaman, *Exploring Dark Z-boson in electron-proton collisions,* manuscript under preparation.

Academic recognition/Awards:

- Received Honorable Mention for Rahul Basu Memorial Award for Best Thesis, 2020.

Pratim Roy

Research Summary:

The description of work described here consists of research undertaken from 20th November, 2020 (date of joining HRI) to 31st March, 2021.

The main direction of research has been studying mixed state entanglement in quantum systems. Determining the characteristics of entanglement in many-body systems and quantum field theories has been an active topic of research in recent years. The majority of studies concentrate on entanglement entropy, which is however, not a suitable quantity for measuring entanglement in mixed states. Consequently, the quantity chosen for study of mixed state is logarithmic negativity, which is one of the measures proposed in the literature for quantifying entanglement in mixed states. Compared to other measures, logarithmic negativity has the desirable property that it is the only one whose calculation does not involve an optimisation over entanglement of different configurations, making it more practical to calculate in different physical situations.

The research work being undertaken consists of two broad areas. Firstly, the properties of logarithmic negativity have been investigated in scalar field theories with a fractional Laplacian. The primary motivation is to investigate the effect of long-range interactions on logarithmic negativity. In the class of models chosen, the presence of a "tunable" parameter essentially controls the range of interactions in the theory. The configuration used in this is a periodic harmonic chain, with the subsystems as two groups of oscillators, separated by a distance. At first, the effect of the long-range interactions is studied with respect to the separation between the two subsystems. It is found that, in common with earlier studies in the literature, the logarithmic negativity decreases with separation, but the effect of the long-range interactions is that at short separations, the fall-off obeys a power law, rather than being exponential.

The logarithmic negativity has also been investigated in the context of a quantum quench, which is a situation in which the parameter(s) in the Hamiltonian of the system undergo change with time. An abrupt change is considered, in which the mass of the theory suddenly drops to zero. The current heuristic understanding of quantum quenches is given by the quasiparticle picture, which states that the post-quench behaviour of the system is governed by the propagation of quasiparticles which are responsible for spreading the perturbation through the system. But the presence of the long-range interactions ensures that the quasiparticle picture does not hold, due to the absence of the Lieb-Robinson velocity. Therefore, it is interesting to investigate a quench for which the quasiparticle picture would not govern the post-quench dynamics. The findings for this part are chiefly the absence of revivals in entanglement that are present in short-range models. The methodology used throughout this work for calculating logarithmic negativity is the technique of correlation matrices, which are widely used in the literature for calculating entanglement entropy and similar quantities.

The results upto this point are detailed in a manuscipt titled "Mixed state entanglement in non-local field theories with fractional Laplacian", which will be submitted for peer review very shortly.

An attempt is also being made to generalise the above results for abrupt quenches to gradual quenches as has been previously done in the literature for other measures

like entanglement entropy and mutual information. This will facilitate meaningful comparison with existing results in the literature, as well as with the results for the abrupt quench in the proper limit.

One of the chief limitations of the results obtained for the logarithmic negativity for long-range models is that the treatment is primarily numerical. This is because of the difficulty in obtaining analytical results. The situation is somewhat better for the conventional scalar field theory (Klein-Gordon model) as the numerical results there can be compared with conformal field theory. This is not the case with, for example, long-range models. Hence there is a need to generalise the conformal field theory results. This is being attempted through trying to calculate the entanglement in an integrable (but not conformal) model, as put forward by Zamolodchikov in the literature. This is slightly longer term ongoing work and it is hoped that it will give some new insight into the quench dynamics of non-conformal models.

Publications:

Preprints:

1. Pratim Roy, *Mixed state entanglement in non-local field theories with fractional Laplacian,* (in preparation)

Arnab Priya Saha

Research Summary:

Cachazo-He-Yuan (CHY) formalism is a remarkable development in quantum field theory. In this formalism S-matrix elements of several theories including scalar, gluon and graviton can be computed using integral representations of moduli space of punctured Riemann spheres. Recently Cachazo, Early, Guevera and Mizera (CEGM) have studied extensions of CHY formalism by introducing scattering equations defined on higher dimensional projective spaces, $\mathbb{CP}^{k-1}$. These amplitudes have realization in terms of Grassmannian cluster algebras. We have derived double soft limits for general n-point CEGM amplitudes for arbitrary k. In another project we have obtained the relation between 6-point CEGM amplitude for $k = 3$ and one-loop 4-point integrand in bi-adjoint ϕ^3 theory using $\mathrm{Gr}\,(3, 6)$ cluster algebra.

Publications:

1. Md. Abhishek, Subramanya Hegde, Arnab Priya Saha, *One-loop integrand from generalised scattering equations,* JHEP **5**, 012, (2021).

2. Md. Abhishek, Subramanya Hegde, Dileep Jatkar, Arnab Priya Saha, *Double Soft Theorem for Generalised Biadjoint Scalar Amplitudes,* SciPost Phys. **10**, 036, (2021).

Conference/Workshops Attended:

1. *Amplitudes*, USA, June, 2021.

2. *Strings*, South Africa, June, 2021.

3. *Recent Developments in S-matrix Program*, India, July, 2021.

Invited Lectures/Seminars:

1. *Double soft theorem in generalized bi-adjoint amplitude*, String Seminars, International Centre for Theoretical Sciences, Bengaluru, June, 2020.

2. *Double soft theorem in generalized bi-adjoint amplitude*, Recent Developments in S-matrix Program, International Centre for Theoretical Sciences, Bengaluru, July, 2020.

3. *One-loop integrand from generalised scattering equations*, Quantum Space-time seminars, Tata Institute of Fundamental Research, Mumbai, April, 2021

Mihir Ranjan Sahoo

Research Summary:

During the period, *i.e*, from 17th December 2020 to present, I have worked on the following projects.

I have investigated the catalytic activities of $Ag_{29}(BDT)_{12}(TPP)_4$ (BDT= 1,2 benzenedithiol, TPP = triphenylphopshine) cluster towards hydrogen evolution reation (HER) through first-principles density functional theory.the optimized struture consists of four TPP ligands connected to 4 Ag atoms of the surface of the cluster which constitutes C3 point group symmetry. Using Norskov's computational hydrogen electrode (CHE) model, we have calcualted the change in free energy of H adsoprtion which is related to the overpotential required to carry out the electrochemical reaction. Our density functional theory calculation shows that S atoms of the ligands are actve sites for HER. This project in collaboration with an experimental group. The manuscript is under preparation.

The second project on which I am working is the determination of ground state energies of different metallic clusters with machine learning method. In this work, we mainly convert the co-oridnates of clusters into Coloumb eignevalues which can be act as descriptors for use in machine learning. This is an ongoing work.

Preprints:

1. Anand Puthirath, Mihir Sahoo, Prasenjit Sen *Catalytic activity of* $Ag_{29}(BDT)_{12}(TPP)_4$ *cluster towards hydrogen evolution reaction* , write (in preparation)

Conference/Workshops Attended:

1. Attended On-line Workshop *2oth International Workshops on Computational Physics and Materials Science: Total Energy and Force Methods* , ICTP, Italy, March, 2021.

2. Attended On-line workshop *2D Materials for Spin-Orbitronics* , ICTP, Italy, May, 2021.

Tousik Samui

Research Summary:

In one of our works, we studied a neutrinophilic $U(1)$ extension of the standard model (SM) which couples only to SM isosinglet neutral fermions, charged under the new group. The neutral fermions couple to the SM matter fields through Yukawa interactions. The neutrinos in the model get their masses from a standard inverse-seesaw mechanism while an added scalar sector is responsible for the breaking of the gauged $U(1)$ leading to a light neutral gauge boson (Z') which has minimal interaction with the SM sector. We studied the phenomenology of having such a light Z' in the context of neutrinophilic interactions as well as the role of allowing kinetic mixing between the new $U(1)$ group with the SM hypercharge group. We showed that current experimental searches allow for a very light Z' if it does not couple to SM fields directly and highlight the search strategies at the LHC. We observed that multi-lepton final states in the form of (4ℓ + MET) and (3ℓ + $2j$ + MET) could be crucial in discovering such a neutrinophilic gauge boson lying in a mass range of 200–500 GeV.

In another work, we studied thermalization of charged SYK model in two different phases. We showed that both the highly chaotic liquid phase and the dilute gas phase thermalize. Surprisingly, the dilute gas state thermalizes instantaneously. We argued that this phenomenon arises because the system in this phase consists of only long-lived quasi-particles at very low density. The liquid state thermalizes exponentially fast. We also showed that the additional introduction of random mass deformation ($q = 2$ SYK term) slows down thermalization but the system thermalizes exponentially fast. This is observed despite the fact that the addition of large $q = 2$ SYK interaction forces spectral statistics to obey Poisson statistics. An interesting new observation was that the effective temperature is non-monotonic during thermalization in the liquid state. It has a bump at relatively long time before settling down to the final value. With non-zero chemical potential, the effective temperature oscillates noticeably before settling down to the final value.

Publications:

1. Tousik Samui and Nilakash Sorokhaibam, *Thermalization in Different Phases of Charged SYK Model*, JHEP **04**, 157 (2021).

2. Aruna Kumar Nayak, Santosh Kumar Rai and Tousik Samui, *Improving Heavy Dijet Resonance Searches Using Jet Substructure at the LHC*, Eur. Phys. J. C **81**, no. 2, 130 (2021).

Preprints:

1. Waleed Abdallah, Anjan Kumar Barik, Santosh Kumar Rai and Tousik Samui, *Search for a Light Z' at LHC in a Neutrinophilic $U(1)$ Model*, arXiv:2106.01362 [hep-ph].

Conference/Workshops Attended:

1. *Anomalies 2020*, India, September, 2020.

Invited Lectures/Seminars:

1. *Improving Heavy Dijet Resonance Searches Using Jet Substructure at the LHC*, Anomalies 2020, IIT Hyderabad, India, September, 2020.

Other Activities:

1. Designed and maintaining a webpage which shows live status of running jobs in HRI-HPC cluster, January 2020 – Present.

Faruk Abdulla

Research Summary:

Over the past year, I have been working on two different problems with my collaborators. In both the problems, we consider a Weyl semimetal (WSM) to begin with. Weyl semimetal is a three dimensional gapless topological material (a semimetal) which hosts Weyl fermions as a low energy excitations. This material has non trivial exotic boundary states which are called the Fermi arc surface states and they are topologically protected.

In the first problem, we have studied Fermi arc surface states at the junction of two Weyl semimetals which are twisted and then tunnel coupled. Our interest has been to understand how the Fermi arcs surface states of the individual slabs get reconstructed at the interface and evolve as we change the twist angle and tunnel coupling strength. This work has been completed and is also available on the web with the identifier PRB 103, 235308 (2021).

