Academic Report (2021-22)

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

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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, study of energy materials, 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 2021 to March 2022. The major events, worldwide, over the last two years were the waves of covid. April 2021 was the onset of the severe second wave in India, and Prayagraj was no exception. However, HRI survived the wave without major loss and has maintained its academic momentum. The next few paragraphs highlight our experience and progress during the last 12 months.

1. Covid response: April to June 2021 were the worst months of covid in the country. Having called back the students to campus after the waning of the first wave there was no time to send them back again. We implemented safety protocols on campus, minimising gathering, and isolated all covid cases and their contacts. The campus medical center and consultant physicians maintained vigil throughout these months. There was only one case of hospitalisation, and no fatalities.

2. Teaching program and students: The 2021-22 period continued in the online mode given the occurence of the second and third waves of covid. 19 students joined the physics M.Sc program - out of a capacity of 20, and 14 students (including some transfers from I.I.T Indore) joined the physics Ph.D program. The first year course for this relatively large batch has been successfully completed. There were 6 students admitted in the mathematics Ph.D program. 11 students submitted their Ph.D thesis during the period, and 7 students completed their M.Sc.

3. Faculty appointments: We have appointed a faculty member to supervise the physics teaching laboratory. Dr. Shyam Lal Gupta has joined in this position. Dr. Debraj Rakshit has joined the physics faculty. He brings expertise in the area of cold atom physics and its interface with quantum information. We expect three members to join over the next few months, these are Sayan Choudhury in condensed matter physics, Bhupendra Mishra in computational astrophysics, and Jishnu Ray in mathematics.

4. Academic events: All events during this period were in the online mode. We had a one day meeting on "Trends in String Theory". We also had a series of talks on the history of Indian Mathematics as part of the "Azadi ka Amrit Mahotsav" year. This included talks by M. S. Raghunathan, Gopalrao Dani, Aditya Kolachana, Venketeswara Pai, A. J. Parameshwaran, Avinash Sathaye and M. D. Srinivas.

5. Extramural funding: HRI scientists have attracted significant external funding for their work. This includes support for quantum computation under the government's QUEST project, and multiple grants on energy issues, e.g, carbon capture, hydrogen storage, energy scavenging, etc. These allow recruitment of research students and postdocs, and give access to external high performance computation.

6. Publications: Despite the second and third waves of covid during this period HRI has maintained a consistent publication record. The total number of publications is 130 over this period.

Pinaki Majumdar

Director

List of Governing Council Members (2021 - 22)

1. **Shri K.N. Vyas**	Chairman, Atomic Energy Commission Secretary, Deptt of Atomic Energy Government 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. 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. Pal, Aprameyo
7. Prakash, Gyan
8. Raghavendra, N.
9. Ramana, D. Surya
10. Ratnakumar, P. K.
11. Shah, Hemangi M.
12. Thangadurai. R.

Faculty Members (Physics)

1. Basu, Anirban
2. Chakraborty, Sudip
3. Das, Tapas Kumar
4. Datta, AseshKrishna
5. De, Aditi Sen
6. Jatkar, Dileep
7. Ghandhi, Raj
8. Ghosh, Tathagata
9. Maharana, Anshuman
10. Majumdar, Pinaki
11. Pareek, T. P.
12. Pati, Arun Kumar
13. Rai, Santosh Kumar

14. Rao, Sumathi
15. Sen, Ashoke
16. Sen, Prasenjit
17. Sen, Ujjwal

Administrative Staff

1. **Shri Ravindra Singh** [Registrar]
2. **Shri Manish Sharma** [Scientific Officer 'E']
3. **Shri Amit Roy** [Consultant I.A.&A.O.]
   (on contract w.e.f. 15.03.2021)
4. **Shri K.K. Suresh Kumar** [Librarian]
5. **Shri Sanjai Verma** [Systems Manager]
6. **Shri A.K. Srivastava** [AEE (Electrical)]
7. **Shri V.K. Srivastava** [AEE (Civil)]
8. **Shri R.P. Sharma** [Manager Guest House]
9. **Smt. Anju Verma** [SO'C']
10. **Shri U.K. Dwivedi** [Cashier]
11. **Shri D. Malhotra** [Upper Division Clerk]
12. **Shri K.K. Srivastava** [Upper Division Clerk]
13. **Shri Yashpal Singh** [Store/Purchase Officer]
14. **Smt. Sumitra** [Office Superintendent]
15. **Smt. Seema Agarwal** [P.A. to Director]
16. **Shri Sudheer Kumar Singh** [Accountant]
17. **Shri Sanjeev Nagar** [Jr. Hindi Translator]
18. **Shri Vivek Kumar** [Junior Library Assistant]
19. **Shri Kamlesh Thakur** [Bearer (Canteen Cadre)]
20. **Shri Kamta Prasad** [Peon/Watchman]
21. **Shri Rajesh Kumar** [Safaiwala]

Visiting Fellow

Mathematics

1. Acharya, Rantadeep
2. Bisai, Bappa
3. Das, Shamik
4. Gehlawat, Sahil
5. Hoque, Saikatul
6. Hazra, Samir
7. Jana, Arijit
8. Maitra, Anwoy
9. Mondal, Sudipa
10. Sen, Sourav
11. Singh, Amrendra

Physics

1. Arindam Bhattacharjee
2. Das, Tisita
3. Ghosh, Nivedita
4. Hegde, Subramanya
5. Kanjilal, Som
6. Kathyat, Deepak Sing
7. Maity, Arghya
8. Kumari, Asmita
9. Mitra, Arpan Krishna
10. Rahaman, Rafiqul
11. Roy, Pratim
12. Tomar, Shalini

Visiting Scientist

1. Deo, Satya (Maths)
2. Girdhar, Aarti (Principal Investigator)
3. Naik, Muna (Inspire Faculty)
4. Dutta, Jayanta (Physics)

Research Scholar

Mathematics

1. Aqib, Mohammad
2. Bansal, Muskan
3. Bhat, Oais Ahmad
4. Bhowmick, Kushal
5. Bisht, Pradeep
6. Chakraborty, Priyanshu
7. Choudhury, Srijonee Shabnam
8. Das, Arpan
9. Das, Bhargab
10. Das, Sudipa
11. Gupta, Shubham
12. Jha, Bina
13. Kanrar, Arpan
14. Karmakar, Debasish
15. Keshari, Parul
16. Krishnarjun, K.
17. Maity, Arup Kumar
18. Nishant
19. Patel, Uday Sureshbhai
20. Pokhrel, Rohit
21. Roy, Arkadeepta
22. Sahoo, Gopinath
23. Tantubay, Santanu
24. Tripathi, Aparna

Physics

1. Abdulla, Faruk
2. Agarwal, Keshav Das
3. G. B., Manasa
4. Abhishek, Md.
5. Bakshi, Sankha Subhra
6. Banerjee, Ratul
7. Barik, Anjan Kumar
8. Basak, Nirnoy
9. Bhattacharyya, Aparajita
10. Bhowmik, Swapnil
11. Bose, Debraj
12. Chaki, Paranjoy
13. Chandra, L. L. Ganesh
14. Chauhan, Aman
15. De, Suman Jyoti
16. Dey, Shyamashish
17. Ghosh, Priya
18. Ghosh, Srijon
19. Ghoshal, Ahana
20. Grover, Sachin
21. Gupta, Rivu
22. Halder, Pritam
23. Kaur, Jagjit
24. Konar, Tanoy Kanti Konar
25. Kumar, Dhirendra
26. Maity, Susovan
27. Mal, Sourav
28. Manna, Sudip

29. Mishra, Shashank
30. Mohan, Brij
31. Mondal, Tanmoy
32. Mondal, Sayan
33. Muhuri, Abhishek
34. K P, Ponnappa
35. Pal, Kalyanbrata
36. Pandey, Vivek
37. Patra, Ayan
38. Raikwal, Deepak
39. Rao, Prerna
40. Rawat, Ashish
41. Roy, Shubhojit
42. Saha, Debarupa
43. Sahoo, Ayan
44. Sarangi, Arijit
45. Roy, Tanaya
46. Sen, Kornikar
47. Shrimali, Divyansh
48. Singh, Kajal
49. Sohail
50. Srivastav, Abhay
51. Srivastava, Chirag

M.Sc. Students

Physics

1. Anisur, SK
2. Atta, Utsav
3. Bora, Sankalpa
4. Chahal, Seema
5. Chakraborty, Aishee
6. Das, Satyam
7. Majumdar, Anish
8. Datta, Sayantan
9. Dutta, Debashis
10. Gehlot, Gourang
11. Ghara, Subhadip
12. Jena, Subhashis
13. Khandewal, Hritik
14. Kumar, Pradeep
15. Modal, Shuva
16. Paul, Shubhajit
17. Pisharody, Vinod Viswambharan
18. Rao, Chiranjeev Bhanushankarbhai
19. Samanta, Mrinmoy

Academic Report - Mathematics

Punita Batra

Research Summary:

In a joint work with Priyanshu Chakraborty, I have constructed a large class of irreducible modules for loop-Virasoro algebra. Here loop-Virasoro means tensoring the Virasoro algebra with a commutative, associative, unital and finitely generated algebra and then classify its irreducible representations.

In a joint work with Santanu Tantubay, I have classified irreducible, integrable representations of full toroidal Lie algebras coordinated by a non-commutative quantum torus. We have submitted this work for publication.

Publications:

1. (With Priyanshu Chakraborty) A Class of irreducible modules for loop-Virasoro algebras, **Accepted to appear in Journal of Algebra and its Applications.**

Preprints:

1. (With Santanu Tantubay) Irreducible, integrable modules for the full toroidal Lie algebras coordinated by rational quantum torus, arXiv2202.07985

Chandan Singh Dalawat

Research Summary:

We have continued the study of primitive extensions of local fields with finite residue field. Efforts are ongoing to combine four related preprints into a single paper for publication ; it would provide a parametrisation of the set of all primitive extensions of a given local field.

While teaching a course in topology, it was observed that the category of filtered sets and filtered mappings should be given greater prominence because a topology is nothing but a certain kind of family of filters (the family of neighbourhood filters) and a uniformity is nothing but a certain kind of filter on the product set. Many constructions, such as the topology underlying a uniformity, become transparent when viewed from the point of view of filters. A systematic account of general topology using the formalism of filters (comparison, pushforward, pullback, etc.) deserves to be written.

Publication:

1. Chandan Singh Dalawat, *Congruent numbers, elliptic curves, and the passage from the local to the global: an update*, in *Resonance-75, Promoting Science Education*, vol. 1 (2022). See also arXiv:2201.11071.

Umesh V Dubey

Research Summary:

We gave a classification of compactly generated tensor t-structures of the unbounded derived category of noetherian schemes in terms of Thomason (or specialization closed) filtrations. This extends the famous Hopkins-Neeman classification of thick subcategories. As an application, we gave a solution to the *tensor telescopic conjecture of t-structures* for separated noetherian schemes, extending the work of Hrebek and Nakamura. This is joint work with Gopinath Sahoo.

The Segal type formula for equivariant K-theory of schemes with a finite group action was first proved by A. Vistoli. In joint work with Vivek M Mallick, we formulated and completed the proof of the analogous formula for equivariant K_0 of tensor triangulated categories with a tensor action of a finite group. The particular case of trivial action was proved earlier by A. Kuznetsov and A. Perry.

We continued the study of principal bundles and Nori fundamental groups with Parul Keshari. The main focus was to get the functorial moduli construction for principal bundles. The construction of moduli for principal bundles over curves was first given by Ramanathan extending the techniques of Mumford and Seshadri.

We studied the (semi-) stability of the tensor product of two (semi-) stable quiver representations over an internal product of quivers with Pradeep Das and N. Raghavendra.

In a joint work in progress with Subham Sarkar, we obtained some class of simple perverse sheaves over affine space with Coxeter type hyperplane arrangements following the quiver description of Kapranov-Schechtmann. Similar results in the low dimension case were obtained by P. Rowley.

Publications:

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

Preprints:

1. Umesh V Dubey and Gopinath Sahoo, *Compactly generated tensor t-structures on the derived category of a Noetherian scheme,* arXiv:2204.05015 [math.AG] (under review).

2. Pradeep Das, Umesh V Dubey and N Raghavendra, *Tensor product of representations of Quivers,* (under review).

3. Umesh V Dubey and Vivek M Mallick, *Segal-Vistoli type formula for equivariant K-theory of tt-categories with a finite group action,* (in preparation).