In the second problem, we are trying to understand the effect of commensurate magnetic field on a time reversal broken lattice Weyl semimetal model, in the Hofstadter regime. We have shown that the model can be solved analytically to compute phase diagram for arbitrary commensurate magnetic field. We also find existence of new interesting phases which are induced by external magnetic field in the three dimensional system.

Publications:

1. Faruk Abdulla, Sumathi Rao, and Ganpathy Murthy, *Fermi Arc Reconstruction at the Interface of Twisted Weyl Semimetals,* Phys. Rev. B **103**, 235308 (2021)

2. Faruk Abdulla, Priyanka Mohan, and Sumathi Rao, *Curvature function renormalization, topological phase transitions, and multicriticality,* Phys. Rev. B **102**, 235129 (2020).

Preprints:

1. Faruk Abdulla, Ankur Das, Sumathi Rao, and Ganpathy Murthy, *Lattice Weyl semimetal in the Hofstadter regime* (in preparation).

Conference/Workshops Attended:

1. Attended *3rd Annual Conference of Quantum Condensed Matter (Q-MAT: 2020)*, organized by S. N. Bose National Centre for Basic Sciences in September 7-11, Kolkata, 2020.

2. *APS March Meeting(online)*, American Physical Society, USA, March, 2021.

Invited Lectures/Seminars:

1. *Phase Diagram of Weyl semimetal in commensurate magnetic field*, APS March Meeting*(online conference)*, American Physical Society, USA, March, 2021.

Md. Abhishek

Research Summary:

During the academic year 2020-2021, in the collaboration with Dileep P. Jatkar, Arnab Priya Saha, and Subramanya Hegde, we have been studying the dual conformal symmetries and Yangian symmetries of $\mathcal{N} = 4$ Super Yang-Mills theory (SYM) and working on the scattering amplitudes of the above theory in the language of positive Grassmannian, tropical algebra and cluster algebra.

With Dileep P. Jatkar, Sachin Grover, and Kajal Singh, we have recently started working on some problems related to the duality between 4-dimensional super conformal field theory (4d SCFT) and 2-dimensional conformal field theory (2d CFT).

Publications:

1. Md. Abhishek, S. Hegde, D. P. Jatkar, and A. P. Saha, *Double Soft Theorem for Generalised Biadjoint Scalar Amplitudes,* SciPost Phys. **10**, 36, (2021). arXiv:2008.07271.

Preprints:

1. Md. Abhishek, S. Hegde, and A. P. Saha, *One-loop integrand from generalised scattering equations,* arXiv:2012.10916.

Conference/Workshops Attended:

1. *Zoomplitudes 2020*, Brown University, USA, 11-15th May, 2020.
2. *Student Talks on Trending Topics in Theory (ST4) 2020*, India, 6-18th July, 2020.
3. *Recent Developments in S-matrix theory*, ICTS, India, 20-31st July, 2020.
4. *Hamilton School on Mathematical Physics*, Trinity College Dublin, Ireland, 24-28th August, 2020.

Other Activities:

1. Teaching Assistant, 'General Relativity' Course, September 2020 - January 2021.
2. Audited 'Quantum Field Theory-1' Course by Ashoke Sen (HRI), September 2020 - January 2021.
3. Audited 'Black Hole Information Paradox' Course by Suvrat Raju (ICTS), January 2021 - April 2021.

Khorsed Alam

Research Summary:

Hydrogen, identified as a possible fuel, is the most efficient energy carriers. One of the most viable way of producing H_2 is through electrochemical water splitting where water is decomposed in an electrochemical cell driven by external bias. H_2 is produced at the cathode via hydrogen evolution reaction. Achieving efficient water splitting requires use of catalysts to minimise the over potential necessary to drive the HER. The free energy of hydrogen adsorption (ΔG_{H*}) on the catalyst surface is identified as good descriptor for HER activity of a catalyst system in acidic medium. Necessary condition for a material to be a good HER catalyst is that ΔG_{H*} needs to be closed to zero. Pt, which is so far the best HER catalyst in acidic medium. Pt is very expensive and one needs alternative low cost and abundant catalyst to replace it.

Recently, few layered transition metal trichalcogenide compounds (such as $CoPS_3$, $NIPS_3$, $FePSe_3$ and $MnPSe_3$) are experimentally found to be good HER catalysts in acidic medium. One intriguing question here would be whether there are other possible TMTC compounds which may not have yet been synthesized, but can be efficient HER catalysts. I have been a part of a recent work where we have combinatorially designed and computationally screened single layers of a large number of TMTC compounds, including those that are not reported in ICSD, for their efficiency as HER catalysts. ΔG_{H*} was calculated at different sites on the basal planes of these compounds to determine their HER efficiency. 13 as yet unknown TMTC compounds are identified as efficient HER catalysts having ΔG_{H*} values close to zero.

In an apparent discrepancy with the experiments, It turns out that the calculated ΔG_{H*} values on the basal planes of $CoPS_3$, $NIPS_3$, $FePSe_3$ and $MnPSe_3$ are not close to zero, and indeed very large. Therefore, basal planes are not probably the HER active sites in this materials. One possibility is that the edges of these materials which are very much present in experimental samples, are the active sites. To test this hypothesis, we have studied HER at the edges of these materials. Low energy edges are identified and ΔG_{H*} at different sites are calculated using DFT. Many edge atoms are identified as the active sites having small ΔG_{H*} values, the details of which depend on the concentration of H^+ ions in the electrolyte. Effect of water solvent on the values are also studied using implicit solvation model developed by Arias et al. This project is currently under review.

As a continuation of our project where we identified 13 unknown TMTC compounds as potential HER catalysts, we are currently studying the dynamical, mechanical and thermodynamic stability of these compounds to test the feasibility of their experimental synthesis. We have already determined their dynamical stability by means of calculating their phonon band structures within the density functional perturbation theory framework. We have also calculated the elastic constants of these materials and applied the Born stability criteria to determine their mechanical stability. Calculations for their thermodynamic stability are performed where we constructed the convex hull on the ternary phase diagram for each of these compounds. 10 compounds are found to be both dynamically and mechanically as well as thermodynamically stable.

Our experimental collaborators have recently demonstrated a hybrid catalyst system having cobalt particle dispersed nitrogen doped graphitic spheres (Co@NGC-

NSs) which show excellent bifunctional catalytic efficiency towards both ORR and OER in alkaline medium at Zn-air battery cathode, performing even better than the benchmarked combination of Pt/IrO2 electrode. In order to have a microscopic picture of possible pathways for ORR and OER and to understand better why Co@NGC-NS acts as a better ORR/OER catalyst, we studied these reactions on a number of model systems, computationally tractable for DFT calculations. Free energies of different intermediates during ORR and OER at different adsorption sites for these model systems are calculated using DFT. Active sites for ORR and OER are identified. We found that even in presence of cobalt, reactions occur on NGC surface, N doping improves ORR whereas presence of Co is responsible for enhanced OER. C sites at appropriate distances from N dopant, in presence of cobalt cluster can provide pathways with higher ORR and lower OER potentials than the ones with NGC alone.

With the experimental collaborators, we are studying the effect of mixed electrolyte (KOH and LiOH) on the performance of zinc-air battery. We are studying the energetics of zincate species formation and decomposition at the electrode during discharge and charging of Zn-air battery.

Publications:

1. Pallavi Thakur, Munaiah Yeddala, Khorsed Alam, Shubhadeep Pal, Prasenjit Sen and Tharangattu N. Narayanan, *Cobalt Nanoparticles Dispersed Nitrogen Doped Graphitic Nano spheres based Rechargeable High Performance Zinc-Air Batteries,* ACS Appl. Energy Mater **3-8**, 7813, (2020).

Preprints:

1. Khorsed Alam, Tisita Das, Sudip Chakraborty and Prasenjit Sen, *Finding the catalytically active sites on the layered tri-chalcogenide compounds $CoPS_3$ and $NiPS_3$ for hydrogen evolution reaction,* (in peer review)

2. Tisita Das, Khorsed Alam, Sudip Chakraborty and Prasenjit Sen, *Probing Active Sites on $MnPSe_3$ and $FePSe_3$ tri-chalcogenides as a Design Strategy for Better Hydrogen Evolution Reaction Catalysts,* (in peer review)

3. Pallavi Thakur, Khorsed Alam, Prasenjit Sen, and Tharangattu N. Narayanan, *Extending the Cyclability of Alkaline Zinc-Air Batteries: Synergistic Roles of Li^+ and K^+ Ions in Electrodics,* (in peer review)

Conference/Workshops Attended:

1. *Smr 3516 - On-line Workshop on Excited Charge Dynamics in Semiconductors*, ICTP, Italy, September, 2020.

2. *3rd Annual Conference on Quantum Condensed Matter, On-line*, September, 2020.

3. *Evolution of Electronic Structure Theory and Experimental Realization (EESTER), On-line*, India, December, 2020.

4. *Smr 3554 - 20th International Workshop on Computational Physics and Materials Science: Total Energy and Force Methods, On-line* , ICTP, Italy, January, 2021.

Academic recognition/Awards:

- HRI-Infosys Prize for Graduate Students, For Excellence in Research in Condensed Matter Physics, 2020.

Other Activities:

1. Presented a poster titled ”DFT Study into Efficient Bi-functional Catalytic Activity of Cobalt Dispersed Nitrogen- doped Graphitic Nanospheres in Rechargeable Zn-air Battery” at EESTER, September, 2020.

2. Presented a poster titled ”Determining dynamical, mechanical and thermdynamical stability ofcombinatorially designed ternary transition metal trichalcogenides forpotential applications as hydrogen evolution reaction catalysts” at the 20th International Workshop on Computational Physics and Materials Science: Total Energy and Force Methods), January, 2021.

Sankha Subhra Bakshi

Research Summary:

Thermal transport in lower dimensional systems is a very interesting field of research itself as there is no general existing framework for expressing the macroscopic thermal transport laws in terms of the microscopics of the system yet.

I studied classical thermal transport by phonons in harmonic lattices in lower dimensional systems using an analytical approach. When anharmonicities are added to the system and they play a bigger role, we have to use numerical simulations. It is very interesting to ask what will happen when there exists thermal phases in the system. I did numerical simulations on a system that can go through phase transition using the Langevin method. Using this method we were able to calculate the temperature profile and the heat current. Unlike linear response theory we can use large thermal bias in this method without losing any generality and it was found that using a large bias in this method produces better results in terms of statistical errors. This method can also be used for quantum systems involving phonons and electrons given that we can assume adiabaticity of the faster degrees of freedom.

I also studied non-equilibrium field theory, namely the Keldysh method, in ordered to study transport phenomenons in quantum systems. Using the Keldysh method I am studying current flow in Mott insulators.