Conference/Workshops Attended:

1. *(Online) Vector Bundles and Algebraic Curves (VBAC) Webinars*, ICMAT, Spain, May 17, 2021, July 5 – 7, 2021, September 13, 2021, October 11, 2021, November 22, 2021, January 24, 2022, March 28, 2022.

2. *Discussion Meeting on Vector Bundles 2022*, Tifr, Mumbai, India, March-April, 2022.

Visits to other Institutes:

1. Tata Institute of Fundamental Research, Mumbai, India, March-April, 2022.

Invited Lectures/Seminars:

1. *Tensor triangular (tt-) geometry and homological residue field*, (online) Motivic homotopy theory seminar, IIT Roorkee, Roorkee, June 10, 2021.

2. *Functorial moduli construction of Consul and King*, Discussion meeting on Vector bundles 2022, Tifr, Mumbai, March 31, 2022.

Other Activities:

1. Graduate Course on Topology - II, HRI, August – December, 2021.

2. Supervising two research scholars from HRI and RAC member of two students from IISER Tirupati and IISER Pune.

3. Attended few online seminars/webinars like VBAC webinars, Motivic homotopy theory seminars, HBNI webinars etc.

4. Involved in writing AMS Mathematical reviews and member of Mathematics Graduate Programme Committee.

Manoj Kumar

Research Summary:

An algebraic structure $(E, +, \circ)$ is said to be a skew left 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 skew right brace can be defined analogously. A skew left 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. For a skew left brace $(G, \cdot, \circ)$, the map $\lambda : (G, \circ) \to Aut\,(G, \cdot),\ \ a \mapsto \lambda_a$, where $\lambda_a(b) = a^{-1} \cdot (a \circ b)$ for all $a, b \in G$, is a group homomorphism. Then λ can also be viewed as a map from $(G, \cdot)$ to $Aut\,(G, \cdot)$, which, in general, may not be a homomorphism. A skew left brace will be called λ-anti-homomorphic (λ-homomorphic) if $\lambda : (G, \cdot) \to Aut\,(G, \cdot)$ is an anti-homomorphism (a homomorphism). Let G and V be non-empty sets, $E \subseteq V \times V$. A *brace system* on G associated with the pair (V, E) is an algebraic system

$$(G, \{\circ_v\}_{v \in V}),$$

where $\circ_v : G \times G \to G$ is a binary operation for all $v \in V$, satisfying the following conditions:

1. $(G, \circ_v)$ is a group for all $v \in V$,
2. $(G, \circ_u, \circ_v)$ is a skew left brace for all pairs $(u, v) \in E$.

If $V = I$ is a linearly ordered set and $E = \{(i, j) \in I \times I \mid i < j\}$, then the brace system $(G, \{\circ_v\}_{v \in V})$ is said to be a *linear brace system*. A linear brace system is said to be symmetric if for any pair $(u, v) \in E$, $(G, \circ_v, \circ_u)$ is also a skew left brace. We show that symmetric skew braces are characterised by λ-anti-homomorphic skew braces, device recursive procedure for constructing symmetric (linear) brace systems on a given λ-homomorphic skew brace and provide a unification method for most of the existing procedures for constructing symmetric skew braces. Specific constructions of recursive procedure on skew braces $(G, \cdot, \circ)$ with abelian $\lambda(G)$ are carried out.

Publications:

1. Valeriy Bardakov, Mikhail Neshchadim and Manoj K. Yadav, *On λ-homomorphic skew braces*, J. Pure Appl. Algebra **226**, Paper No. 106961, 37 pp., (2022).

Preprints:

1. Valeriy Bardakov, Mikhail Neshchadim and Manoj K. Yadav, *Symmetric skew braces and brace systems*, https://arxiv.org/abs/2204.12247.

Conference/Workshops Attended:

1. *Braces in Bracelet Bay*, UK, Virtual, January, 2022.
2. *Emerging trends in pure and applied Mathematics*, India, Virtual, March, 2022.

Invited Lectures/Seminars:

1. *Skew braces and solutions of the Yang Baxter Equation*, Emerging trends in pure and applied Mathematics, Tezpur University, Tezpur, Virtual, March, 2022.

2. *Commutators in finite groups*, In House Symposium, IISER Bhopal, Virtual, March, 2022.

Other Activities:

1. Organised a virtual activity "Group Theory Sangam conference", June 01 - 04, 2021 (jointly with many other group theorists in India).

2. Organised a virtual activity "Workshop on Group Theory 22", February 04 - 05, 2021 (jointly with Anupam Singh (IISER Pune) and Amit Kulshrestha (IISER Mohali)).

3. Taught Algebra I course at HRI during January - May 2022.

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

5. Refereed research papers for national and international journals.

6. Instructed Arpan Kanrar for him second semester graduate Project Course at HRI.

7. Served HRI on several committees.

Aprameyo Pal

Research Summary:

One of the most important conjectures in arithmetic geometry and number theory is Birch—Swinnerton–Dyer (BSD) conjecture which states that the vanishing order of the Hasse-Weil L-function at s=1 is equal to the rank of the abelian group of rational points of the elliptic curve over rational numbers. Furthermore, there exists an explicit formula relating the leading coefficient of the Taylor expansion of the L-function at s=1 with the order of the Mordell-Weil group. Deep results of Gross-Zagier, Kolyvagin, Kato, and Skinner-Urban etc. settled most parts of BSD conjecture (p-parts in some cases) in the rank 0 and rank 1 case. However, the higher rank cases have turned out to be extremely difficult but it has fostered some of the most productive research of the recent decades. Over number fields, there have been some recent breakthroughs by Bertolini, Darmon, Rotger, and collaborators via the construction of an Euler system of Beilinson-Flach elements, and Diagonal cycles (in the higher chow group of the modular curve) to prove new cases of BSD conjectures. These algebraic cycles have several important corollaries e.g. Dasgupta's factorization formula for the tensor product of two modular forms, exceptional zero conjecture of symmetric square, construction of Stark-Heegner points, etc. We have continued our work on the factorization of a triple product p-adic Rankin L-series along with Prof. Carlos d. v. Piquero. We have successfully constructed a Chow-Heegner class which is a generalization of a Chow-Heegner point. These Chow-Heegner classes form an Euler system and would be used along with the Darmon-Rotger diagonal classes to finish the proof of the factorization.

The Shimura-Taniyama conjecture (Proved by Wiles, Taylor-Wiles) can be seen as a special case of the Langlands Conjecture (in dimension 2) relating 2-dimensional Galois representations and automorphic forms. So, it is imperative to know more about Langland's correspondence in more generality. Other than GL_2, our knowledge is quite limited. Again, much is known over the global function field in characteristic p by the results of Drinfeld, and Lafforgue. In characteristic zero, Harris, Taylor & Henniart have proved the local Langlands correspondence for GL_n for ℓ-adic representations. For p-adic representations, a lot of new technical difficulties arise. Accordingly, the p-adic Langlands programme is one of the most active themes in current research. By fundamental results due to Colmez, Breuil, and Paskunas, the case of $GL_2(\mathbb{Q}_p)$ is now resolved. Fontaine's notion of (φ, Γ)-modules lies at the heart of the p-adic Langlands correspondence. We are working (with Prof. Gergely Zabradi) on the Iwasawa theory of multi-variable (φ, Γ)–modules, which are expected to arise naturally in p-adic Langlands correspondence of higher rank reductive groups. After proving Fontaine's equivalence of categories to multivariable set-up, recently we extended our results to the base change of the multivariable Robba ring to include analytic Iwasawa cohomology.

Along with the above two themes, I have also collaborated with Prof. R. Thangadurai, and Dr. Veekesh Kumar to obtain a criterion for an algebraic integer from the information on the trace of powers of algebraic numbers, using local (p-adic) and transcendence techniques.

Publications:

1. Cohomology and overconvergence for representations of powers of Galois groups *(with Gergely Zabradi)*, *Journal of the Institute of Mathematics of Jussieu 20(2) (2021), 361-421*.

Preprints:

1. On the trace of linear combination of powers of algebraic numbers, *(with Veekesh Kumar, and R. Thangadurai)*, https://arxiv.org/abs/2202.04452.

Conference/Workshops Attended:

1. ICTS workshop on "Elliptic curves and Special values of L-Functions" (online), 2-7th August, 2021.

2. 36th Annual Ramanujan Mathematical Society Conference (RMS 2021), 4th August, 2021.

Invited Lectures/Seminars:

1. On "p-adic Galois representations and multivariable (φ, Γ)-modules" as invited speaker in 36th Annual Ramanujan Mathematical Society Conference (RMS 2021), 4th August, 2021.

Other Activities:

1. Organized a seminar on "Average rank of elliptic curves and applications to BSD conjecture" following Bhargava-Shankar, Winter semseter 2021-2022.

2. Gave a course on "p-adic numbers, p-adic analysis and zeta functions", Summer semester 2022.

Gyan Prakash

Research Summary:

Vinogradov showed that every sufficiently large odd natural number can be written as a sum of three primes. Matomaki and Shao in 2015 showed that in fact every sufficiently large odd natural number n can be written as $n = p_1 + p_2 + p_3$ where p_i is a prime and $p_i + 2$ has at most two prime factors for each $i \in \{1, 2, 3\}$. Let $c > 1$ be a real number which is "close" to 1 and $E \geq 1$ be a natural number. In 2017, Tolev studied the following problem: Given any sufficiently large real number N does there exists primes p_1, p_2, p_3 such that p_i+2 has at most k prime factors, $|p_1^c+p_2^c+p_3^c-N| < (\log N)^{-E}$ and k is small. He proved the answer is affirmative if $k = 30$. Since then various authors have improved this result and the best known result is that the answer to the above question is affirmative with $k = 21$. In a recent work in progress we have tried to improve this result and subject to checking some calculations, we are able to show that the result holds with $k = 13$.

Preprints:

1. with Priyamvad Srivastav: A diophanitine inequality with prime numbers of special type. *in preparation.*

Other Activities:

1. Taught Analysis II course to first year graduate students during August-December 2021.

Raghavendra Nyshadham

Research Summary:

I have continued working on formalisation over univalent foundations. I have also been working on the results of Eschmeier, Putinar, and others, on the relations between operators on Frechet spaces and sheaves on Stein complex analytic spaces.

Other Activities:

1. Gave a graduate course on differential manifolds from August to December, 2021.

D. Surya Ramana

Research Summary:

My research activity is about investigating if large but otherwise arbitrary subsets of "interesting subsets" of the natural numbers retain certain properties of these interesting sets. This theme is a mix of combinatorics linked to Ramsey theory and additive representation problems in analytic number theory. Alongside work on some problems on this theme, a preprint, with Ritika Sharma, on a problem on Ramanujan Exapansions was put in final form. More precisely, in this work we extend to arithmetical functions in several variables the asymptotic formulae with error terms obtained in the literature for the partial sums of an arithmetic function with an absolutely convergent Ramanujan expansion, assuming a suitable decay rate for the coefficients.

Preprint:

1. D. S. Ramana and R. Sharma, *Partial sums of arithmetical functions of several variables with absolutely convergent Ramanujan expansions*,to be submitted.

Other Activities:

1. Taught Algebra - II (August - December 2021), which is largely basic commutative algebra, and is a part of the graduate teaching programme in mathematics of the institute.

2. 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).

3. Member, Board of the School of Mathematics, Statistics and Computational, Central University of Rajasthan.

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).

Peetta Kandy Ratnakumar

Research Summary:

One of the problems that I have been working on concerns with the boundedness of the Bi-linear λ-twisted convolution operator

$$B_\lambda(f,g)(z) := f \times_\lambda g(z) := \int_{\mathbb{C}^n} f(z-w)g(w)e^{i\frac{\lambda}{2}\mathrm{im}(z\cdot\bar{w})}dw,$$

from $L^p(\mathbb{C}^n) \times L^q(\mathbb{C}^n) \to L^r(\mathbb{C}^n)$ for $1 \leq p,q,r \leq \infty, 0 < \lambda \in \mathbb{R} \setminus \{0\}$. I could prove a complete characterisation of the triple (p,q,r) for which B_λ satisfy the above boundedness, in the case $\frac{1}{p}+\frac{1}{q} \geq 1$. A special case of this was done earlier with Arup Kumar Maity, based on a different argument and is submitted for publication.

The above bilinear estimate has connection with the study of Fourier as well as Weyl multiplier problems. In fact, jointly with Arup Kumar Maity, we could prove a Fourier multiplier theorem in the spirit of the classical results of Hahn and Bagby for Fourier multipliers of the form $m_1 \times m_2$, with m_1 and m_2 also from the Lebesgue as well as Lorentz spaces. This preprint is almost ready for submission.