Conference/Workshops Attended:

1. *Introduction to Physics of Ultracold Gases*, India, April, 2021.
2. *Open system transport in superconducting wires*, India, April, 2021.

Ratul Banerjee

Research Summary:

Quantum resources such as, quantum entanglement, is necessary to get adventage in different information processing tasks over it's classical counterparts. For some of the tasks, it is needed to localize this quantum resource in a smaller part of the whole system. Moreover, quantifying multipartite entanglement is hard. We took a measure, called "localizable entanglement" - which is defined as the amount of entanglement generated in a smaller part of a N-party state by performing optimal local measurements on the rest of the system. On the other hand, genuine multipartite entanglement measures can capture certain features of a multisite composite system that are inaccessible via bipartite quantum correlation quantifiers. We merge these two concepts by introducing localizable genuine multimode entanglement for continuous variable systems, both for Gaussian and non-Gaussian multimode parent states. In this direction , we reported a compact form of localizable generalized geometric measure for multimode Gaussian states when Gaussian measurements are performed in some of the modes. We show that non-Gaussian measurements can concentrate more genuine multimode entanglement compared to the Gaussian ones.

Publications:

1. Ratul Banerjee, Srijon Ghosh, Shiladitya Mal, Aditi Sen De, *Spreading Nonlocality in Quantum Network,* Phys. Rev. Research **2**, 043355, (2020).

2. Ratul Banerjee,Amit Kumar Pal, Aditi Sen De, *Uniform decoherence effect on localizable entanglement in random multiqubit pure states,* Phys. Rev. A **101**, 042339, (2020).

Preprints:

1. Ratul Banerjee, Saptarshi Roy, Tamoghna Das, Aditi Sen De, *Localizing genuine multimode entanglement: Asymmetric gains via non-Gaussianity* arXiv:2103.10388v1

Conference/Workshops Attended:

1. *QIPA 2020*, HRI,Allahabad,India , October, 2020.

Other Activities:

1. Member of the organizing committee-QIPA 2020,HRI,October,2020.

2. Pesented poster titled- *Uniform Decoherence Effect on Localizable Entanglement in Random Multiqubit Pure States* in *QIPA-2020*,October,2020.

Anjan Kumar Barik

Research Summary:

In this academic year , I worked on a project under the supervision of Prof. Santosh Kumar Rai . The name of the project was "Search for a light $Z^{'}$ at LHC in a neutrinophilic $U(1)$ model" . Soon it will be in arXiv preprint .

Preprints:

1. Waleed Abdallah, Anjan Kumar Barik, Santosh Kumar Rai and Tousik Samui *Search for a light $Z^{'}$ at LHC in a neutrinophilic $U(1)$ model.*
(in preparation)

Nirnoy Basak

Research Summary:

In the academic year 2020-21 I was involved in two projects, both regarding weyl Semimetal.

In the first one which I was doing with Arijit Kundu(IIT Kanpur) and Udit Khanna (Weismann Institute), I tried to calculate Kubo conductivity in two perpendicular directions. We took a thin slab of Weyl semimetal which destroyed the isotropy along one direction and resulted in the flatbands. In that case we were comparing their conductivity response with a normal conductor and a normal insulator and see where will the material lie between them. This project is near finishing and soon we would publish the results.

In the next project we took a Weyl semimetal, insulator and superconductor junction and calculate the normal conductance, thermal conductance, thermal power and check the figure of merit namely the Wiedermann Franz law. Our objective is to check if the conductances show a periodic feature with the barrier variables as shown by Krishnendu Sengupta and Subhro Bhattacharjee in an early work on transport through Dirac material. This case was checked for two kinds of barriers, one thin and another thick barrier. Our plan is to calculate the similar quantities for a superconductor-Weyl semimetal-superconductor junction namely SNS junction.

Other Activities:

1. Tutorship in the Condensed Matter Physics 2 Course, February-May , 2021.

Swapnil Bhowmick

Research Summary:

After reading about general QRTs, I have started reading about entanglement as a resource theory. This includes separability criteria, distillation, LOCC operations and different types of entanglement measures.

Other Activities:

1. Tutor for electrodynamics course from May-Aug 2021

Debraj Bose

Research Summary:

I've studied phonon and electron dynamics in the Holstein model at finite temperature using a Langevin equation based method. Assuming adiabaticity of the phonons (larger natural time scale compared to the electrons), the phonon trajectories are first obtained using a stochastic equation of motion. Next, those are used as inputs to calculate the electron Green's function.

The main effort has gone into understanding the problem on a many site cluster. There, the single particle electronic density of states is analysed numerically. In the low temperature and weak electron-phonon coupling limits, the analytical results are reproduced. It was done previously for a two site problem. Many site 1 electron problem also it has been done. The problem has been done for many site many electron but for small system size.For many site many electron problem the numerics is getting out of hand. Hence, trying to build a new scheme for many site many electron for large size.

Another line of work that is being done is the Non-equilibrium response of the Mott insulator at finite temperature. The analytic calculations of the previous work is being done. The focus is now on the numerical and development and new problems from thereon.

Other Activities:

1. Tutorship for Condensed Matter-I, Aug-Jan, 2020.

Leela Ganesh Chandra Lakkaraju

Research Summary:

During last year, I have mainly worked in two directions. (1) investigations of quantum correlations in states of spin systems with variable range interaction. (2) analysis of $\mathcal{PT}$ symmetric systems. Let us discuss them in detail,

We studied XY model with variable range interactions and in the presence of a uniform transverse magnetic field. We show the generation of entanglement with an increase in the range of interactions that vary either exponentially or polynomially as the distance between the sites increases. We find that such entanglement enhancement is not ubiquitous and is dependent on the factorization points. We find that the temperature at which the canonical equilibrium state has non-zero entanglement increases with the increase in the range of interactions, thereby demonstrating enhanced robustness in entanglement against temperature in the presence of long-range interactions.

We consider the XYZ model with similar variable range interaction and observe the creation of long-range entanglement in dynamics both in the absence and presence of system-bath interactions. When part of the system interacts with the bath repeatedly we observe that long-range entanglement of the subparts which are not attached with the environment remains constant with time in the beginning of the evolution, called as freezing of entanglement, thereby demonstrating a method to protect long-range entanglement.

In another project, we prove that if a source produces an entangled state shared between two parties, Alice and Bob, situated in a far-apart location, the information about the operations performed by Alice whose subsystem evolves according to $\mathcal{PT}$-symmetric Hamiltonian can be gathered by Bob, if the density matrix is in complex Hilbert space. Employing quantum simulation of $\mathcal{PT}$-symmetric evolution, feasible with currently available technologies, we propose a scheme of sharing quantum random bit-string between two parties when one of them has access to a source generating pseudo-random numbers.

Preprints:

1. Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Saptarshi Roy, Aditi Sen (De), *Distribution of entanglement with variable range interactions,* arXiv:2006.09257v1.

2. Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen (De), *Decoherence-free mechanism to protect long-range entanglement against decoherence,* arXiv:2012.12882v1.

3. Leela Ganesh Chandra Lakkaraju, Shiladitya Mal Aditi Sen(De), *Randomness Amplification under Simulated $\mathcal{PT}$-symmetric Evolution,* arXiv:2012.12882v1.

Conference/Workshops Attended:

1. *Young quantum at HRI - 2020*, India, October, 2020. Presented a poster on *Distribution of entanglement with variable range interactions*

2. *Qiskit Global Summer School by IBM*, Online, August, 2020.

Other Activities:

1. Member of the organising committee of Young quantum conference at HRI.
2. Developed website for Young Quantum Conference 2020 Conference. https://www.hri.res.in/ confqic/youqu20/

Suman Jyoti De

Research Summary:

The research work that I have done during the academic year "2020-2021", is given below

The first part of my research work is related to Chiral detection of Majorana bound states at the edge of a quantum spin Hall insulator. Here we talked about a hybrid setup consisting of a superconductivity-proximitized quantum spin Hall (QSH) insulator and a quantum anomalous Hall (QAH) insulator which is proposed for chiral injection of electrons into the Majorana bound state (MBS).We also explored the effect of disorder in this set up and found that the conductance peak due to MBS is immune to disorder and paves the way for a clear detection of the $2e^2/h$ zero bias peak arising from the MBS.

The second 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 having spin rotation and other having three chiral mode without any spin rotation over some region of space.

I am also working on interface reconstruction in bilayer graphene system in presence of electron-electron interaction and also in presence of spatially varying bias voltage V_g between the layers.

Publications:

1. Amartya Saha, Suman Jyoti De, Sumathi Rao, Yuval Gefen, Ganpathy Murthy, *Emergence of spin-active channels at a quantum Hall interface,* Physical Review B Letter **103**, L081401, (2021).

Preprints:

1. Amartya Saha, Suman Jyoti De, Sumathi Rao, Yuval Gefen, Ganpathy Murthy, *Emergence of spin-active channels at a quantum Hall interface,* 2009.10539v1.

2. Vivekananda Adak, Aabir Mukhopadhyay, Suman Jyoti De, Udit Khanna, Sumathi Rao, Sourin Das, *Chiral detection of Majorana bound states at the edge of a quantum spin Hall insulator,* 2106.04596v1.

Conference/Workshops Attended:

1. *I have attended the QMAT conference at S.N. Bose National Center for Basic Sciences*, India, 7-11 September, 2020.

2. *I have attended the APS March Meeting 2021*, USA, 15-19 March, 2021.

Atri Dey

Research Summary:

In the paper "LHC signals of triplet scalars as dark matter portal: cut-based approach and improvement with gradient boosting and neural networks", We consider a scenario where an SU(2) triplet scalar acts as the portal fora scalar dark matter particle. We identify regions of the parameter space, where such atriplet coexists with the usual Higgs doublet consistently with all theoretical as well asneutrino, accelerator and dark matter constraints, and the triplet-dominated neutral statehas substantial invisible branching fraction. LHC signals are investigated for such regions,in the final state same-sign dilepton + 2 jets + missingE_T. While straightforward detectabilityat the high-luminosity run is predicted for some benchmark points in a cut-based analysis,there are other benchmarks where one has to resort to gradient boosting/neural networktechniques in order to achieve appreciable signal signi cance.

ON the other hand, in the paper "Muon g-2 and a type-X two Higgs doublet scenario: some studies in high-scale validity", We study the high-scale validity of a Type-X two Higgs doublet scenario which provides an explanation of the observed value of muon (g-2). This region admits of a pseudoscalar physical state, which is well below the observed 125-GeV scalar in mass. A second neutral scalar particle can be both above and below 125 GeV in such a scenario. Admissible regions in the parameter space are obtained by using the most recent data on muon (g-2), theoretical constraints such as low-scale perturbativity and vacuum stability, and also all experimental constraints, including the available LHC results. Among other things, both the aforesaid orders of CP-even neutral scalar masses are included in our benchmark studies. Two-loop renormalisation group equations are used to predict the values of various couplings at high scales, and the regions in the space spanned by low-scale parameters, which retain perturbative unitarity as well as vacuum stability upto various scales are identified. We thus conclude that such a scenario, while successfully explaining the observed muon (g-2), can be valid upto energy scales ranging from 10^4 GeV to the Planck scale, thus opening up directions of thought on its ultraviolet completion.