We have also studied the Weyl multipliers for (L^p, L^q) for $1 \leq p,q \leq \infty$, based on the above bi-linear estimate. This work is expected to be finished in a months time, including the Lorentz pairs $(L^{p,s}, L^{q,s})$, $1 \leq p,q,s \leq \infty$.

Publications:

1. Ramesh Manna , P.K. Ratnakumar, *Global Fourier Integral Operators in the Plane and the Square Function, Journal of Fourier Analysis and Applications, 28, no. 2, Paper No. 1-28, (2022),*

Preprints:

1. Arup Kumar Maity, P. K. Ratnakumar, On $L^p \to L^q$ boundedness of the twisted convolution operators (submitted)
2. P. K. Ratnakumar, Bi-linear twisted convolution maps between Lebesgue spaces (preprint)
3. Arup Kumar Maity, P. K. Ratnakumar, Fourier multipliers via twisted convolution (preprint)
4. Arup Kumar Maity, P. K. Ratnakumar, Weyl multipliers for (L^p, L^q) (under preparation)

Conference/Workshops Attended:

1. 17th Discussion meeting in Harmonic Analysis, IISER Mohali(online), India, January, 2022

Invited Lectures/Seminars:

1. Analysis and Probability seminar, IISER Mohali, On Translation and Modulation invariant Hilbert spaces, India, June 2021.

Other Activities:

1. Serving as convenor in the Mathematics Graduate Studies Committee, HRI.

Hemangi Shah

Research Summary:

The theory of harmonic manifolds is a key area of study in Differential Geometry. Towards this I have shown that the asymptotically harmonic manifolds with minimal horospheres are flat if they are homogeneous. This strengthens a result by J. Heber, which proves that asymptotically harmonic manifolds with minimal horospheres are flat if they are Einstein and homogeneous. Thus the conjecture is resolved in the category of asymptotically harmonic homogeneous spaces: Any asymptotically harmonic manifold is either of polynomial volume growth or of exponential volume growth provided it is homogeneous.

Preprints:

1. Asymptotically harmonic homogeneous manifolds satisfying Euclid's Parallel Postulate.

Conference/Workshops Attended:

1. Analysis on singular spaces, Virtual conference, September 2021, Germany.
2. Trends in Calculus of Variation and PDES, Virtual Conference, May 2022, UK.

Other Activities:

1. I taught Topology-I, graduate course, January-May, 2021.
2. Delivered a seminar on, Participation in Scientific Activities, HRI, Graduate Students, 16th May 2022.
3. I am a member of Foreign Travel Committee, Jan 2020-todate.
4. Member of meeting on the syllabus on Topology and Differential Manifolds, May 2022.
5. During 2021-2022 I have reviewed 14 Math reviews for Mathscinet.
6. Reviewed articles for Math. Student, 2021.

Ravindranathan Thangadurai

Research Summary:

Let $\lambda_1, \ldots, \lambda_k$ and $\alpha_1, \ldots, \alpha_k$ be nonzero algebraic numbers for some integer $k \geq 1$ and let $L = \mathbb{Q}(\lambda_1, \ldots, \lambda_k, \alpha_1, \ldots, \alpha_k)$ be the number field. Let K be the Galois closure of L and let h be the order of the torsion subgroup of $K^\times$. We prove an extension of a result of B. de Smit as follows: *Take* $\lambda_i = b_i \in \mathbb{Q}$ *for* $i = 1, \ldots, k$ *such that* $b_1 + \cdots + b_k = n \neq 0$ *and* α_j*'s are some of the Galois conjugates (not necessarily distinct) of* α_1 *for all* $j = 2, \ldots, k$ *and* $d \geq 1$ *is the degree of* α_1. *If* $\mathrm{Tr}_{L/\mathbb{Q}}(b_1\alpha_1^j + \cdots + b_k\alpha_k^j) \in \mathbb{Z}$ *for all* $j = 1, 2, \ldots, d + d[\log_2(nd)] + 1$, *then* α_1 *is an algebraic integer.* We then prove a general result for the infinite version as follows. *Suppose* $\mathrm{Tr}_{L/\mathbb{Q}}(\lambda_i\alpha_i^a) \neq 0$ *for all integers* $a \in \{0, 1, 2, \ldots, h-1\}$ *and for all integers* $i = 1, \ldots, k$. *If* $\mathrm{Tr}_{L/\mathbb{Q}}(\lambda_1\alpha_1^n + \cdots + \lambda_k\alpha_k^n) \in \mathbb{Z}$ *holds true for infinitely many natural numbers* n, *then each* α_i *is an algebraic integer for all* $i = 1, \ldots, k$. Here the extra assumption is a necessary condition for $k > 1$. We also prove a Diophantine result which states: *For a given rational number* p/q, *there are at most finitely many natural numbers* n *such that* $\mathrm{Tr}_{L/\mathbb{Q}}(\lambda_1\alpha_1^n + \cdots + \lambda_k\alpha_k^n) = p/q$. Finally, we give a criterion for an algebraic integer to be a root of unity in terms of trace. This is a joint work with Aprameyo Pal and Veekesh Kumar.

Publications:

1. Veekesh Kumar and R. Thangadurai, *On simultaneous approximation of algebraic numbers*, To appear in., *Mathematika*.

Preprints:

1. Aprameyo Pal, Veekesh Kumar and R. Thangadurai, *On the trace of linear combination of powers of algebraic numbers*, *Preprint*, 2021.

Conference/Workshops Attended:

1. "Mathematical Analysis and Riemannian Geometry" (ISMARG - 2021), Online, Bhairab Ganguly College, Kolkata, 29-30, September, 2021.
2. M. V. Subbarao Symposium on Number Theory, Online, IISER Pune, July 12-16, 2021.
3. ICCGNFT 2021, Online, KSOM, Kozhikode, October 21-24, 2021.
4. Workshop on Number Theory and Combinatorics, RKMVERI, Belur, March 14-15, 2022.

Visits to other Institutes:

1. RKMVERI, Belur, March 14-15, 2022.

Invited Lectures/Seminars:

1. *Linear Independence of Special Values of Jacobi Theta Constants*, Subbarao Symposium on Number Theory, Online, IISER, Pune, July 12-16, 2021.

2. *Riemann contributions to Number Theory*, Webinar on "Mathematical Analysis and Riemannian Geometry (ISMARG - 2021), Bhairab Ganguly College, Kolkata, September, 29-30, 2021.

3. *On the trace of powers of algebraic numbers*, Online, ICCGNFT 2021, KSOM, Kozhikode, October 21-24, 2021.

4. *Algebra Course*, AFS 2, online, Shiv Nadar university, 29th November 2021 - 08th January, 2022.

5. *3 by 3 magic squares and A.P in rational points on Elliptic curves*, Webinar, Assam Don Bosco University, December, 22, 2021.

6. *Ramanujan and Divisor Function*, Webinar, National Mathematics Day, IIIT Raipur, December, 22, 2021.

7. *Ramanujan and Divisor Function*, Webinar, Shivaji University, Kolhapur, January 01, 2022.

8. *Linear Algebra*, ISI North-East Centre Winter School in Mathematics, Online, ISI Tezpur, January 17-22, 2022.

9. *Extensions of Fermat Little Theorem*, Workshop on Number Theory and Combinatorics, RKMVERI, Belur, March 14-15, 2022.

Other Activities:

1. External expert on Promotional and Selection Committee in SMU at Indian Statistical Institute, Kolkata during May 28, 2021.

2. Member of Board of Studies in Physical Sciences, North-Eastern Hill University, Shillong, April, 2021-March, 2022.

3. Organized the online mode RMS Symposium on Number Theory during August 04 - 07, 2021.

4. Gave a graduate level course on Analysis - I, January, 2022.

Satya Deo

Research Summary:

I continue to work around the Topological Tverberg theorem of Topological Combinatorics. Last year we published two papers dealing with the disjoint support property and strongly independent set of points used in proving the Topological Tverberg theorem. During the current year of report we have worked further on the disjoint support property of higher dimensional spheres and got some interesting results. These results have been accepted for publication in the journal 'Topology and its Applications'. We have also studied the dimension of the Tvernerg set and solved an old problem in this area which has been submitted for publication. The work is going on and we hope to settle some other problems that are still open.

Publications:

1. Snigdha Bharati Choudhury, Satya Deo and Shubhankar Podder, *Existence of continuous maps from d-spheres, $d \geq 1$, to its various triangulations having the disjoint support property* , **Topology and its Applications**, 314, 108-112(2022)

Preprints:

1. Snigdha Bharati Chaudhury, Satya Deo and Shubhankar Podder, *A Problem on Tverberg set* (submitted)

Conference/Workshops Attended:

1. *Annual Conference of the Calcutta Math Society*. Kolkata, July 12-14, 2021
2. *Conference on Raghunathan's 80th Birth day*, Bombay, Aug 9-11, 2021
3. *Prof B.L.Sharma Higher Math Trust workshop on Metric Spaces*, Allahabad, Oct 25, 2021
4. *Annual conference of Bharat Ganit Parishad*, Lucknow, Nov 17, 2021
5. *Annual conference of the Indian Math Society*, Aurangabad, Nov 4-7, 2021
6. *Workshop at RKMVERY*, Belure, Kolkata, March 14-15, 2022.

Visits to other Institutes:

1. IIT Patna, Patna (Selection Committee metting online), Jan 4-5, 2022
2. BIT, Mesra, Ranchi, (Selection Committee meeting online), June 18-19, 2021.

Invited Lectures/Seminars:

1. *On the Tverberg Theorem*, Annual Conference of the Calcutta Math Society. July 12-14, 2021
2. *On Metric Spaces*, Prof B.L.Sharma Trust workshop on Metric Spaces, Oct 25, 2021
3. *On Topological Combinatorics*, Bharat Ganit Parishad Conference at Lucknow, Nov 17, 2021
4. *On the Inverse Function Theorem*, Hindu College, Delhi University, Lecture for Students, Jan 31, 2022
5. *On the Colored Tverberg Theorem*, Workshop at RKMVERY, Belure, Lecture, March 14-15, 2022.

Other Activities:

1. General Secretary, NASI, Continuing.
2. General Secretary, Indian Math Society, Continuing
3. Editor-in-Chief, NASI Science Letters, Continuing.

Muna Naik

Research Summary:

Let S be a Damek–Ricci space equipped with the Laplace–Beltrami operator Δ. We characterize all eigenfunctions of Δ through sphere, ball and shell averages as the radius (of sphere, ball or shell) tends to infinity. We also study similar problems in the context of Euclidean space $\mathbb{R}^n$.

Publications:

1. M. Naik, R. P. Sarkar: *Asymptotic mean value property for eigenfunctions of the Laplace–Beltrami operator on Damek–Ricci space.* Annali di Matematica Pura ed Applicata.
   https://doi.org/10.1007/s10231-021-01172-9

2. M. Naik: *Generalized mean value property in limit for eigenfunctions of the Laplacian on* $\mathbb{R}^n$, Colloq. Math. 169 (2022), no. 2, 255–267.

Invited Lectures/Seminars:

1. *Given twenty-seven online lectures on Riemannaian Symmetric Space at Indian Institute of Science, Bangalore* (21st March, 2022 – 27th June, 2022).

Academic recognition/Awards:

- INSPIRE faculty fellowship award from the Department of Science and Technology, Government of India (DST/INSPIRE/04/2020/001193, IFA20-MA-151).

Nilanjan Bag

Research Summary:

My research interest in the last several years centered around exponential and character sums. In the last academic year I have mainly focused on a conjecture on generalized quadratic Gauss sums. With A. R. León and W. P. Zhang, I have made progress towards a relation between power mean values of generalized quadratic Gauss sums and power moments of generalized quadratic Gauss sums weighted by L-functions. Our results along with a result of Ping Xi which proves a conjecture of W. P. Zhang .

In another project with I. E. Shparlinski, I have used some elementary arguments to obtain a new bound on bilinear sums with weighted Kloosterman sums. Our bounds complement those recently obtained by E. Kowalsky, P. Michel and W. Sawin .

Publications:

1. N. Bag, A. R. León and W. P. Zhang, *An explicit evaluation of 10-th power moment of generalized of quadratic Gauss sums and some applications*, Functiones et approximatio, 2021.

Preprint:

1. N. Bag, A. R. León and W. P. Zhang, *On some conjectures on generalized quadratic Gauss sums and related problems*. (under review)

2. N. Bag, I. E. Shparlinski, *Bounds on bilinear sums of Kloosterman sums*. (under review)

Invited Lectures/Seminars:

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

2. Special topic presentation in Math 8510 Analytic Number Theory, University of Virginia.
   Title: Gross-Koblitz formula and number of F_p-points on elliptic curves. (April 28, 2021)

Conference and Workshop attended

1. International conference on class groups of number fields and related topics (Online), KSOM, 2021.

2. Elliptic curves and the special values of L-functions (Online), ICTS, 2021.

Saikatul Haque

Research Summary:

I have been working on well-posedness and ill-posedness of nonlinear dispersive partial differential equations, namely the Schrödinger equation, wave equation and Benjamin–Bona–Mahony (BBM) Equation. These equations have several applications in physical, biological and chemical sciences. Below I am describing the research done in the last year on these problems:

- **Schrödinger equation:** (submitted) We have considered the following mixed fractional nonlinear Schrödinger equation with inhomogeneous nonlinearity:

$$iu_t - (-\Delta)^{s_1}u - (-\Delta)^{s_2}u + \frac{|u|^\sigma}{|x|^b}u = 0 \text{ in } \mathbb{R}\times\mathbb{R}^d, \quad u(0,\cdot) = u_0 \text{ on } \mathbb{R}^d,$$

  with certain nontrivial conditions on s_1, s_2, σ and b. We have carried out a classical (i.e. the case $s_1 = s_2 = 1$, $b = 0$) well-posedness study for this problem by establishing a certain new Strichartz estimate involving Lorentz spaces. This is a joint work with D Bhimani (IISER-Pune), H Hichem (California State University), T Lou (Guangzhou University) and it extends Aloui-Tayachi (Discrete Contin Dyn Syst **41**, no 11, 5409–5437, 2021), Guo-Wang (J Anal Math **124**, 1–38, 2014) and Keel-Tao (Amer J Math **120**, no 5, 955–980, 1998).

- **Wave equation:** (submitted) Jointly with D Bhimani, we have studied ill-posedness of the wave equation

$$u_{tt} - \Delta u = \pm u^\rho(\bar{u})^{\sigma-\rho} \text{ in } \mathbb{R}\times\mathcal{M}, \quad (u(0,\cdot), u_t(0,\cdot)) = (u_0, u_1) \text{ on } \mathcal{M}$$

  with $0 \le \rho \le \max(\rho, 2) \le \sigma$ are integers, $\mathcal{M} = \mathbb{R}^d$ or $\mathbb{T}^d$. We have established norm inflation with infinite loss of regularity (stronger phenomenon than just ill-posedness) in Fourier amalgam space $\widehat{w}_s^{p,q}(\mathcal{M})$ (which coincides with Sobolev space $H^s(\mathcal{M})$ if $p = q = 2$) and Wiener amalgam space $W_s^{2,q}(\mathcal{M})$ with negative regularity i.e. $s < 0$. This work extends the work of Christ-Colliander-Tao (arXiv:math/0311048, 2003), Forlano-Okamoto (Dyn Partial Differ Equ **17**, no 4, 361–381, 2020) and Lebeau (Bull Soc Math France **133**, no 1, 145–157, 2005).

- **BBM equation:** (published) We (with D Bhimani) have recently published an article on the issue of norm inflation with infinite loss of regularity for the Benjamin–Bona–Mahony equation, namely

$$u_t + u_x + uu_x - u_{xxt} = 0 \text{ in } \mathbb{R}\times\mathcal{M}, \quad u(0,\cdot) = u_0 \text{ on } \mathcal{M},$$

  with $\mathcal{M} = \mathbb{R}$ or $\mathbb{T}$. Note that Bona-Tzvetkov (Discrete Contin. Dyn. Syst **23**, no 4, 1241–1252, 2009), Panthee (Discrete Contin Dyn Syst.30, no 1, 253–259, 2011) and Bona-Dai (J Math Anal Appl 446, no 1, 879–885, 2017) have proved a weaker version of this ill-posedness result.

- **Strichartz estimate:** (on going) With Prof P K Ratnakumar we are interested in finding all possible inhomogeneous Strichartz estimate in classical situation i.e. finding all $(q,r), (\tilde{q},\tilde{r})$ for which

$$\left\| \int_0^t e^{i(t-\tau)\Delta} g(\tau) d\tau \right\|_{L_t^q L_x^r} \le C\|g\|_{L_t^{\tilde{q}'} L_x^{\tilde{r}'}}, \quad \forall g \in L_t^{\tilde{q}'} L_x^{\tilde{r}'}$$

is satisfied. Only partial results are known in this direction, see work of Strichartz (Duke Math J **44**, no 3, 705–714, 1977), Vilela (Trans Amer Math Soc **359**, no. 5, 2123–2136, 2007) etc.

Publications:

1. D. G. Bhimani and S. Haque, *Norm Inflation for Benjamin–Bona–Mahony Equation in Fourier Amalgam and Wiener Amalgam Spaces with Negative Regularity,* Mathematics **9**, 3145, (2021).

Preprints:

1. D. G. Bhimani, H. Hajaiej, S. Haque and T. Luo, *A sharp Gagliardo-Nirenberg inequality and its application to fractional problems with inhomogeneous nonlinearity,* (submitted).

2. D. G. Bhimani and Saikatul Haque, *Norm inflation with infinite loss of regularity at general initial data for nonlinear wave equations in Wiener amalgam and Fourier amalgam spaces,* arXiv:2106.13635 (submitted).

Invited Lectures/Seminars:

1. *Mixed fractional Strichartz estimate*, Extension talk, Harish-Chandra Research Institute (HRI), Allahabad (Prayagraj), India, March, 2022.

Arijit Jana

Research Summary:

I joined HRI Prayagraj in February 2022. In this period of my research work, I have studied Lauricella hypergeometric series. We have tried to develop a finite field analogue for one of the Lauricella hypergeometric series. We have also used the powerful WZ-method to deduce some supercongruences for sums involving certain rising factorials.

Conference/Workshops Attended:

1. International Conference on "Emerging trends in Pure and Applied Mathematics" held on March 12-13, 2022 in blended mode, organized by Tezpur University.

Invited Lectures/Seminars:

1. HRI PDF joining talk. (February 24, 2022)
   Title: Ramanujan's series for $\frac{1}{\pi}$, and related supercongruences.

Amrendra Singh Gill

Research Summary:

I joined HRI Prayagraj as Post-Doctoral Fellow in Feb. 2022. During this period Feb.-Mar. 2022, I started to work on briefly surveying the theory of finite-type invariants for knots. Introduced by Vassiliev, these invariants are more popularly also known as Vassiliev invariants. Goussarov, Polyak and Viro extended the notion of finite-type invariants to virtual knots using the virtualization operation. I am particularly looking at their theory from the lens of virtual knots in order to define some new ordering on these invariants.

Invited Lectures/Seminars:

1. Some new unknotting invariants and corresponding Gordian complex of virtual knots, PDF-Joining seminar, HRI, Prayagraj, March 2022.

Anwoy Maitra

Research Summary:

Over the past year, I have mainly worked on questions and problems in *S*everal *C*omplex *V*ariables (SCV) that all have to do, in one way or another, with the metric geometry of domains in complex Euclidean space or complex manifolds, regarded as being endowed with some intrinsic (pseudo)distance ("intrinsic" means that the distance is defined entirely in terms of the complex structure of the domain or manifold in question). In most cases, the distance considered is the so-called Kobayashi distance, a particularly important intrinsic distance in SCV. It has been demonstrated in the recent works of several authors that metric geometric ideas and techniques can be effectively used to investigate questions native to SCV (such as the continuous extension of isometries, Wolff–Denjoy-type theorems, the localization of intrinsic distances etc.), and my work can be broadly described by this theme. The preprint mentioned below, joint with Vikramjeet Singh Chandel and Amar Deep Sarkar, has been submitted and is currently under review. It seems very likely that further interesting results in this direction can be obtained, and work (joint with the aforesaid collaborators) is currently underway on this topic.

Preprints:

1. Vikramjeet Singh Chandel, Anwoy Maitra, and Amar Deep Sarkar, *Notions of visibility with respect to the Kobayashi distance: comparison and applications*, arXiv:2111.00549.

Visits to other Institutes:

1. IIT Kanpur, Kanpur, India, April, 2022.

Sourav Sen

Research Summary:

Since April 2021, I have been working on the following two problems (i) On double Asanuma threefolds: A counter-example to the Cancellation Problem: In this paper we have constructed a family of affine threefolds inside the five-dimensional affine space and named them double Asanuma threefolds. We have studied a few algebro-geometric properties regarding the (additive) group actions on these varieties. We have also studied an invariant regarding the additive group actions called Makar-Limanov invariant for this family. We are strongly suspecting that this family would provide a new three-dimensional counter-example to the celebrated Zariski Cancellation Problem in positive characteristic. Hence we are trying to classify the isomorphism classes of this family and eshtablish the stable isomorphism of this family in orded to prove our conjecture. (ii) Cohomology of averaging family operators & diassociative family algebras: In this joint work with Apurba Das, we have defined the family version of averaging algebra and diassociative algebra indexed by a semigroup. Next we studied the cohomology on these families and as an application we are trying to study the one-parameter formal deformation theory on these mathematical structures.

Publications:

1. Apurba Das, Sourav Sen, *Nijenhuis operators on Hom-Lie algebras*. Comm. Algebra **50, no. 3**, 1038–1054, 2022.

Conference/Workshops Attended:

1. Spring School named Invariants in Algebraic Geometry, France, May, 2022.

Visits to other Institutes:

1. Indian Statistical Institute (ISI) Kolkata, India, 14th February to 4th March, 2022.

Invited Lectures/Seminars:

1. *Tame degree functions in arbitrary characteristic*, Spring School named Invariants in Algebraic Geometry, University of Burgundy, France, May, 2022.

Other Activities:

1. Member of the Organizing Committee of Motivic Homotopy Theory Seminar.
2. Member of the Organizing Committee of 'Minicourse on Stable Homotopy Groups of Spheres' by Prof. Dan Isaksen, April 27, 28, 29, 2021.

Kushal Bhowmick

Research Summary:

In the academic year(2021-22), my primary focus is to study the main ideas behind the proof of the following important recent result by Bhargava, Skinner and Zhang.

Theorem 1. A majority of elliptic curves over $\mathbb{Q}$, when ordered by height, satisfy BSD rank conjecture.

More precisely, this paper shows that the BSD rank conjecture holds for more than 66%.

One of the most important ingredients in the proof of theorem 1 comes from the following spectacular theorem by Bhargava and Shankar.

Theorem 2. If $p \leq 5$, the average size of $Sel_p(E/\mathbb{Q})$ is $p+1$.

For $p = 2$, it is proved using 2-coverings of elliptic curves, connection between binary quartic forms and elements in the 2-Selmer groups of elliptic curves.
For $p = 3, 5$ similar techniques can be used with some modification.
On the basis of parity considerations by the results of T.Dokchitser and V.Dokchitser, one obtains the "generic" p -Selmer group has $\mathbb{F}_p$ - dimension 0 or 1. Consequently, Theorem 1 follows from Theorem 2 combined with the next theorem.

Theorem 3. If $Sel_p(E/\mathbb{Q})$ has $\mathbb{F}_p$ - dimension 0 or 1, then the BSD rank conjecture holds for E over $\mathbb{Q}$ under some arithmetic assumptions on the pair (E, p).

The proof of Theorem 3 involves the use of Cyclotomic Iwasawa Main Conjecture.

A positive integer n is called a "congruent number" if n equals the area of a right-angled triangle with length of each side is a rational number. It is a well-known fact that n is a congruent number if and only if the elliptic curve $E_n : y^2 = x^3 - n^2x$ has positive rank over $\mathbb{Q}$. For the elliptic curve E_n, Heath-Brown employed a method based on character sums to obtain deep results on the behavior of the size of the 2-Selmer group $Sel_2(E_n/\mathbb{Q})$ arising from the isogeny $[2] : E_n \to E_n$. He also obtained the asymptotic formula which yields a sharp upper bound on the average rank of the elliptic curves in this family. We are trying to find such an asymptotic formula for θ congruent numbers. We are also trying to use the techniques of Bhargava and Shankar to obtain the upper bound obtained by Heath-Brown in a different manner. This will be my main focus in the following academic year.

Conference/Workshops Attended:

1. *Elliptic curves and the special values of L-functions*, (Online) ICTS, August, 2021.
2. *Seminar Series on "Rank of Elliptic Curves"*, (Online) HRI, August-November 2021.
3. *Online course on "p-adic numbers, p-adic analysis and zeta values"*, HRI, February-May 2022.