Publications:

1. Atri Dey, Jayita Lahiri and Biswarup Mukhopadhyaya, *LHC signals of triplet scalars as dark matter portal: cut-based approach and improvement with gradient boosting and neural networks,* JHEP 06 (2020) 126 - 10.1007/JHEP06(2020)126,46 Pages,2020.

Preprints:

1. Atri Dey, Jayita Lahiri and Biswarup Mukhopadhyaya, *Muon g-2 and a type-X two Higgs doublet scenario: some studies in high-scale validity,* 2106.01449 [hep-ph].

Conference/Workshops Attended:

1. *XXIV DAE-BRNS High Energy Physics Symposium*, India, December, 2020.

Invited Lectures/Seminars:

1. *LHC signals of triplet scalars as dark matter portal: cut-based approach and improvement with gradient boosting and neural networks*, XXIV DAE-BRNS High Energy Physics Symposium, NISER, Jatni, Odisha, 752050, December, 2020.

Shyamashish Dey

Research Summary:

Last academic year and continuing now, I am working with Prof. Santosh Kumar Rai and Purusottam Ghosh on a project which explores Left Right symmetric Dark Matter model and it's collider searches.

Preprints:

1. Shyamashish Dey, Purusottam Ghosh and Santosh Kumar Rai *Doubly Charged scalar and Fermionic Dark Matter with extended Minimal Left Right Symmetric Model* (in preparation)

Avirup Ghosh

Research Summary:

In the academic year 2020-21 I have studied the phenomenology of a decaying FIMP dark matter and its connection with neutrino phenomenology. I have constructed three distinct models, all of which are simple extension of the standard model (SM) and studied their phenomenology.
I have further studied how the XENON1T electronic recoil data can pose constraints on the parameter space of a decaying fermionic dark matter.

Preprints:

1. Laura Covi, Avirup Ghosh, Tanmoy Mondal, Biswarup Mukhopadhyaya

   Models of decaying FIMP Dark Matter: potential links with the Neutrino Sector, e-Print: ArXiv: 2008.12550

2. Koushik Dutta, Avirup Ghosh, Arpan Kar,Biswarup Mukhopadhyaya,

   Decaying fermionic dark matter and XENON1T electronic recoil excess, e-Print:ArXiv: 2103.14664

Srijon Ghosh

Research Summary:

In the last academic year, my research work was mainly focused on the effects of environment on various physically implementable systems. In the literature this studies is well known as the open quantum system. To be precise, I along with my collaborators were concentrated to model the systems that depicts quantum thermal devices (quantum battery, quantum refrigerator etc.) with quantum spin chains supplemented by the basic theory of quantum thermodynamics and able to show the counter-intuitive behavior of physically measurable quantities in precense of decoherence. I also work on the distribution and freezing like properties of quantum resources for e.g., entanglement on a variable range quantum spin-chain in presence of noisy environments.

Publications:

1. Ratul Banerjee, Srijon Ghosh, Shiladitya Mal and Aditi Sen(De), *Spreading nonlocality in a quantum network,* Phys. Rev. Research **2**, 043355, (2020).

Preprints:

1. Srijon Ghosh, Titas Chanda, Shiladitya Mal, Aditi Sen De, *Fast charging of quantum battery assisted by noise* , arXiv : 2005.12859.

2. Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Saptarshi Roy, Aditi Sen De, *Distribution of entanglement with variable range interactions* , arXiv : 2006.09257.

3. Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen De, *Decoherence-free mechanism to protect long-range entanglement against decoherence* , arXiv : 2012.12882

Conference/Workshops Attended:

1. *Q-MAT : 2020: 3rd Annual Conference of Quantum Condensed Matter, SN Bose National Center for Basic Sciences* (Gave a talk), India, September, 2020.

2. *YouQu20, Harish Chandra Research Institute*, (Presented a poster) India, October, 2020.

Other Activities:

1. Organizer, YouQu20 Harish-Chandra Research Institute, October, 2020.

Ahana Ghoshal

Research Summary:

My research work is in the general area of quantum information and computation under the guidance of Prof. Ujjwal Sen. In the previous academic year, I have worked on different aspects of quantum information, like open quantum systems, quantum transistors, quantum refrigerators, etc. In particular, I worked on quantum thermal transistors which can cause the transistor effect with good amplification properties in the transient regime. We found three broad classes of transient quantum thermal transistors - the first having a smaller amplification than the steady state quantum thermal transistor, the second with better amplification but a smaller operating region in terms of temperature, and the third that gives higher amplification with a larger operating region. The last type is of particular interest as it also operates in the region where the steady state thermal transistors lose the transistor effect i.e., a necessarily transient transistor.

In another work I have dealt with quantum absorption refrigerators. We showed that quantum absorption refrigerators, which has traditionally been studied as of three qubits, each of which is connected to a thermal reservoir, can also be constructed by using three qubits and two thermal baths, where two of the qubits, including the qubit to be cooled, are connected to a common bath. With a careful choice of the system, bath, and qubit-bath interaction parameters within the Born-Markov and rotating wave approximations, one of the qubits attached to the common bath achieves a cooling in the steady-state. We observed that the proposed refrigerator may also operate in a parameter regime where no or negligible steady-state cooling is achieved, but there is considerable transient cooling. The steady-state temperature can be lowered significantly by an increase in the strength of the few-body interaction terms existing due to the use of the common bath in the refrigerator setup, proving the importance of the two-bath setup over the conventional three-bath construction.

In other direction, I examined the elements of the balance equation of entropy in open quantum evolutions, and their response as we go over from a Markovian to a non-Markovian situation. In particular, we looked at the heat current and entropy production rate in the non-Markovian reduced evolution, and a Markovian limit of the same, experienced by one of two interacting systems immersed in a Markovian bath. The analysis naturally led us to define a heat current deficit and an entropy production rate deficit, being differences between the global and local versions of the corresponding quantities. The investigation brought us, in certain cases, to a complementarity of the time-integrated heat current deficit with the relative entropy of entanglement between the two systems. I am also doing some more work on open quantum system and have started working in the general direction of quantum information.

Publications:

1. Riddhi Ghosh, Ahana Ghoshal, and Ujjwal Sen, *Quantum thermal transistors: Operation characteristics in steady state versus transient regimes,* Phys. Rev. A **103**, 052613, (2021).

Preprints:

1. Ahana Ghoshal, Sreetama Das, Amit Kumar Pal, Aditi Sen(De), Ujjwal Sen, *Three cooling off in two baths: Beyond two-body system-bath interactions in quantum refrigerators,* arXiv:2012.08399.

2. Ahana Ghoshal and Ujjwal Sen, *Heat current and entropy production rate in local non-Markovian quantum dynamics of global Markovian evolution,* arXiv:2102.06694.

Conference/Workshops Attended:

1. *QMAT-2020*, SN Bose National Center for Basic Sciences, Kolkata, India, 07-11 Sep, 2020. Presented a talk on "Population inversion and entanglement in single and double glassy Jaynes-Cummings models".

2. *Young Quantum 2020*, Harish-Chandra Research Institute, Allahabad, India, 12-15 Oct, 2020. Presented a poster on "Population inversion and entanglement in single and double glassy Jaynes-Cummings models".

Sachin Grover

Research Summary:

In a project, with Prof. Dileep P. Jatkar, we have looked at the techniques of resurgence, trans-series and asymptotics in physics in closer details. We are also trying to understand the space of solvable quantum mechanics models through deformations in quantum mechanics.

Through two other projects, we are exploring the conformal field theories (CFTs) in two dimensions and also the correspondence of the four-dimensional superconformal field theories (SCFTs) with the two-dimensional CFTs. These projects are part of the collaboration with Prof. Jatkar, Dr Subramanya Hegde and with Prof. Jatkar, Md. Abhishek and Kajal Singh respectively.

Conference/Workshops Attended:

1. *Summer School on Superstring Theory and Related Topics — (smr 3551)*, Online School, International Center for Theoretical Physics (ICTP), Trieste, Italy, 24 August-4 September 2020, held via zoom.

2. *2nd Hamilton School on Mathematical Physics 2020* , Online School, Dublin, Ireland, 24-28 August 2020, held via zoom.

3. *Student Talks on Trending Topics in Theory (ST4) 2020*, 6-18 July 2020, held via zoom.

Other Activities:

1. Tutor for Quantum Field Theory-2 ,HRI, February-June 2021.

2. Course attended: String Theory, Instructor- Prof. Dileep P. Jatkar, HRI, March-June 2021.

3. Course attended: The Black Hole Information Paradox, Instructor- Prof. Suvrat Raju, International Center for Theoretical Sciences (ICTS), Bangalore, Spring 2021.

Rivu Gupta

Research Summary:

In the previous year, my research was primarily focused on quantum information theory, with particular emphasis on the theory of entanglement, quantum communication protocols and quantum correlations. In this respect, me and my collaborators studied the behavior of quantum correlations in the presence of noisy environment and also the performance of communication protocols aided by pre-processing operations. We also worked on the *"monogamy"* relation satisfied by diverse quantum correlation measures. All the works were based on the generation of random states and their statistical behavior pertaining to the theory under investigation, was highlighted.

In the first work, we investigated the effects of local decoherence on quantum correlations of Haar uniformly simulated two-qubit initial states with different ranks and checked whether the results obtained for a specific class of states persist even for random states or not. Specifically, when either one of the qubits or both the qubits of random two-qubit states were independently sent through dephasing and depolarizing non-Markovian channels, we showed generic traits followed by quantum correlations in the form of entanglement and discord. We found that both the measures showed revival after the collapse due to the presence of non-Marokovianity irrespective of the ranks of the input quantum states. We reported a counter-intuitive phenomena for both the measures which we called *constructive effect of non-Markovianity*.

Our next work was based on two quantum communication protocols, viz. *quantum dense coding* and *quantum teleportation*. We investigated the patterns of capabilities obtained from the two quantum communication tasks for Haar uniformly generated random shared channels. We applied local pre-processing operations in the form of dichotomic positive operator valued measurements (POVM)s (exclusive of the encoding and decoding strategies) on the shared state before starting the protocol and reported that the performance was enhanced by such pre-processing mechanism for random states.