Invited Lectures/Seminars:

1. *Selmer Groups, Tate-Shafarevich Groups, the descent exact sequence, L-functions associated to an elliptic curve and BSD conjecture*, Online seminar series on "Rank of Elliptic Curves", HRI, August-November 2021.

Priyanshu Chakraborty

Research Summary:

In the academic year 2021-2022, I have studied some papers related to Virasoro Lie algebras, Witt algebras and loop algebras related to some well known Lie algebras. I have completed two project, one of which is related to loop-Witt Lie algebras (partially done in this academic year) and other related to loop-Virasoro algebras.

Publications:

1. Partial clssification of irreducible modules for loop-Witt algebras , Priyanshu Chakraborty, S.Eswara Rao, Journal of Lie theory, (32) **(2022)**, 267-279.

2. A class of irreducible modules for loop-Virasoro algebras, Priyanshu Chakraborty, Punita Batra, To be appear in Journal of algebra and its application, https://doi.org/10.1142/S0219498823501566

Conference/Workshops Attended:

1. The International conference on recent trends in mathematics (ICRTM) at department of mathematics, Hansraj college, University of Delhi, 22-24 dec, 2021 (online).

2. National conference of Academy for progress of mathematics on Recent Advances on Mathematical Analysis and Applications (NCAPM-RAMAA-2022) at department of mathematics, BHU, Varanasi, 7th-8th May, 2022 (online).

3. Recent Advances in Mathematics and related areas at department of mathematics KSoM, 21th-24th april, 2022 (online).

Invited Lectures/Seminars:

1. Presented an online talk titled " Partial clssification of irreducible modules for loop-Witt algebras " in the International conference on recent trends in mathematics (ICRTM) at department of mathematics, Hansraj college, University of Delhi, 22-24 dec, 2021 .

2. Presented an online talk titled " A class of irreducible modules for loop-Virasoro algebras" in national conference of Academy for progress of mathematics on Recent Advances on Mathematical Analysis and Applications (NCAPM-RAMAA-2022) at department of mathematics, BHU, Varanasi, 7th-8th May, 2022.

3. Presented an online talk titled " A class of irreducible modules for loop-Virasoro algebras" in Recent Advances in Mathematics and related areas at department of mathematics KSoM, 21th-24th april, 2022.

Srijonee Shabnam Chaudhury

Research Summary:

Currently I am working on 'Schur-Siegel-Smyth Trace Problem'. From some recent results it seems that it is not very difficult to prove some results on trace problem if we try to find it for some combinatorial objects (such as graph, matrix etc.) attached with an algebraic integer. In my current project I have tried to do the same for some special types of matrices. In particular, I have obtained the following -

Let $\mathcal{S}, \mathcal{T}, \mathcal{C}$ be three sets of some special types of connected positive definite matrices. The *Absolute Trace* of a square matrix A is defined by

$$\frac{\text{Trace of matrix A}}{\text{Order of A}}$$

In this paper, we extend the notion of absolute trace by defining *trace-k measure* of A = mean value of the power sums of eigenvalues of A. And we obtain the greatest lower bound of this measure for any $n \times n$ matrix in $\mathcal{S} \cup \mathcal{T} \cup \mathcal{C}$. Using this we find some criteria which assure when an integer polynomial can not be a characteristic or minimal polynomial of an integer symmetric matrix. We also obtain here the smallest limit point of the set of all *absolute trace-k measure* of matrices in $\mathcal{S} \cup \mathcal{T} \cup \mathcal{C}$.

Finally, we exhibit that the famous result of Smyth on density of absolute trace measure of totally positive integers is also true for the set of symmetric integer connected positive definite matrices.

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 (https://arxiv.org/abs/2112.14489)

Conference/Workshops Attended:

1. International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2018, HRI

2. International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2019, HRI

3. Workshop on Additive Combinatorics – 2020, ICTS, Bangalore

4. IIT Guwahati , for AIS (Advanced Instructional School) on Modular Form, May,2019 .

5. International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2021, KSOM

6. Recent Advances in Mathematics and Related Areas (April 21, 2022 - April 24, 2022), KSOM (Hybrid Conference)

Visits to other Institutes:

1. Kerala School of Mathematics (KSOM) Kozhikode, Kerala, India (October 20,2021 - November 30, 2021).

Invited Lectures/Seminars:

1. Sum of Integral Squares in non-totally Real Fields and Beyond, International Conference on Class Group of Number Fields and Related Topics (ICCGNFRT) – 2021, KSOM, Kozhikode, Kerala, India.

   Date of my talk- 24th October, 2021

Bhargab Das

Research Summary:

In the academic year 2011-22, I have explored the arithmetic properties of elliptic curves extensively along with my first-year PhD course works. I have studied the group structure of rational points on elliptic curves over various fields followed by the famous Mordell-Weil theorem. After that I have explored the Selmer and Tate-Shafarevich group which is directly linked to computing the algebraic rank of an elliptic curve. Now my main focus is to continue this study in more general aspects like abelian varieties and reduction of those types of curves.

Conference/Workshops Attended:

1. Elliptic curves and the special values of L-functions (ONLINE), ICTS, India, August 2021

Invited Lectures/Seminars:

1. Topic: Universal Bundles
   Project I, HRI, Prayagraj, July 2021

2. Topic: Rational Points on Elliptic Curves
   Rank of Elliptic Curves, HRI, Prayagraj, September 2021

3. Topic: The Arithmetic of Elliptic curves
   Project II, HRI, Prayagraj, January 2022

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 $\alpha_{ij} \in R$. In 2001, A. Kihel and O. Kihel conjectured that there is no Diophantine triple in $\mathbb{Z}$ with the property $D(1)$ which is also a triple with the property $D(n)$ for some $n \neq 1$. In 2015, Zhang and Grossman found a counter example to this claim. Many authors have worked in this direction. I(jointly work with Kalyan Chakraborty and Azizul Hoque) proved that, in $\mathbb{Z}$, for every integer n, there exist infinitely many Diophantine triples having all positive elements with the property $D(n)$ which also have the property $D(t)$ for $t \in \mathbb{Z}$ with $n \neq t$. We have also proved that, in $\mathbb{Z}[i]$, there are infinitely many Diophantine triples with the property $D(-1)$ which also have the property $D(n)$ for two distinct n's other than $n = -1$ and these triples are not equivalent to any Diophantine triple with the property $D(1)$. Moreover, I have studied p-adic numbers. Also, I have read some papers related to Diophantine m-tuples over polynomial rings. Currently, I am working on two projects. The first one is based on the rank of elliptic curves over rational numbers, for a given torsion subgroup. Here elliptic curves are coming from Diophantine m-tuples. And the last one is related to Diophantine m-tuples with the property $D(n)$ over polynomial rings.

Publications:

1. S. Gupta, *D(-1) tuples in imaginary quadratic fields*, Acta Math. Hungar., **164** (2021), 556-569.

Preprints:

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

2. K. Chakraborty, S. Gupta, A. Hoque, *Diophantine triples with the property $D(n)$ for distinct n*, submitted.

Conference/Workshops Attended:

1. *Modular Forms, An online conference in honour of Prof. B Ramakrishnan's 60th birthday* , India, September 17-19, 2021.

2. *International Conference on Class Groups of Number Fields and Related Topics-2021*, Kerala School of Mathematics, Kozhikode, India, October 21-24, 2021.

3. *Recent Advances in Mathematics and Related Areas-2022*, Kerala School of Mathematics, Kozhikode, India, April 21-24 , 2022.

Invited Lectures/Seminars:

1. *D(-1) tuples in imaginary quadratic fields,* International Conference on Class Groups of Number Fields and Related Topics-2021, Kerala School of Mathematics, Kozhikode, India, October 21-24, 2021.

2. *D(-1) tuples in imaginary quadratic fields,* Recent Advances in Mathematics and Related Areas-2022, Kerala School of Mathematics, Kozhikode, India, April 21-24, 2022.

Arpan Kanrar

Research Summary:

In the academic year 2021-2022, I have studied books related homological algebra along with my first-year PhD course works. Parallelly, I have been exploring the topics group theory and combinatorial group theory.

Publications:

1. Arpan Kanrar, *Wolstenholme's theorem revisited*, Elemente der Mathematik DOI 10.4171/EM/457, (2021).

Invited Lectures/Seminars:

1. **Topic** : First order right derived functor and a set of classes of equivalent extensions.
   Project I, HRI, Prayagraj, July 2021.

2. **Topic** : Extensions and second cohomology of groups.
   Project II, HRI, Prayagraj, January 2022.

Parul Keshari

Research Summary:

In a joint work with Umesh V. Dubey, we are trying to identify the moduli of principal bundles to Kronecker representations with additional properties. This work is still under progress.

The other project is a joint work with Dr. Anoop Singh. In this project we have calculated the Picard group of the Hodge moduli spaces of Lie algebroid connections, automorphism group of Hodge moduli spaces of Lie algebroid connection with fixed determinant and Chow group of de Rham moduli spaces of Lie algebroid connections.

Krishnarjun Krishnamoorthy

Research Summary:

1. The question of persistence of classical chaotic behaviour in the quantum level, particularly as one approaces the semiclassical limit has been in the interest of mathematicians and physicists alike. In particular, when the classical geometry is hyperbolic (that is when there is negative curvature), nearby geodesics tend to diverge and the dynamics is known to be chaotic. The persistence of this chaotic behaviour in the quantum level was first investigated by Runick and Sarnak with connection to the theory of Maass forms. In particular, when the surface was the arithmetic quotient of the upper half plane, the action of a self adjoint commutative family of operators called the Hecke operators was expected to make the study of this problem in these surfaces particularly interesting and therefore might lend itself to a solution. Substantial progress was made towards this problem by Lindenstrauss and Soundararajan leading to a proof of the Quantum Unique Ergodicity conjecture for arithmetic surfaces (particularly $\mathcal{H}/SL(2,\mathbb{Z})$) in 2010. This was quickly followed by analogous proofs for number fields and modular forms therein generalizing and resetting the classical arguments in a more adelic setting.

   The Quantum Unique Ergodicity question is very intimately tied to a classical problem in analytic number theory and therein lies the interest of analytic number theorists in answering this question. The subconvexity problem in various contexts asks for improvement over the "convexity bound" obtained by complex analytic arguments on various central values of classical L functions. The existing proofs however leave much to wish for. In particular, there is a direct correspondence between improving the rate of convergence of the QUE problem and obtaining sharper subconvexity bounds. All classical approaches to solving this problem involved improving subconvexity estimates and deducing QUE as a consequence.

   In a recent work, in the holomorphic case we explore this connection further and deduce a substantially strong subconvexity bound and reprove the QUE theorem with an improved rate of convergence simultaneously thereby furthering this deep connection.

2. A closely connected question to the QUE problem is the "Sup-Norm Problem" which asks for bounds on the supremum norms of L^2 normalized eigenfunctions of the hyperbolic laplacian on arithmetic quotients. Again this problem has deep consequences in arithmetic and is once again connected to another aspect of the subconvexity problem. In an ongoing project we investigate methods to improve the existing bounds on the supnorm problem which have proven to be a natural barrier resisting all known methods of improvement.

3. It is an age old problem to study the existence and distribution of zeros and poles of classical L functions, the most famous example of this series of questions being the Riemann hypothesis. In a recent work, we study this problem from a qualitative perspective and show that counter examples to these classical conjectures, if they exist show substantial deviation from all the known examples of

various L functions available in literature. In particular, a corollary of our work states that if the Riemann hypothesis has a single counter example, it then has an infinitude of counter examples.

Publications:

1. (joint work with Kalyan Chakraborty) "On some symmetries of the base n expansion of $1/m$: The class number connection", to appear in ***Pacific Journal of Mathematics***.

2. (joint work with Rishabh Agnihotri and Kalyan Chakraborty) " Sign Changes in Restricted coefficients of Hilbert Modular Forms", to appear in ***Ramanujan Journal***.

3. (joint work with Kalyan Chakraborty) "On moments of non-normal number fields", to appear in ***Journal of Number Theory*** **238** 183-196 (2022),

4. "Generalized divisor problem for new forms of higher level", ***Czech. Math. J.*** **72**, 259–263 (2022).

Preprints:

1. "Weight aspect subconvexity and holomorphic quantum unique ergodicity for $\mathcal{H}/SL(2,\mathbb{Z})$" *under communication*.

2. "On the Poles of certain L functions" *under communication*

3. "Sup norm problem for eisenstein series and subconvexity bounds for Epstein zeta functions" *In preparation*.

Conference/Workshops Attended:

1. Internation Conference on Class Groups of Number Fields and Related Topics - 2022 at the Kerala School of Mathematics.

2. Recent Advances in Mathematics and Related Areas - 2022 at the Kerala School of Mathematics

Visits to other Institutes:

1. Visit to Kerala School of Mathematics

Other Activities:

1. Was a tutor at Summer Program in Mathematics held at Kerala School of Mathematics during May 2022.

2. Ongoing lecture series on "An introduction to arithmetic quantum chaos" at Kerala School of Mathematics.

Arup Kumar Maity

Research Summary:

This academic year, I focused on Young's type inequality in the context of twisted convolution. It's easy to prove that the triple's range is larger than the ordinary convolution. Our goal is to demonstrate the triple's full spectrum. However, we have achieved partial success by specifying one necessary and one sufficient condition. We're still looking for the best range.

We looked at the $L^p - L^q$ boundedness of a singular operator whose kernel possesses singularity on the unit sphere as well as at infinity in another paper.That is actually completeness of study of kernel of quadratic form raised to some negative power. To show our main theorem, we use the multiplier technique.

Preprints:

1. With Shyam Swarup Mondal, A note on singular integral, submitted.
2. With P. K. Ratnakumar, On $L^p - L^q$ boundedness of the twisted convolution operators, submitted.

Conference/Workshops Attended:

1. 17th Discussion Meeting in Harmonic Analysis, NISER, Bhubaneswar, 5th-8th January 2022.
2. Recent advances in Mathematics and related areas, KSoM, Kozhikode, 21st-24th April 2022.

Invited Lectures/Seminars:

1. On $L^p - L^q$ Multiplier, 17th Discussion Meeting in Harmonic Analysis, NISER, Bhubaneswar, 7th January 2022.

Nishant

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:

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

The connection between solutions of solutions of set theoretical Yang-Baxter equation and skew braces is well known .We have defined the abelian and non-abelian second cohomology group for the extension of skew braces. If H and I be two skew brace such that I be a non abelian group then we shown that there exist a bijection between skew brace Extensions of H by I and Extensions of H by $Z(I)$. Let G be a group and $R : G \to G$ such that $R(x)R(y) = R(xR(x)yR(x)^{-1})$ then R is called a Rota-Baxter operator and (G, R) is called Rota-Baxter group. It is known that every Rota-Baxter operator on group induces a non-degenerate solution of set theoretical Yang-Baxter equation. We define the abelian and non-abelian second cohomology group for abelian and non-abelian extension of Rota-Baxter group and construct a Wells' like exact sequence relating the abelian second cohomology group with inducible automorphisms of extensions of Rota-Baxter group.

Preprints:

1. Nishant, *Extensions and Well's type exact sequence of skew braces*, submitted
2. A.Das , Nishant, *Extensions, cohomology and a fundamental sequence of Wells for Rota-Baxter groups*, under preparation.
3. A.Das, Nishant, *A unified extension theory of Rota-Baxter algebras, dendriform algebras, and a fundamental sequence of Wells*, under preparation.

Conference/Workshops Attended:

1. *Braces in Bracelet Bay, LMS Regional Meeting and Workshop Swansea University,* January 4-6th, 2022
2. *Online workshop on Group Theory 2022*, 4-5 February 2022
3. *Presented an online talk " Cohomology, Extensions and Automorphisms of Skew Braces"* in International e-confrence on pure and applied mathematical sciences (ICPAMS-2022) 04-07 May 2022.

Uday Sureshbhai Patel

Research Summary:

Apart from the coursework, we started learning the basics of Fourier Analysis. Using techniques of Fourier Transform, we studied the Heisenberg's inequality and its measure theoretic version: Benedicks Theorem. We also studied the basics of Lebesgue spaces (L^p spaces) and various interpolation theorems, and we rigorously learnt the proof of Stein's Interpolation Theorem. Now we plan to study Singular Integrals and Littlewood-Paley theory in the direction of Euclidean Harmonic Analysis.

Conference/Workshops Attended:

1. 17^{th} Discussion Meeting in Harmonic Analysis, Online, NISER Bhubaneswar, $5^{\text{th}} - 8^{\text{th}}$ January, 2022.

Invited Lectures/Seminars:

1. *Heisenberg's inequality and Benedicks Theorem*, Project Talk, HRI, Prayagraj, July 29, 2021.

2. *On Analytic Interpolation Theorem*, Project Talk, HRI, Prayagraj, February 5, 2022.

Gopinath Sahoo

Research Summary:

The notion of t-structures on triangulated categories has been introduced by Belinson et al. It has been useful in the study of derived equivalences, tilting theory and stability conditions on triangulated categories. One of our goals was to classify compactly generated t-structures on the unbounded derived category of a Noetherian scheme. Recently, we have been able to obtain the classification which is a generalization of the earlier results for commutative rings to schemes.

Hrbek and Nakamura have reformulated the telescope conjecture for t-structures and proved that the conjecture is true for the derived category of a Noetherian ring. The telescope conjecture for t-structures asks if every homotopically smashing t-structure is compactly generated. Using our classification result we have shown that a tensor version of the telescope conjecture is true for Noetherian separated schemes.

The natural counterpart of t-structures is the notion of weight structure, introduced by Bondarko. One can ask similar questions about weight structures. Continuing our earlier investigation we are trying to understand the weight structures of the derived category of a Noetherian scheme.

Preprints:

1. Umesh V. Dubey and Gopinath Sahoo, *Compactly generated tensor t-structures on the derived category of a Noetherian scheme*, https://arxiv.org/abs/2204.05015

Santanu Tantubay

Research Summary:

In the academic year 2021-2022, I have studied some papers related to quantum torus, integrable modules and loop algebras related to some well known Lie algebras. I have completed two project, one of which is related to loop of derivation space of rational quantum torus and other related to integrable modules for the full toroidal Lie algebras co-ordinated by rational quantum torus.

Publications:

1. Irreducible modules for the loop of derivations of rational quantum torus, Santanu Tantubay, Journal of Algebra and Its Applications, https://doi.org/10.1142/S0219498823501608

Preprints:

1. Irreducible Integrable Modules for the full Toroidal Lie algebras co-ordinated by rational quantum torus, Santanu Tantubay, Punita Batra, https://arxiv.org/abs/2202.07985

Conference/Workshops Attended:

1. Recent Advances in Mathematics and related areas at department of mathematics KSoM, 21th-24th april, 2022 (online).

Invited Lectures/Seminars:

1. Presented an online talk titled " Irreducible modules for the loop of derivations of rational quantum torus" in Recent Advances in Mathematics and related areas at department of mathematics KSoM, 21th-24th april, 2022.

Aparna Tripathi

Research Summary:

Apart from the course work, we started learning the basics of Algebraic number theory and Elementary Number Theory. Using Group action and Jordan's theorem, we studied different extensions of Euler's theorem. Also, we learnt the basics of rational approximation of real numbers and using continued fraction, we studied that the quadratic irrationals are badly approximable. Then we learnt Liuoville theorem and as an application, we learnt the first example of a transcendental number. We plan to continue in the direction algebraic number theory and introduction to transcendental number theory.

Invited Lectures/Seminars:

1. *Extensions of Fermat Little Theorem*, Project Talk, HRI, Prayagraj, July 30, 2021.
2. *Quadratic Irrationals are badly approximable*, Project Talk, HRI, Prayagraj, February 6, 2022.

Other Activities:

1. Volutnteer for Harsha School - Outreach Programme for Underpreviledge Students, HRI, Prayagraj, 2022.

Academic Report - Physics

Anirban Basu

Research Summary:

My research has focussed on analyzing modular graph functions that arise in the low momentum expansion of one and two loop amplitudes in superstring theory. The aim has been to obtain eigenvalue equations satisfied by these graphs, which provide useful information about the contributions of these graphs to certain terms in the effective action.

Publications:

1. Anirban Basu, *Poisson equation for genus two string invariants: a conjecture*, JHEP **04** 050 (2021)

Conference/Workshops Attended:

1. *Indian Strings Meeting 2021* (Virtually at Indian Institute of Technology, Roorkee from 12 to 17 December 2021)

Other Activities:

1. Taught "Electrodynamics" from May to August 2021
2. Taught "Quantum Field Theory 1" from October 2021 to January 2022

Sudip Chakraborty

Research Summary:

Materials modeling for energy scavenging through cutting edge computational methodology is the prime focus of our research. In the last year, we have worked extensively on the physics of materials for solar cells and fundamentals behind different catalytic reaction for efficient hydrogen generation and carbon emission. We theoretically predict novel materials for efficient and stable solar cells, where the fundamental electronic and excited state properties are being envisaged. In this context, we have investigated Rashba-Dresselhaus and Pseudo-Rashba effect in the promising solar cell materials, which is arising from the relativistic spin-orbit coupling. Recently, we have resolved a long standing problem related to Pseudo-Rashba effect, which could exists in centrosymmetric inorganic halide perovskite system in the presence of heavy element like lead, while the normal Rashba phenomena is believed to be present in non-centrosymmetric structures till now. We have also worked on high pressure driven optical properties tuning in hybrid perovskite materials named piezochromism.

The computational design and theoretical prediction of catalytic materials for water splitting through hydrogen evolution reaction and oxygen reduction reaction along with electrochemical reduction of CO_2 to envisage carbon capture and utilization are another research focus of our research. We have systematically investigated different catalytic reaction mechanism on a plethora of emerging and novel materials family from the first principles electronic structure calculations within the framework of density functional theory (DFT) formalism, while having a profound understanding of the electronic structure, adsorption free energy based reaction coordinate and charge transfer. With the help of DFT calculations, we could explore the electron transfer process based on Bader charge analysis, charge density distribution and electron Localization function in these catalytic materials.

All these efforts, connected with the common string Energy, manifested into thirteen published articles in the last year, while there are twelve more works, which are in the process of submission or under review. The published articles are not only on pure theoretical investigations, but few of them are also the successful outcome of the ongoing feedback between experimental investigations and our theoretical prediction and analysis based on electronic structure theory.

Publications:

1. S. Mondal, S. Sarkar, D. Bagchi, T. Das, R. Das, A. Singh, Ponnappa K. P., C. Vinod, Sudip Chakraborty, S. Peter, *Morphology Tuned Pt_3Ge Accelerates Water Dissociation to Industrial Standard Hydrogen Production over a wide pH Range*, Advanced Materials, 34, 30, 2202294 (2022). [Impact Factor: 30.1]

2. Manasa G. B., M. K. Nazeeruddin, Sudip Chakraborty, *Evolution of Hybrid Organic-Inorganic Perovskite Materials under External Pressure*, Applied Physics Reviews, 8, 041409(2021). (Editor's Choice Featured Article) [Impact Factor: 19.6]

3. P. Kour, M. Reddy, S. Pal, S. Sidhik, T. Das, P. Pandey, S. Mukherjee, Sudip Chakraborty, A. Mohite, S. Ogale, *An Organic-Inorganic Perovskitoid with Zwitterion Cysteamine Linker and Its Crystal-Crystal Transformation to Ruddlesden-Popper Phase*, Angewandte Chemie, **60**, 18750(2021). [Impact Factor: 15.3]

4. D. Gupta, Sudip Chakraborty, R. Amorim, R. Ahuja, T. Nagaih, *Local electrocatalytic activity of PtRu supported on nitrogen doped carbon nanotubes towards methanol oxidation by scanning electrochemical microscopy*, Journal of Materials Chemistry A, **9**, 21291 (2021). [Impact Factor: 12.7]

5. A. Gopakumar, Ponnappa. K. P., X. Yuan, Z. Azimi, F. Kremer, C. Jagadish, Sudip Chakraborty, H. Tan, *Epitaxial growth of GaAs nanowires on synthetic mica by metal-organic chemical vapor deposition*, ACS Applied Materials Interfaces,**14**, 3395 (2022) [Impact Factor: 9.2]

6. S Sarkar, A Rawat, T. Das, M Gaboardi, Sudip Chakraborty, C. Vinod, Sebastian Peter, *Structure Tailored Non-Noble Metal based Ternary Chalcogenide Nanocrystals for Pt-like Electrocatalytic Hydrogen Production* ChemSusChem, **14**, 3074(2021). [Impact Factor: 8.9]

7. J. Kaur, Sudip Chakraborty, *Tuning Spin Texture and Spectroscopic Limited Maximum Efficiency through Chemical Composition Space in Double Halide Perovskites*, ACS Applied Energy Materials, **5**, 5579 (2022). [Impact Factor: 6.0]