We also worked on the well known *monogamy principle* followed by quantum correlation measures and its relation with the "generalised geometric measure" (GGM). We investigated quantum correlations present in a multipartite system by exploring connections between monogamy score, localizable quantum correlations, and genuine multipartite entanglement (GME) content of the state.

Publications:

1. Rivu Gupta, Shashank Gupta, Shiladitya Mal, and Aditi Sen(De), *Performance of dense coding and teleportation for random states: Augmentation via preprocessing*, Phys. Rev. A **103**, 032608, (2021).

Preprints:

1. Rivu Gupta, Shashank Gupta, Shiladitya Mal, and Aditi Sen(De), *Constructive Feedback of Non-Markovianity on Resources in Random Quantum States*, arXiv:2005.04009

2. Rivu Gupta, Saptarshi Roy, Shiladitya Mal, and Aditi Sen(De), *Emergence of Mono -gamy under Static and Dynamic Scenarios,* arXiv:2102.04940

Conference/Workshops Attended:

1. *Young Quantum 2020*, Harish Chandra Research Institute, (October 12-15), 2020. (Presented a poster: *Constructive Feedback of Non-Markovianity on Resources in Random Quantum States,*)

Arpan Kar

Research Summary:

In the academic year 2020-2021, I have worked on two different aspects of dark matter (DM) search, namely, indirect and direct searches. A brief description of my research work performed in this academic year is given below.

I have investigated the possibilities for probing MeV DM particles and primordial black holes (PBHs) (for masses $\sim 10^{15}$–10^{17} g) at the upcoming radio telescope Square kilometer Array (SKA), using photon signals from the Inverse Compton (IC) effect within a galactic halo. Pair-annihilation or decay of MeV DM particles (into e^+e^- pairs) or Hawking radiation from a population of PBHs generates mildly relativistic $e^{\pm}$ which can lead to radio signals through the IC scattering on low energy cosmic microwave background (CMB) photons. I have studied the ability of the SKA to detect such signals coming from nearby ultra-faint dwarf galaxies Segue I and Ursa Major II as well as the globular cluster ω-cen and the Coma cluster. I find that with ~ 100 hours of observation, the SKA improves the Planck constraints on the DM annihilation/decay rate and the PBH abundance for masses in the range ~ 1 to few tens of MeV and above 10^{15} to 10^{17} g, respectively. Importantly, the SKA limits are independent of the assumed magnetic fields within the galaxies. Previously allowed regions of diffusion parameters of MeV electrons inside a dwarf galaxy that give rise to observable signals at the SKA are also excluded. For objects like dwarf galaxies, predicted SKA constraints depend on both the DM and diffusion parameters. Independent observations in different frequency bands, e.g., radio and γ-ray frequencies, may break this degeneracy and thus enable one to constrain the combined parameter space of DM and diffusion. However, the constraints are independent of diffusion parameters for galaxy clusters such as Coma.

In addition, in the light of the recently observed XENON1T electronic recoil (ER) data (published in June, 2020), I have examined the prospects of constraining the parameter space of a generic fermionic warm dark matter (WDM) particle, decaying into a standard model (SM) neutrino and a photon. The photon as a decay product, when produced inside the XENON1T chamber, interacts with an electron of a xenon (Xe) atom, leading to a contribution in the observed ER data. I have added this DM induced signal over four distinct backgrounds (taking one at a time) and perform a χ^2 fit against the XENON1T data to obtain the best-fit values of the DM decay width and the associated 95% confidence level (C.L.) bands for DM mass varied in the range $2-18$ keV. By comparing the constraints, obtained by fitting the XENON1T data, with the upper limits, arising from various existing astrophysical and cosmological observations, I find that a fair amount of the DM parameter space is allowed at 95% C.L., for each of the background models considered.

Publications:

1. Arpan Kar, Bhaskar Dutta, and Louis E. Strigari, *Constraints on MeV dark matter and primordial black holes: Inverse Compton signals at the SKA,* Journal of Cosmology and Astroparticle Physics **2021**, 011, (2021).

2. Arpan Kar, Avirup Ghosh and Biswarup Mukhopadhyaya, *Search for decaying*

heavy dark matter in an effective interaction framework: a comparison of γ-ray and radio observations, Journal of Cosmology and Astroparticle Physics **2020**, 003, (2020).

3. Arpan Kar, Biswarup Mukhopadhyaya, Steven Tingay, Ben McKinley, Marijke Haverkorn, Sam McSweeney, Natasha Hurley-Walker, Sourav Mitra and Tirthankar Roy Choudhury, *Dark matter annihilation in ω Centauri: Astrophysical implications derived from the MWA radio data,* Physics of the Dark Universe **30**, 100689, (2020).

Preprints:

1. Arpan Kar, Koushik Dutta, Avirup Ghosh, and Biswarup Mukhopadhyaya, *Decaying fermionic warm dark matter and XENON1T electronic recoil excess,* arXiv:2103.14664

Conference/Workshops Attended:

1. *Less Travelled Path of Dark Matter: Axions and Primordial Black Holes (Online)*, India, November, 2020.

Academic recognition/Awards:

- Infosys Award 2020.

Ratul Mahanta

Research Summary:

During the academic year 2020-2021, I focused largely on the two research projects listed below, in collaboration with others.

(1) In closed superstring field theory, we extended a known domain in complex external momenta variables where the infrared safe part of the off-shell n-point Green's function is analytic. In particular, up to the four-point function we recovered the full primitive domain as in the case of a standard local QFT. This establishes many standard analyticity properties for the S-matrix of superstring theory.

(2) We studied the impact of non-thermal hot dark matter particles (that are produced from inflaton/moduli decay) on the CMB and large scale structure, by taking into account their non-thermal momentum distribution function. We obtained a relaxation of the mass bound on hot DM particles that is compatible with the existing evidence.

Publications:

1. Ritabrata Bhattacharya and Ratul Mahanta, *"Analyticity of off-shell Green's functions in superstring field theory"*, JHEP **01** (2021) 010.

2. Sukannya Bhattacharya, Subinoy Das, Koushik Dutta, Mayukh Raj Gangopadhyay, Ratul Mahanta and Anshuman Maharana, *"Nonthermal hot dark matter from inflaton or moduli decay: Momentum distribution and relaxation of the cosmological mass bound"*, Phys. Rev. D **103**, 063503.

Conference/Workshops Attended:

1. *XXIV DAE-BRNS High Energy Physics Symposium*, National Institute of Science Education and Research (NISER), Bhubaneshwar, India, December, 2020.

Invited Lectures/Seminars:

1. *"Analyticity of Off-shell Green's Functions in Superstring Field Theory"*, XXIV DAE-BRNS High Energy Physics Symposium, National Institute of Science Education and Research (NISER), Bhubaneshwar, India, December 2020.

2. *"Introductory lecture on WZW models"*, Chennai Mathematical Institute (CMI), Chennai, India, February 2021.

3. *"Modular Averages for WZW Correlators, and $N \leftrightarrow k$ Correspondence"*, Chennai Mathematical Institute (CMI), Chennai, India, February 2021.

Academic recognition/Awards:

- Infosys scholarship for senior students (HRI), 2020-21.

Susovan Maity

Research Summary:

The system I have been working on, is low angular momentum accretion disc around Kerr (rotating) blackhole in hydrostatic equilibrium. The formation of shock in this accretion flow and its effect on producing multitransonicity has been studied in detail in the paper "Influence of flow thickness on general relativistic low angular momentum accretion around spinning black holes" published in PRD. Various important dynamical quantities have been calculated and the effect of black hole spin and different general relativistic prescription has been studied in this paper which was submitted as a pre-print past year.

This year we have mainly studied how linear peturbation behaves in the stationary transonic flow background using method of analogue gravity. The discrepancy of critical points not coinciding with the sonic points in the accretion discs in hydrostatic equilibrium has been resolved by analysing the causal structure of the analogue spacetime using Carter-Penrose Diagram. It is established that critical points always act as acoustic horizon even if they do not coincide with the sonic point. The location of the shock has also been established as the white hole horizon. Such results have been described in the work titled "Carter-Penrose diagrams for emergent spacetime in axisymmetrically accreting black hole systems".

Non-linear perturbation in emergent gravity in non relativistic Bondi flow has also been studied further. Several dynamical quantities and their evolution has been studied at higher orders of perturbation in the work titled "Dynamical analogue spacetimes in non-relativistic flows".

Publications:

1. Tarafdar, P., Maity, S., & Das, T. K., *Influence of flow thickness on general relativistic low angular momentum accretion around spinning black holes, Phys, Rev. D,* Physical Review D **103**, 023023, (2021).

Preprints:

1. Maity, S., Shaikh, M. A., Tarafdar, P., & Das, T. K., *Carter-Penrose diagrams for emergenr spacetime in axisymmetrically accreting black hole systems,* arXiv:2106.07598.
2. Fernandes, K., Maity, S., & Das, T. K., *Dynamical analogue spacetimes in non-relativistic flows,* arXiv:2106.07618.

Academic recognition/Awards:

- Infosys Scholarship, 2020.

Other Activities:

1. Mentored Masters Project student Vasudev Mittal in the year 2020-2021 jointly with my thesis supervisor.

Brij Mohan

Research Summary:

In the last academic year 2020-2021, *i.e.*, 1st April 2020 to 31st March 2021, I have mainly worked on the reverse quantum speed limit of open quantum systems. The reverse quantum speed limit determines how slow a quantum system evolves in time. Thus, it sets the upper bound on the evolution time of a quantum system. We have generalized the notion of the reverse quantum speed limit for CPTP maps using purification. Also, we have evaluated the reverse speed limit for a two-level quantum system interacting with the dephasing/dissipative environment.

In addition to this, I have studied the addition of entangled states, volatility of quantum information and the speed limit for quantum observables.

Conference/Workshops Attended:

1. *Young Quantum - 2020 (YouQu-2020)*, India, 12-15th October, 2020 (Online). (Presented a poster on ' Reverse Quantum Speed Limit')
2. *QFTA-2020*, India, 4 - 9th December, 2020 (Online). (Presented a poster on ' Reverse Quantum Speed Limit')
3. *Is Quantum Theory exact? Exploring Quantum Boundaries*, NA, 10 - 11th December, 2020 (Online).

Tanmoy Mondal

Research Summary:

In the last academic year, I've studied phonon dynamics in a classical, anharmonic model using the Langevin equation, mainly on linear and square lattice.

I have studied the same model on triangular lattice to investigate the effect of geometric frustration. To describe the model, it is composed of local 'double-well' potentials at each site and a quadratic nearest-neighbour term. It may be thought of as an effective phonon Hamiltonian after integrating out microscopic electron degrees of freedom from a more fundamental electron-phonon (e.g. Holstein) model. Here, no ordered ground state exists and the static structure factor is featureless in the thermodynamic limit. Thermal tunneling dominated responses are observed at much lower temperatures compared to a system having ordered ground state. As the moves don't have any obvious spatial correlation, the momentum modes are not eigen states of the system. So, the momentum selectivity of spectral weight transfer is subdued. At high temperatures, the asymptotic behaviour is consistent with a local, quartic oscillator model.

For another work, I am working on the dynamics of classical anti-ferromagnetic Heisenberg model on Kagome lattice. Here also the geometric frustration does not allow any ordered ground state.The auto-correlation function indicates the presence of more than one time scale in the system.

We plane to study the above mentioned frustrated spin model more meticulously along with some more fundamental electron model to have a proper understanding of effects of frustration on magnetic systems.

Kalyanbrata Pal

Research Summary:

In the last academic year I have studied some basic topics on Astrophysics.I have mainly followed the book Astrophysics For Physicist by Arnab Rai Choudhuri. I have also studied some topics in astrophysics from books written by Dan Majos, Hannu Karttunen etc.

At present I am working on cosmology, mainly early universe, primordial star and galaxy formation with Prof. Tapas Das and Dr. Jayanta Dutta. My main goal is to study the metallicity in the EMP(extremely metal poor)stars and to get idea about the ambience of early universe. Scientific papers by BEERS and CHRISTLIEB, ANNA FREBEL etc I have studied to explore the field. Also tried to familiar myself with data release by GAIA and SAGA mission.

In future I also want to work on 21-cm cosmology.

Vivek Pandey

Research Summary:

In the last academic year 2020-2021, I have mainly studied apparatus-based quantum measurements in detail and information gain in this measurement process. Along with this, I have also studied indefinite causal order and Page-Wootters formalism in little detail.

Conference/Workshops Attended:

1. *YouQu 2020*, Harish-Chandra Research Institute, India, 12-15 October, 2020.

Other Activities:

1. Tutor QM-1 course, January-April, 2021.

Tanaya Ray

Research Summary:

We have established an inequality involving the quantum coherence of an arbitrary mixed quantum state in arbitrary dimension and a noncommutativity estimator of an arbitrary observable in the mentioned state. The noncommutativity estimator uses the commutator of the observable and its incoherent i.e. classical part. The relation provides a direct method of obtaining an estimate of the quantum coherence of an arbitrary quantum state . This can have potentially useful applications, because neither for providing the quantitative estimate nor for the qualitative witnessing do we require the usual methods of quantum state tomography or resort to the existing witness operators. We believe that the relation can be easily tested and put to use with existing experimental quantum information set-ups.

Preprints:

1. T. Ray, A. K. Pati and U. Sen, Estimating quantum coherence by noncommutativity of any observable and its incoherent part, arXiv:2004.07729 [quantph].

Conference/Workshops Attended:

1. *YouQu 2020*, India, October, 2020 (with Poster presentation).

Other Activities:

1. Tutorship of Quantum Mechanics III course, August-December, 2020.
2. Tutorship of Statistical mechanics Course, January-June, 2021.

Md Afsar Reja

Research Summary:

I have done two mandatory projects under the guidence of Prof. Asesh K Datta in which I have learned the basics of supersymmetry (SUSY) and its phenomenology and collider physics in general. To deal with a realistic physics problem I have also learned the technique of recasting the published Large Hadron Collider (LHC) analyses using the CheckMATE2 package. Finally, I have implemented and validated an interesting ATLAS analysis in CheckMATE2.

Subsequently, I started studying the neutralino sector of the $B - L$ SUSY Standard Model (BLSSM). In contrast to the popular Minimal Supersymmetric Standard Model (MSSM) having four neutralino states, BLSSM has got an augmented neutralino sector with seven of them. We find that the mixings among the various basis states leading to these neutralinos can be quite non-trivial and these can affect their phenomenology at the LHC. Our present study focuses on how light these states could get to be in light of current experimental analyses.

Conference/Workshops Attended:

1. *Terascale summer school, DESY*, Germany (online), August, 2020.
2. *Tools 2020, Institut de Physique des 2 Infinis de Lyon (IP2I), Lyon*, France (online), November, 2020.

Saptarshi Roy

Research Summary:

In the academic year "2020-2021" (1st April 2020 to 31st March 2021), my research works were mainly focused on two major directions – (1) study of non-classical correlations in finite and infinite dimensional systems, and (2) quantum teleportation.

In the sector of studies of non-classical correlations, we investigate robustness in the violation of Collins-Linden-Gisin-Masser-Popescu (CGLMP) inequality from the dual perspective of noise in measurements as well as in states. We examine the robustness in the sequential violation of CGLMP inequality using weak measurements, and find that even for higher dimensions, two observers showing a simultaneous violation of the CGLMP inequality as obtained for two-qubit states persists. We also study the restrictions in the distribution of correlations, both classical and quantum in multiparty states. Here we investigate quantum correlations (QCs) present in a multipartite system by exploring connections between monogamy score (MS), localizable quantum correlations (LQC), and genuine multipartite entanglement (GME) content of the state. We show that there is a critical value of GME beyond which all states become monogamous and it is investigated by considering different powers of MS which provide various layers of monogamy relations. Unlike quantum correlations, the shareability of classical correlations (CCs) between two-parties of a multipartite state is assumed to be free since there exist states for which CCs for each of the reduced states can simultaneously reach their algebraic maximum value. However, when one randomly picks out states from the state space, we find that the probability of obtaining those states possessing the algebraic maximum value is vanishingly small. We explore the possibility of nontrivial upper bound by Haar uniformly generating random multipartite states and computing the frequency distribution for various CC measures, conventional classical correlators, and two axiomatic measures of classical correlations, namely the classical part of quantum discord and local work of work-deficit.

We then move on to the investigation of quantum entanglement in quantum simulators, namely continuous variable systems and quantum spin chains. Firstly, distribution of quantum entanglement is investigated for an anisotropic quantum XY model with variable range interactions and a uniform transverse magnetic field. We report that the entanglement growth between distant sites with an increased interaction range is not ubiquitous and is dependent on the relative location of the system parameters with respect to the factorization points. We report that the temperature at which the canonical equilibrium state becomes entangled increases with the increase in the range of interactions, thereby demonstrating enhanced robustness in entanglement against temperature in the presence of long-range interactions. In the continuous variable sector, we introduce localizable genuine multimode entanglement, both for Gaussian and non-Gaussian multimode parent states. We report a compact form of localizable generalized geometric measure for multimode Gaussian states when Gaussian measurements are performed in some of the modes. We show that non-Gaussian measurements can concentrate more genuine multimode entanglement compared to the Gaussian ones.

In quantum teleportation, the state to be teleported is assumed to be completely unknown. We show, prior information about the input state can be utilized to en-

hance the efficiency of quantum teleportation which we quantify using the first two moments of fidelity. The input knowledge is introduced by relaxing the uniformity assumption in the distribution of the input state and considering non-uniform distributions, namely the polar cap and von Mises-Fisher densities. For these distributions,we show that the average fidelity increases while the deviation decreases with the increase of information content about the input ensemble thereby establishing its role as a resource.

Publications:

1. S. Haldar, Saptarshi Roy, T. Chanda, A. Sen (De), U. Sen, *Multipartite entanglement at dynamical quantum phase transitions with non-uniformly spaced criticalities,* Phys. Rev. B **101**, 22430, (2020).

2. Saptarshi Roy, T. Das, A. Sen (De), *Computable genuine multimode entanglement measure: Gaussian vs. non-Gaussian,* Phys. Rev. A **102**, 012421, (2020).

3. Saptarshi Roy and A. Ghosal, *Rating the performance of noisy teleportation using fluctuations in fidelity,* Phys. Rev. A **102**, 012428, (2020).

4. S. Haldar, Saptarshi Roy, T. Chanda, A. Sen (De), *Response of macroscopic and microscopic dynamical quantifiers to the quantum critical region,* Phys. Rev. Research **2**, 033249, (2020).

5. Saptarshi Roy, T. Das, D. Das, A. Sen (De), U. Sen, *How efficient is transport of quantum cargo through multiple highways?,* Annals of Physics **422**, 168281, (2020).

6. Saptarshi Roy, A. Bera, S. Mal, A. Sen (De), U. Sen, *Recycling the resource: Sequential usage of shared state in quantum teleportation with weak measurements,* Phys. Lett. A **392**, 127243, (2021).

7. Saptarshi Roy, S. Mal, A. Sen (De), *Restrictions on shareability of classical correlations for random multipartite quantum states,* Phys. Rev. A **103**, 052401, (2021).

Preprints:

1. L. G. C. Lakkaraju, S. Ghosh, Saptarshi Roy, A. Sen (De), *Distribution of entanglement with variable range interactions,* arXiv:2006.09257 [quant-ph].

2. Saptarshi Roy, S. Mal, A. Sen (De), *Gain in performance of quantum teleportation with uniformity breaking distributions,* arXiv:2010.14552 [quant-ph].

3. Saptarshi Roy, A. Kumari, S. Mal, A. Sen (De), *Robustness of Higher Dimensional Nonlocality against dual noise and sequential measurements,* arXiv:2012.12200 [quant-ph].

4. R. Gupta, Saptarshi Roy, S. Mal, A. Sen (De), *Emergence of Monogamy under Static and Dynamic Scenarios,* arXiv:2102.04940 [quant-ph].

5. R. Banerjee, Saptarshi Roy, T. Das, A. Sen (De), *Localizing genuine multimode entanglement: Asymmetric gains via non-Gaussianity,* arXiv:2103.10388 [quant-ph].

Conference/Workshops Attended:

1. *Young Qunatum*, India, October, 2020.

Invited Lectures/Seminars:

1. *Computations of genuine multimode entanglement measure: Gaussian vs non-Gaussian* , Young Quantum, Allahabad, Germany, October, 2020.
2. *Multipartite entanglement at dynamical quantum phase transitions*, Group meeting, Saarland University, Germany, March, 2021.

Other Activities:

1. Taken part in the organization of Young Qunatum, 2020.

Subhojit Roy

Research Summary:

During the academic year 2020-'21, I circulated one research paper on the arXiv (which subsequently got accepted in the Journal of High Energy Physics (JHEP)) presenting a detailed phenomenological study of a relatively light, highly bino-like neutralino (cold) dark matter (DM) in the framework of a Z_3-symmetric Next-to-Minimal Supersymmetric Standard Model (NMSSM). It was shown that, in contrary to the existing notion, such a neutralino can get to be as light as a few tens of a GeV while still conforming to all relevant constraints, both theoretical and experimental of which the latter take into account the pertinent ones from various colliders including the Large Hadron Collider (LHC) and DM experiments. This work was done in collaboration with Waleed Abdallah and AseshKrishna Datta.