8. N. Koshi, D. Murthy, Sudip Chakraborty, S. Lee, S. Bhattacharjee, *Probing Photoexcited Charge Carrier Trapping and Defect Formation in Synergistic Doping of $SrTiO_3$*, ACS Applied Energy Materials **1**, 1159 (2022). [Impact Factor: 6.0]

9. T. Das, K. Alam, Sudip Chakraborty, P. Sen, *Probing active sites on $MnPSe_3$ and $FePSe_3$ tri-chalcogenides as a design strategy for better hydrogen evolution reaction catalyst*, International Journal of Hydrogen Energy, **46**, 37928 (2021). [Impact Factor: 5.82]

10. K. Alam, T. Das, Sudip Chakraborty, P. Sen, *Identifying the catalytically active sites on the layered tri-chalcogenide compounds $CoPS_3$ and $NiPS_3$ for efficient hydrogen evolution reaction*, PhysChemChemPhys, **23**, 23967 (2021). [Impact Factor: 3.68]

11. D. Kumar, J. Kaur, P. P. Mohanty, R. Ahuja, Sudip Chakraborty, *Recent Advancements in Non-toxic Halide Perovskites: Beyond Divalent Composition Space*, ACS Omega, **6**, 33240(2021). [Invited Perspective Article] [Impact Factor: 3.51]

12. S. Parmar, T. Das, B. Ray, B. Debnath, S. Gosavi, G. Shanker, S. Datar, Sudip Chakraborty, S. B. Ogale, *N, H Dual-doped Black Anatase TiO_2 Thin Films towards Significant Self-Activation in Electrocatalytic Hydrogen Evolution Reaction in Alkaline Media*, Advanced Energy and Sustainability Research, 2100137(2021). [Invited Article]

13. A. Sarangi, Manasa G.B., Sudip Chakraborty, *Tuning Composition Space in Lead-Free Divalent and Tetravalent Halide Perovskites: A Critical Review*, Emergent Materials -Accepted (2021) doi:10.1007/s42247-021-00297-0. [Invited Review Article]

Preprints:

1. Manasa G. B., Sudip Chakraborty, *Rationalization of Double Perovskite Oxides as Energy Materials: A Theoretical Insight from Electronic and Optical Properties* (Under Review in ACS Materials Au).

2. P. Mohanty, R. Ahuja, Sudip Chakraborty, *Progress and Challenges in Layered Two-dimensional Hybrid Perovskites* (Under Review in Nanotechnology).

3. H. Banerjee, J. Kaur, M. K.Nazeeruddin, Sudip Chakraborty, *Tuning Paradigm of External Stimuli Driven Electronic, Optical and Magnetic Properties in Hybrid Perovskites and Metal Organic Complexes* (Under Review in Materials Today).

4. T. Das, Sudip Chakraborty, P. Sen, *Competing Effect of External Strain, Functionalization and Vacancy Defect Towards Enhanced HER Activity in Transition Metal Phosphorous based Trichalcogenide Monolayers* (Under Review in ACS Applied Energy Materials).

5. S. Gratious, A. Karmakar, D. Kumar, S. Kundu, Sudip Chakraborty, S. Mandal, *Incorporating $Au_1$1 Nanocluster on MoS_2 Nanosheet Edges for Promoting Hydrogen Evolution Reaction at the Interface* (Under Review in Catalysis Science and Technology).

6. A. Karmakar, T. Das, K. Karthick, S. Kumaravel, S. Sankar, R. Madhu, Sudip Chakraborty, S. Kundu, *Tuning the Electronic Structure of Ni Vacancy Enriched AuNi Spherical Nanoalloy via Electrochemical Etching for Water Oxidation Study in Alkaline and Neutral medium* (Under Review in Inorganic Chemistry).

7. D. Gupta, A. Kafle, S. Kaur, P. P. Mohanty, T. Das, Sudip Chakraborty, R. Ahuja, T. Nagaiah, *High Yield Selective electrochemical conversion of N_2 to NH_3 via morphology controlled silver phosphate under ambient conditions* (Under Review in Journal of Materials Chemistry A).

8. D. Gupta, A. Kafle, P. P. Mohanty, T. Das, Sudip Chakraborty, R. Ahuja, T. Nagaiah, *Self-powered NH_3 synthesis by trifunctional Co_2B based high power density Zn-air batteries* (Under Review in Energy and Environmental Sciences).

9. S. Singh, A. Neveu, K. Jayanthi, T. Das, Sudip Chakraborty, A. Navrotsky, V. Pralong, P. Barpanda, *Facile Synthesis and Phase Stability of Cu-based $Na_2Cu(SO_4)_2.xH_2O$ (x = 0-2) Sulfate Minerals as Conversion type Battery Electrodes* (Under Review in Dalton Transactions).

10. N. Kitchamsetti, M. Samtham, P. Didwal, D. Kumar, D. Singh, S. Bimli, P. Chikatea, D. Bashaa, S. Kumar, C. Park, Sudip Chakraborty, R. Devan, *Theory Abide Experimental Investigations on Morphology Driven Enhancement of Electrochemical Energy Storage Performance for Manganese Titanate Perovskites Electrodes* (Under Review in Journal of Power Sources).

11. S. Kaur, M. Kumar, D. Gupta, P. P. Mohanty, T. Das, Sudip Chakraborty, R. Ahuja, T. Nagaiah, *Efficient CO_2 utilization and sustainable energy conversion via aqueous Zn-CO_2 batteries* (Under Review in Applied Catalysis B).

12. N Sethulakshmi, S. Nellaiappan, Ponnappa K.P., T. Das, Sudip Chakraborty, S. Sharma, *Hydrazine Assisted Water Oxidation and its Mechanism over Nanocoral* $CuCo_2S_4$ (Under Review in Journal of Electroanalytical Chemistry).

Conference/Workshops Attended:

1. Session Chair (online) in Frontiers In Materials for Technological Applications (FIMTA 2021) organized by CSIR-IMMT, Bhubaneswar (August 04-06, 2021).

Invited Lectures/Seminars:

1. Delivered an Invited Talk (online) in Photovoltaics and Solar Energy Theme Symposium at 3nd Indian Materials Conclave and 32nd Annual General Meeting of Materials Research Society of India (MRSI) (December 20-23, 2021).

Academic recognition/Awards:

1. Awarded Rising Stars of 2022 by American Chemical Society (ACS) Materials Au among 300 world wide nominations as the sole recipient from India.
2. Awarded Ministry of Education Academic Research Fund (MOE AcRF), NTU, Singapore.
3. DST Funded Centre of Excellence on Carbon Capture and Utilization at JNCASR, Bangalore as co-Principal Investigator

Other Activities:

1. Teaching course: Quantum Mechanics-III (October 2021 to January 2022)
2. Supervising Ph.D and Postdoctoral Fellows.
3. External Ph.D Thesis Examiner: JNCASR Bangalore
4. Editorial Activity: Guest Editor for European Physical Journal (EPJ ST) Special Issue: Advances in Low-Dimensional and Nanostructured Materials for Sustainable Energy Conversion and Storage
5. Reviewer Activity: JACS, ACS Energy Letters, Nano Energy, Chemistry of Materials, ACS Applied Energy Materials
6. Selection Committee Participation: RISE (TCG-CREST)

Tapas Kunar Das

Research Summary:

My broad areas of research are astrophysics, general relativity, and dynamical systems. I have been working on black hole astrophysics, analogue gravity phenomena, theory

of traversable wormholes, and application of the theory of dynamical systems in large scale fluid flow under strong gravity. Recently I have started exploring the nonlinear

and chaotic behaviour of accreting astrophysical compact objects and its signatures as revealed in observational data.

Publications:

1. Fernandes, Karan., Maity, Susovan., & Das, Tapas K., *Dynamical spacetimes from nonlinear perturbations*, Physical Review D Letters, **To appear**, `Manuscript Number LP17166`, (**2022**).

2. Fernandes, Karan., Maity, Susovan., & Das, Tapas K., *Dynamical analogue spacetimes in non-relativistic flows*, Physical Review D, **To Appear**, `Manuscript Number DP12655`, (**2022**).

Preprints:

1. Mitra, Arpan Krishna., Chakraborty, Aishee., Tarafdae, Pratik., & Das, Tapas K., *Multi-criticality and related bifurcation in accretion discs around non-rotating black holes – an analytical study*, arXiv:2111.13592 [astro-ph.HE], (**2021**).

2. Datta, Satadal., & Das, Tapas K., *Lagrangian description of transonic black hole accretion flow and the emergent spacetime*, Physical Review D, **Under Review**, `Manuscript Number DS13158`, (**2022**).

3. Maity, Susovan.,Shaikh, Md. Arif., Tarafdar, Pratik., & Das, Tapas K., *Carter-Penrose diagrams for emergent spacetime in axisymmetrically accreting black hole systems*, Physical Review D, **Under Review**, `Manuscript Number DS13186`, (**2022**).

Visits to other Institutes:

1. Physics & Applied Mathematics Unit (PAMU), Indian Statistical Institute, Kolkata, West Bengal, India.

2. Physics Department, Ramakrishna Mission Vivekananda Centenary College, Rahara, West Bengal, India.

3. Sarojini Naidu College for Women, Kolkata, West Bengal, India.

Other Activities:

1. Taught courses (Mathematical Methods - I) to M.Sc. students of HRI.
2. Served as a member of the Medical Committee, HRI.
3. Supervised two Ph.D. students and mentored two post doctoral fellows.

Aditi Sen De

Research Summary:

In the second revolution of quantum technologies, multipartite entangled states are shown to play a crucial role in designing computational and communication tasks. During 2021-22, we propose a measurement-based protocol for generating multipartite entangled states where weak entangling measurement on two parties serves as the basic unit of operation. In the literature, the potential of this kind of joint measurement has been less studied compared to the exploration of various features of multipartite entangled states. Note that although projective joint measurements can not be taken as the basic operation for the purpose of creating entanglement between more number of parties starting from a lesser number of parties, weak entangling measurement has the potential to fulfill this task. We call the proposed expansion procedure, the "multipartite entanglement inflation" process. Surprisingly, we find that maximally entangled states as inputs are worse than that of the non-maximally entangled states, Haar uniformly generated pure states having a moderate amount of entanglement and the Werner state with a certain threshold noise.

From a different perspective, we have explored characteristics in the Non-Hermitian Hamiltonian with both parity and time reversal symmetry, (together called PT-symmetry). It is known that they can have real energy spectrum while the breaking of symmetry leads to the complex eigenenergy. The phase transition from symmetry broken to an unbroken phase occurs at the exceptional point. These results simulate a significant amount of research to characterize non-Hermitian quantum theory, both theoretically and experimentally, especially in optics, cold atoms, cavities. In this respect, discrete systems like tight binding model, quantum spin systems, specifically, one-dimensional quantum XY models turn out to be important platforms to verify the properties in non-Hermitian Hamiltonian. It was also noticed that instead of PT-symmetry, linear rotation operator, R, which rotates each spin by a certain amount around a fixed axis, along with time reversal operator can together prompt non-Hermiticity in the quantum spin models. On the other hand, in the traditional quantum theory, one-dimensional quantum spin models possess a factorization surface where the ground states are fully separable having vanishing bipartite as well as multipartite entanglement. We found that in the non-Hermitian counterpart of these models, these factorization surfaces either can predict the exceptional points where the unbroken-to-broken transition occurs or can guarantee the reality of the spectrum, thereby proposing a procedure to reveal the unbroken phase.

The quest for small quantum thermal machines that can supersede their classical counterparts in performance has been an important and vibrant component in the field of quantum thermodynamics. We explore a small quantum refrigerator and a quantum battery in which the working substance is made of paradigmatic nearest-neighbor quantum spin models, the XYZ and the XY model with Dzyaloshinskii-Moriya interactions, each of which is in contact with a bosonic bath. We identify a specific range of interaction strengths, tuned appropriately to ensure a cooling of the selected spin. Moreover, we investigate the performance of a quantum battery exposed to local Markovian and non-Markovian dephasing noises.

Publications:

1. R. Banerjee, A.K. Pal and A. Sen(De), *Hierarchies of localizable entanglement due to spatial distribution of local noise*, Phys. Rev. Research **4**, 023035 (2022).

2. S. Ghosh and A. Sen(De), *Dimensional enhancements in quantum battery with imperfections*, Phys. Rev. A **105**, 022628 (2022).

3. T.K. Konar, S. Ghosh, A.K. Pal, and A. Sen(De), *Designing robust quantum refrigerators in disordered spin models*, Phys. Rev. A **105**, 022214 (2022).