In a subsequent work with Arindam Chatterjee and AseshKrishna Datta, we have started studying the problem of baryon asymmetry of the Universe in reference to the NMSSM. We investigate the parameter space of the NMSSM that allows for a strong, first order electroweak phase transition to satisfy the well-known set of Sakharov's conditions leading to baryogenesis by subjecting the same to the constraints from the LHC and DM experiments. For this project, I had to study the basics of finite temperature quantum field theory and cosmology in some detail.

In yet another work with AseshKrishna Datta, we have been studying the discovery potential of light neutralino states of the NMSSM arising in the decays of the lighter top squarks that are produced in pairs at the LHC. The study requires thorough recasts of relevant experimental analyses from recent times. I started working on the required computational setup.

Publications:

1. Subhojit Roy with Waleed Abdallah and AseshKrishna Datta, *A relatively light, highly bino-like dark matter in the Z_3-symmetric NMSSM and recent LHC searches*, arXiv:2012.04026 (accepted for publication in JHEP).

Conference/Workshops Attended:

1. *(Re)interpreting the results of new physics searches at the LHC, CERN, February, 2021 (online).*

2. *Searching for long-lived particles at the LHC and beyond: Eighth workshop of the LHC LLP Community, November, 2020 (online).*

3. *Tools 2020, Institut de Physique des 2 Infinis (IP2I) Lyon, France, November, 2020 (online).*

4. *Anomalies 2020, IIT-Hyderabad, India, September, 2020 (online).*

Invited Lectures/Seminars:

1. *A relatively light bino-like dark matter in the Z_3-symmetric NMSSM and its implications for the LHC*, Anomalies 2020, Indian Institute of Technology, Hyderabad, India, September, 2020 (online).

Kornikar Sen

Research Summary:

In the previous academic year, I have worked on certain aspects of quantum information theory, including measurement-device independence of quantum devices.

Particularly, I have explored measurement device-independent entanglement witnesses. There always exists an entanglement witness for every entangled quantum state. Negativity of the expectation value of an entanglement witness operator guarantees entanglement of the corresponding state, given that the measurement devices involved are perfect, i.e., the performed measurements actually constitute the witness operator for the state under consideration. In a realistic situation, there are two possible ways of measurements to drive the process away from the ideal one. Firstly, wrong measurements may be performed, and secondly, while the measurement operators are implemented correctly, the detection process is noisy. Entanglement witnesses are prone to both of these imperfections. The concept of measurement-device-independent entanglement witnesses was introduced to remove the first problem. We have analyzed the "detection loophole" in the context of measurement-device-independent entanglement witnesses, which deal with the second problem of imprecise measurements. We have obtained an upper bound on the entanglement witness function in the measurement-device-independent entanglement witness scenario, below which entanglement is guaranteed for given non-ideal detector efficiencies, that can involve both lost events and dark counts.

In the next work, I have considered noisy measurement device-independent entanglement witnesses. As discussed previously, masurement device-independent entanglement witnesses (MDI-EWs) never detect fake entanglement even under wrong measurements. A crucial assumption in the case of faithful detection of entanglement employing MDI-EWs is that the preparation devices producing "quantum inputs" - which are inputs additional to the quantum state whose entanglement is to be detected - are perfect and there is no noise during their transmission. We have relaxed these assumptions and provided a general framework for studying the effect of noise on the quantum inputs, invoking uniform and non-uniform noise models. We have derived sufficient conditions on the uniform noisy map for retaining the characteristic of MDI-EWs. We have found that in the context of non-uniform and entangling noise, fake entanglement detection is possible even by MDI-EWs. We have also investigated various paradigmatic models of local noise and found conditions of revealing entanglement in the class of Werner states.

Publications:

1. Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen(De), and Ujjwal Sen, *Detection loophole in measurement-device-independent entanglement witnesses,* Phys. Rev. A **103**, 032415, (2021).

Preprints:

1. Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Detection loophole in measurement-device-independent entanglement witness,* arXiv:2004.09101.

2. Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Noisy quantum input loophole in measurement-device-independent entanglement witnesses,* arXiv:2012.09089.

Conference/Workshops Attended:

1. *Young Quantum - 2020 (YouQu-2020)*, India, October, 2020.

Other Activities:

1. Tutorship for Numerical Methods Course, Jan-May, 2021.

Divyansh Shrimali

Research Summary:

Extending the work based on the approach towards estimation of non linear functionals of density operators using quantum networks, the current work focuses on determining the spectra of a given system which can in general be mixed or pure. The proposed protocol is for both interacting as well as non interacting systems. The aim is to give a mechanism to define appropriate density function of the the system complying with standard properties reducing which subsystems of the system can be extracted. For that, giving a reasonable estimation of a local Hamiltonian of a otherwise composite system was contemplated, and a way forward with reference to optimization in Hilbert-Schmidt space is proposed. So far, the ways to come up with precise and required transformations is being worked on which will have to be optimized to retrieve local Hamiltonian. Later the same protocol will be tested on composite system of more than two subsystems.

Another project undertaken involves study of scrambling for information as a no go result even with a quantum machine learning ansatz. It was proposed that the reason why scrambling for unitary operator involved in quantum process, under any cost function ansatz, will ultimately end up in a plateau, establishing a need for exponential increase of required training data needed with respect to the parameters involved.

Other Activities:

1. Internal arxiv flashback online meetings.

Kajal Singh

Research Summary:

During the academic year 2020-2021, I mainly studied the interplay between Kahler moduli stabilisation and the statistics of the phenomenologically interesting quantities in the string landscape. This work is done in collaboration with Igor Broeckel, Michele Cicoli, Kuver Sinha and Anshuman Maharana. In the first part of year, we focused on the statistics of the supersymmetry breaking scale by considering three general scenarios of moduli stabilisation. In the second part, we focused on the statistics of axion physics in the string landscape.

I am also working on dualities between 4D Super Conformal Field Theory (SCFT) and 2D CFT with Dileep Jatkar, Md. Abhishek and Sachin Grover.

Publications:

1. Igor Broeckel, Michele Cicoli, Anshuman Maharana, Kajal Singh, Kuver Sinha, *Moduli Stabilisation and the Statistics of SUSY Breaking in the Landscape,* JHEP **10**, 015, (2020).

2. Sukannya Bhattacharya, Koushik Dutta, Mayukh Raj Gangopadhyay, Anshuman Maharana, Kajal Singh, *Fibre Inflation and Precision CMB Data,* Phys.Rev.D **102**, 123531, (2020).

Conference/Workshops Attended:

1. *19th String Phenomenology 2020 (SP20)*, Virtual conference by Northeastern University, Boston, USA, June 2020

2. *Hamilton School on Mathematical Physics*, Digital School by Trinity College, Dublin, Ireland, August 2020.

3. *Student Talks on Trending Topics in Theory (st4)*, India, July 2020.

Sohail

Research Summary:

In the academic year 2019-2020 I have worked on quantum channels and Choi- Jamiolkowski isomorphism and explored their mathematical structures. In this work we have defined convolution product for super operators. In addition to this I have worked on teleportation of quantum coherence and their remote preparation, uncertainty relation for pre and post selection system, usefulness of higher moment weak values of observables for quantum states reconstruction. I have also worked on entanglement content of the quantum addition of quantum states and their comparison with the that of classical mixture.

Publications:

1. Sohail and Ujjwal Sen, *Witnessing nonseparability of bipartite quantum operations,* Physics Letters A Volume 404,127411, (2021).

Preprints:

1. Sohail, Brij Mohan, Chirag Srivastava, Arun K. Pati, Ujjwal Sen, *Quantum information can remain without physical body in volatile form,* arXiv:2105.03250v1.

Conference/Workshops Attended:

1. *QFTA2020*, India, Dec, 2020.
2. *Young Quantum*, India, October, 2020.

Other Activities:

1. Quantum Information and computation-I tutorship during the semester Aug-Dec 2020

Abhay Srivastav

Research Summary:

In the last academic year 2020-2021, I studied process matrix formalism and its role in understanding indefinite causal order which broadens the concept of causality. Also I studied LOCC distinguishability of UPB states.

Conference/Workshops Attended:

1. *Vienna Summer School 2020 on Gravitational Quantum Physics*, Austria, September, 2020.
2. *Young Quantum 2020*, India, October, 2020.

Other Activities:

1. Tutored Advanced Statistical Mechanics, September 2020 - January 2021.
2. Tutored Mathematical Methods 1, January - April, 2021.

Chirag Srivastava

Research Summary:

In the previous academic year, I have worked on various aspects of quantum information like measurement-device independence of entanglement witnesses, resource theory of quantum coherence, and wave-particle duality. I have also explored areas like dynamical quantum phase transition in the fully connected quantum Ising model and disordered quenches of quantum Rabi model near quantum phase transition.

Specifically, in one of the works, I have worked on entanglement witnesses. Entanglement witnesses form an effective method to locally detect entanglement in the laboratory without having the prior knowledge of the full density matrix. However, separable states can be erroneously indicated as entangled in such detections in the presence of wrong measurements or loss in detectors. Measurement-device-independent entanglement witnesses (MDI-EWs) never detect fake entanglement even under wrong measurements and for a particular kind of lossy detectors. A crucial assumption in the case of faithful detection of entanglement employing MDI-EWs is that the preparation devices producing "quantum inputs" - which are inputs additional to the quantum state whose entanglement is to be detected - are perfect and there is no noise during their transmission. Here, we relaxed these assumptions and provided a general framework for studying the effect of noise on the quantum inputs, invoking uniform and non-uniform noise models. We derived sufficient conditions on the uniform noisy map for retaining the characteristic of MDI-EWs. We found that in the context of non-uniform and entangling noise, fake entanglement detection is possible even by MDI-EWs. We also investigated various paradigmatic models of local noise and find conditions of revealing entanglement in the class of Werner states.

In another work, I have dealt with certain aspects of quantum coherence. One of the fundamental features of quantum mechanics is the superposition principle, a manifestation of which is embodied in quantum coherence. Coherence of a quantum state is invariably defined with respect to a preferred set of pointer states, and there exist quantum coherence measures with respect to deterministically as well as probabilistically distinguishable sets of quantum state vectors. Here we studied the resource theory of quantum coherence with respect to an arbitrary set of quantum state vectors, that may not even be probabilistically distinguishable. Geometrically, a probabilistically indistinguishable set of quantum state vectors forms a linearly dependent set. We found the free states of the resource theory, and analyzed the corresponding free operations, obtaining a necessary condition for an arbitrary quantum operation to be free. We identified a class of measures of the quantum coherence, and in particular established a monotonicity property of the measures. We found a connection of an arbitrary set of quantum state vectors with positive operator valued measurements with respect to the resource theory being considered, which paves the way for an alternate definition of the free states. We noticed that the resource theory of magic can be looked upon as a resource theory of quantum coherence with respect to a set of quantum state vectors that are probabilistically indistinguishable. We subsequently examined the wave-particle duality in a double-slit set-up in which superposition of probabilistically indistinguishable quantum state vectors is possible. Specifically, we reported a complementary relation between quantum coherence and path distinguishability in

such a set-up.

In the work on dynamical quantum phase transitions, we studied dynamical properties of the finite-size fully connected Ising model with a transverse field at zero temperature. In a quench dynamics, we studied the time period and the first critical time, which play important roles in the dynamical phase transitions, based on a dynamical order parameter and the Loschmidt rate, respectively. When all the spins are initially polarized in the direction of their mutual interaction, we showed that both the time period and critical time diverges logarithmically with the system size at the dynamical critical point. When all the spins are initially in the direction of transverse field, both the time period and critical time exhibit logarithmic or power-law divergences depending on the final field strength. In the case of convergence, we provided estimates for the finite-size scaling and converged value. We also investigated the equilibrium phase transitions, presenting approximate ground and first excited states away from the criticality, and compared their energy gap and bipartite and multipartite entanglements with the exact eigenstates.

In the work on quantum Rabi model, we analyzed the response to disorder in quenches on a non-adiabaticity quantifier for the quantum Rabi model, which possesses a phase transition between normal and superradiant phases. We considered a disordered version of a quench in the Rabi model, in which the system residing in the ground state of an initial Hamiltonian of the normal phase is quenched to the final Hamiltonian corresponding to the critical point. The disorder was inserted either in the total time of the quench or in the quench parameter itself. We solved the corresponding quantum dynamics numerically, and found that the non-adiabatic effects are unaffected by the presence of disorder in the total time of the quench. This result is then independently confirmed by the application of adiabatic perturbation theory and the Kibble-Zurek mechanism. For the disorder in the quench parameter, we reported a monotonic increase in the adiabaticity with the strength of the disorder. Lastly, we considered a quench where the final Hamiltonian is chosen as the average over the disordered final Hamiltonians, and showed that this quench is more adiabatic than the average of the quenches with the disorder in final Hamiltonian.

Publications:

1. Chirag Srivastava, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Sequential measurement-device-independent entanglement detection by multiple observers* , Phys. Rev. A **103**, 032408, (2021).

2. Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Detection loophole in measurement-device-independent entanglement witness,* Phys. Rev. A **103**, 032415, (2021).

3. Chirag Srivastava, Sreetama Das, Ujjwal Sen, *Resource theory of quantum coherence with probabilistically non-distinguishable pointers and corresponding wave-particle duality,* Phys. Rev. A **103**, 022417, (2021).

Preprints:

1. Arun Sehrawat, Chirag Srivastava, Ujjwal Sen, *Equilibrium and dynamical phase transitions in fully connected quantum Ising model: Approximate energy eigenstates and critical time,* arXiv:2012.00561.

2. Chirag Srivastava, Ujjwal Sen, *Scaling of non-adiabaticity in disordered quench of quantum Rabi model close to phase transition ,* arXiv:2012.04568.

3. Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Noisy quantum input loophole in measurement-device-independent entanglement witnesses,* arXiv:2012.04568.

Conference/Workshops Attended:

1. *Young Quantum 2020 - Harish-Chandra Research Institute*, India, October, 2020.

Academic recognition/Awards:

- Infosys Award, 2020-21.

Other Activities:

1. Presented a talk on "Resource theory of quantum coherence with probabilistically non-distinguishable pointers and corresponding wave-particle duality" in the online conference You-Qu 2020 - Harish-Chandra Research Institute, October, 2020.

Mathematics Conferences/Workshops

1. *Online Advanced Instructional Course on Local Arithmetic*, January 18 - May 21, 2021.

Physics Conferences/Workshops

1. *An online conference: Young Quantum 2020 (YouQu2020)*, October 12 - 15, 2020.

Recent Graduates

Mathematics

1. **Subha Sarkar**, *On some problems in additive combinatorics and related areas*.
2. **Mithun Kumar Das**, *Some Topics on Dirichlet L-functions*.
3. **Anoop Singh**, *Problems in the theory of connections in algebraic geometry*.

Physics

1. **Samiran Roy**, *New Physics with neutral and charged current measurements at Long-Baseline Neutrino Experiments*.
2. **Gautam Sharma**, *Uncertainty Relations, Quantum Coherence and Quantum Measurement*.
3. **Abhishek Joshi**, *Thermal phase transitions in correlated Bose and Fermi superfluids*.
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Computer Centre

1. The computing facilities of the Institute are one of the best in the country. It provides all the support to the academics and research activities and also to the administrative activities. The computing facilities are available to users round the clock $24 \times 7 \times 365$ all over the campus including the residential area.

2. The entire HRI campus wide network is connected with 1 Gbps Optical Fibre Cable backbone providing the network and Internet connectivity to each and every office, hostels and guest house and the residential area helping the scientists, researchers, administrative members and all other members and visitors 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, Windows and Mac operating systems.

4. Latest versions of several applications software and packages were configured 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. The Operating Systems and all the important and the necessary application packages were upgraded on Mail Servers, Webmail Servers, 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 and breakdown. Firewall rules were upgradded and fine tuned to enhance the security level of the servers and network services to protect them from Internet attacks.

6. Some additional security features were added in the Mail Servers and all other External Servers facing the Internet directly outside the DMZ.

7. On-line activities were arranged to organise the interviews of Ph.D. students and for holding academics and administrative meetings due to Covid-19 pandemic.

8. The 6 year old SMF batteries of the centralised Online UPS Systems were replaced with the new ones.

9. The Wi-Fi network were further enhanced in the hostels, guest house and other places of the campus where students are currently residing.

10. A new version of Anti-Virus was purchased and installed on the 30 desktop computers running Microsoft Windows operating system.

11. One new scanner and one new colour printer were purchased for the computer centre, which provides printing and scanning facilities to all the members of the Institute.

Current activities and plans:

1. It is planned to purchase Linux and Windows based All-in-One desktop computers for the faculty members, Ph.D. students, post doctoral fellows and administrative members of the Institute.

2. It is planned to purchase new servers for running basic computer services such as firewall services, mail, webmail, dns, dhcp+ddns, proxy and ldap services.

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 it's packages.

Library

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 : 8.00 AM to 2.00 AM (Midnight)
Sunday & Gazetted holidays : 8.00 AM to 8.00 PM

The Institute's 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, Refe rence Books, Print Journals, Technical Magazines, General Magazines, E-Resources & Digital Collections, CDs & DVDs, Theses, Bound Volumes of Journals, Dailies, Faculty & Institute Publications etc., added to this.

Glimpse of the Library:

Resources	Details
Total Collection:	**61846**
No. of Books - Print	21678
No. of Bound Volumes - Print	38292
Gratis/Books - Print	1876
Total Collection: Journals	**144**
International Journals :	**133**
Online	128
Print	05
National Journals :	**11**
Print	10
Online	1
E-Books:	**2311** (Lecture Notes in Mathematics and Archives)

Subscribed E-Resources, Databases:		
ScienceDirect	DAE-Elsevier Consortium	Elsevier Publication
MathScienet	Database of Reviews, Abstracts and Bibliographic Information	American Mathematical Society (AMS)
Project Euclid Journals	32 Journals Package	Duke University Press
JSTOR	83 Journals Package	Ithaka Publication
PROLA	Physical Review Journals Archive	American Physical Society
Life Time Databases/Archives:		
DMJ 100 Archive	Duke Mathematics Journal Package Back volumes-Vol.1 (1935) to Vol.100 (1999)	Duke University Press
AIP Archive	8 Journals Package	American Institute of Physics
IoP Journals Archive	56 Journals Package	Institute of Physics
Springer Journal Archive	123 Journals Package	Springer

Other Resources and Facilities:

Theses	114
CD's/DVD's	100
Newspapers	6
Seating Capacity	43
Carpet Area	650 Sq. Mts
Computers for Users/OPAC	4 No's
Library Management Software	Koha 19.11 Version with RFID Technology

Newly added materials during April 2020 to March 2021:

Books	162
Gratis-Books	39
E-books	35

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 & helps in effective implementation or use of the process.
Reader's Assistance	Library Website/Web OPAC
Web Enabled Library Catalogue Services	Self-Issue/Return System
Circulation Services (Issue/Return)	RFID enabled Security Gate system
Reference	Off-Campus Services through E-mail
Referral	Orientation for newly joined library members
Reprographic	Display of Faculty/PDF/Students Publications
New Arrivals service	Display of Institute Publications
Spiral Binding	Library Advisory Committee
Newspaper Clippings	Stock Verification
Book Exhibition	18 Hours uninterrupted Services
Theses Consultation Facilities	
Inter Library Loan	

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 Professor as the Chairman & other faculty representatives as members. Library Advisory Committee plays an advisory and advocacy role regarding the library in its support of teaching, learning, research and community-building needs of the Institute. 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.

Details are as follows	
Prof. D. Surya Ramana	Convenor
Dr. Anirban Basu	Member
Dr. N. Raghavendra	Member
Mr. K.K. Suresh Kumar, Librarian	Member

Library Team:

Total 9 Staff Members	
Library Staff	04
Other Staff Members	05

Library Management Software/Computerisation of in-house activities:

Library is automated and enabled with RFID Technology by using KOHA 19.11 version (Open Source Library Management Software). All in-house activities in the Library including Acquisition, Cataloguing, Circulation and Serials Control etc., are fully computerized using KOHA 19.11 version. The Online Public Access Catalogue (OPAC) of the Library is operational on Intranet. It can be accessed online to search more than 61846+ bibliographic records, available in the Library database through a web-based search interface (Web OPAC).

RFID Technology:

The Library has recently implemented the **Radio Frequency IDentification (RFID)** system. It is the best automated library automation system used worldwide and is an effective way of managing collections of the library and providing enhanced services to the users having benefits like: self check-out of books, self-check-in, to find misplaced reading materials, sorting, inventory accuracy, stock verification procedures, security control, Smart Card issuance, etc. It is an automatic data capture technology that uses tiny microchips and miniature antennas affixed to documents. RFID plays a vital role in redefining the library processes to make everyone's job easier right from the USERS to LIBRARY STAFF MEMBERS.

ICT enabled services:

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, services and BEST PRACTICES 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.

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 and made different sections like Religion, Language, Literature, Biography, Poem, Fiction, Novels, Science literature, Children's literature, and General reading book. 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** to HRI user community.

Construction Activity

The construction of buildings works is still hampered in campus due to order of Allahabad High Court in reference of PIL related to Ganga Pollution. Therefore no buildings construction work was carried out during last Financial Year 2020-21. Covid-19 has also affected most periods in this financial year therefore except routine maintenance works (AMCs) no new/renovation work was done.