4. S. Roy, S. Mal, and A. Sen(De), *Gain in performance of teleportation with uniformity-breaking distributions*, Phys. Rev. A **105**, 022610 (2022).

5. R. Gupta, S. Gupta, S. Mal, and A. Sen(De), *Constructive feedback of non-Markovianity on resources in random quantum states*, Phys. Rev. A **105**, 012424 (2022).

6. P. Halder, S. Mal, and A. Sen(De), *Measurement-based multipartite entanglement inflation*, Phys. Rev. A **104**, 062412 (2021).

7. L.G. C. Lakkaraju and A. Sen(De), *Detection of an unbroken phase of a non-Hermitian system via a Hermitian factorization surface*, Phys. Rev. A **104**, 052222 (2021).

8. L.G. C. Lakkaraju, S. Ghosh, S. Roy and A. Sen(De), *Distribution of entanglement with variable range interactions*, Phys. Lett. A **418**, 127703 (2021).

9. A. Patra, S. Mal, and A. Sen(De), *Efficient nonlinear witnessing of non-absolutely separable states with lossy detectors*, Phys. Rev. A **104**, 032427 (2021).

10. S. Ghosh, T. Chanda, S. Mal and A. Sen(De), *Fast charging of quantum battery assisted by noise*, Phys. Rev. A **104**, 032207 (2021).

11. 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*, Phys. Rev. A **104**, 042208 (2021).

12. K. Sen, C. Srivastava, S. Mal, A. Sen(De), and U. Sen, *Noisy quantum input loophole in measurement-device-independent entanglement witnesses*, Phys. Rev. A **104**, 012429 (2021).

13. S. Halder, S. Mal, and A. Sen(De), *Characterization and Generation of Absolutely Separable States*, Phys. Rev. A **103**, 052431 (2021).

14. S. Roy, S. Mal and A. Sen(De), *Restrictions on sharability of classical correlations for random multipartite quantum states*, Phys. Rev. A **103**, 052401 (2021).

Preprints:

1. T. Konar, LG.C. Lakkaraju, and A. Sen(De), *Quantum Battery with Non-Hermitian Charging*, arXiv:2203.09497.

2. A. Patra, R. Gupta, S. Roy and A. Sen(De), *Significance of fidelity deviation in continuous variable teleportation*, arXiv:2203.06684.

3. P. Haldar, R. Banerjee, S. Mal and A. Sen(De), *Limits of network nonlocality probed by time-like separated observers*, arXiv:2203.05353.

4. R. Gupta, A. Maity, S. Mal and A. Sen(De), *Statistics of Entanglement Transformation with Hierarchies among Catalysts*, arXiv:2202.01540.

5. T. K. Konar, S. Ghosh, A.K. Pal, and A. Sen(De), *Beyond Qubits: Building Quantum Refrigerators in Higher Dimensions*, arXiv:2112.13765.

6. K. Das Agarwal, LG.C. Lakkaraju, and A. Sen(De), *Predicting Critical Phases from Entanglement Dynamics in XXZ Alternating Chain*, arXiv:2112.12099.

7. P. Haldar, R. Banerjee, S. Ghosh, A.K. Pal, and A. Sen(De), *Circulating Genuine Multiparty Entanglement in Quantum Network*, arXiv:2112.10122.

8. A. Patra, S. Mal, and A. Sen(De), *Coherence measure of ensembles with nonlocality without entanglement*, arXiv:2112.04430.

9. R. Gupta, S. Roy, T. Das, and A. Sen(De), *Quantum illumination with a light absorbing target*, arXiv:2111.01069.

10. T. K. Konar, L.G.C.Lakkaraju S. Ghosh, and A. Sen(De), *Quantum Battery with Ultracold Atoms: Bosons vs. Fermions*, arXiv:2109.06816.

11. R. Gupta, S. Roy, T. Das, and A. Sen(De), *Quantum illumination with noisy probes: Conditional advantages of non-Gaussianity*, arXiv:2107.02774.

Conference/Workshops Attended:

1. National Quantum Science and Technology Symposium, IIIT Hyderabad, July, 2021.

2. Qiskit India Week of Quantum, August, 2021.

3. National Conference on Quantum Condensed Matter, December, 2021.

4. SSB prize talk series at IISERTVM, January, 2022.

5. International Conference on Quantum Information and Foundation, 14-24 February, 2022.

Invited Lectures/Seminars:

1. *Recent trends in quantum communication*, National Quantum Science and Technology Symposium, IIIT Hyderabad, July, 2021.

2. *Journey in Quantum - An Academia Perspective* and participated in panel discussion on equal representation of women in quantum, Qiskit India Week of Quantum, August, 2021.

3. *Quantum thermal machines*, National Conference on Quantum Condensed Matter, December 2021.

4. *Recent developments in Quantum Technologies*, SSB prize talk series at IISERTVM, Jan 2022.

5. *Quantum thermal machines*, International Conference on Quantum Information and Foundation, 14-24 Feb 2022.

Academic recognition/Awards:

1. Selected as a Fellow of Indian Academy of Sceince.

Other Activities:

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

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

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

4. Serving as referees in national and international journals.

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

AseshKrishna Datta

Research Summary:

During the academic year 2021-2022, 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, phenomenology of Electroweak Phase Transitions (EWPT) in the early Universe and hence that of resulting Gravitational Waves (GWs) and Electroweak Baryogenesis (EWBG) that can explain the observed baryon asymmetry in the Universe.

In a work that got published in *JHEP* in April, 2021, I, along with my graduate student and a postdoctoral fellow from our Institute, demonstrated in much detail how, in contrary to the common notion, a relatively light ($\sim$ a few tens of GeV) and a highly bino-like neutralino dark matter still remains viable in a scenario like the Z_3-symmetric Next-to-Minimal SUSY Standard Model (Z_3-NMSSM).

In a recently circulated work (which subsequently got accepted in *JHEP*) with my graduate student and a faculty member from a University in India, we explored how such a light neutralino, which is the Lightest SUSY Particle (LSP), opens up the possibility of existence of other light states in the form of singlet-like scalars of the Z_3-NMSSM that escape searches at the LHC. This is rather intriguing in view of the fact that such light scalars could potentially trigger a first order EWPT in the early Universe thus giving rise to GWs and leading to EWBG. Our work demonstrates in detail the collider-cosmology connection of such a possibility and reflects on the region of the parameter space over which such situations arise. Further, it sheds light on the prospects of the upcoming runs of the LHC and the future GW experiments in unraveling such an interplay. That the Minimal SUSY extension of the Standard Model (MSSM) has recently been shown to be inadequate for explaining EWBG adds a special relevance to our findings.

In an ongoing work with my graduate student and others from another Indian Institute, we have been looking for a possibly enhanced sensitivity in the searches for the lighter electroweakinos at the LHC when those arise in the decays of the top squarks within the framework of Z_3-NMSSM. Both conventional cut-based approach and machine learning techniques using ROOT-TMVA are being employed for a comparative study. Given that relatively light top squarks and electroweakinos constitute scenarios that are highly theoretically motivated but, at the same time, receiving stringent lower bounds on their masses from the LHC experiments, exploiting their interplay and collective contributions seems to be an interesting option.

In another recently circulated work (in collaboration with a faculty member from an Indian institute and two postdoctoral fellows from two different institutes) we explored the nontrivial dependencies of the bottom and the tau Yukawa couplings on the parameters of a SUSY scenario like the Non-Holomorphic SUSY Standard Model (NHSSM) and their implications for the LHC. These are over and above their well-known dependencies on a parameter like $\tan\beta$.

In a different collaboration (that is continuing for much too long), with faculty members from institutes abroad, I have been studying the LHC phenomenology of a rather fat Z'-like resonance in the so-called $B-L$ SUSY Standard Model (BLSSM). It was nearing completion when I last reported but met with unfortunate, recurrent stoppages (partly, from my side). I am trying hard to see the work through.

In the same framework, with an erstwhile (new) graduate student at HRI, I started pursuing the novel phenomenology of relatively light electroweakinos that could have evaded the latest LHC searches. Unfortunately, after more than six months of work, the student left HRI and I could not, on my own, take forward the work to its logical conclusion.

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,* JHEP **04**, 122, (2021).

Preprints:

1. AseshKrishna Datta, with Arindam Chatterjee and Subhojit Roy, *Electroweak Phase Transition in the Z_3-invariant NMSSM: Implications of LHC and Dark matter Searches and Prospects of Detecting the Gravitational Waves* arXiv:2202.12476 [hep-ph] *(accepted for publication in JHEP).*

2. AseshKrishna Datta, with Utpal Chattopadhyay, Samadrita Mukherjee and Abhaya Kumar Swain, *Associated production of heavy Higgs bosons with a $b\bar{b}$ pair in the Nonholomorphic MSSM and LHC searches,* arXiv:2201.00621 [hep-ph].

Conference/Workshops Attended:

1. *The XVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021),* China, August, 2021 (partially attended, online)

Visits to other Institutes:

1. School of Physical Sciences, IACS, Kolkata, India, Feb.–Mar., 2022.

Other Activities:

1. Supervising one graduate students towards his Ph.D. theses.

2. Was supervising a new graduate student (for more than six months) who subsequently left HRI.

3. Serving doctoral committees of several graduate students.

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

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

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 and address related issues. In addition, I have become part of the REDTOP Collaboration, and have done work related to that, and contributed to the Snowmass effort, as reflected below

Publications:

1. W. Abdallah, R. Gandhi and S. Roy, "A simple solution to the LSND, MiniBooNE and muon $g-2$ anomalies," PoS **EPS-HEP2021**, 193 (2022) doi:10.22323/1.398.0193

2. W. Abdallah, R. Gandhi and S. Roy, Phys. Rev. D **104**, no.5, 055028 (2021) doi:10.1103/PhysRevD.104.055028 [arXiv:2010.06159 [hep-ph]].

Preprints:

1. W. Abdallah, R. Gandhi and S. Roy, "Requirements on common solutions to the LSND and MiniBooNE excesses: a post-MicroBooNE study," [arXiv:2202.09373 [hep-ph]].

2. J. Elam *et al.* [REDTOP], "The REDTOP experiment: Rare η/η' Decays To Probe New Physics," [arXiv:2203.07651 [hep-ex]].

3. M. A. Acero, C. A. Argüelles, M. Hostert, D. Kalra, G. Karagiorgi, K. J. Kelly, B. Littlejohn, P. Machado, W. Pettus and M. Toups, *et al.* "White Paper on Light Sterile Neutrino Searches and Related Phenomenology," [arXiv:2203.07323 [hep-ex]].

4. A. A. Abud *et al.* [DUNE], "Snowmass Neutrino Frontier: DUNE Physics Summary," [arXiv:2203.06100 [hep-ex]].

Other Activities:

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

Tathagata Ghosh

Research Summary:

My main research focus in the past year has been on non-standard neutrino interactions and dark matter. A brief description of the research carried on these topics are given below.

Neutrinos are the Standard Model (SM) particles which we understand the least, often due to how weakly they interact with the other SM particles. Beyond this, very little is known about interactions among the neutrinos, i.e., their self-interactions. The SM predicts neutrino self-interactions at a level beyond any current experimental capabilities, leaving open the possibility for beyond-the-SM interactions across many energy scales. In **arXiv:2203.01955 [hep-ph]**, we review the current knowledge of neutrino self-interactions from a vast array of probes, from cosmology, to astrophysics, to the laboratory. We also discuss theoretical motivations for such self-interactions, including neutrino masses and possible connections to dark matter. Looking forward, we discuss the capabilities of searches in the next generation and beyond, highlighting the possibility of future discovery of this beyond-the-SM physics.

In **JHEP 03 (2022) 068 [arXiv:2109.04490 [hep-ph]** we work out the non-standard neutrino self interactions within a specific ultraviolet (UV)-complete model and discuss its detailed phenomenological signatures. To be more precise, here, we study the non-standard interactions of neutrinos with light leptonic scalars (ϕ) in a global $(B-L)$-conserved model. The model utilizes Type-II seesaw motivated neutrino interactions with an $SU(2)_L$-triplet scalar, along with an additional singlet in the scalar sector. This UV-completion leads to an enriched spectrum and consequently new observable signatures. We examine the low-energy lepton flavor violation constraints, as well as the perturbativity and unitarity constraints on the model parameters. Then we lay out a search strategy for the unique signature of the model resulting from the leptonic scalars at the hadron colliders via the processes $H^{\pm\pm} \to W^{\pm}W^{\pm}\phi$ and $H^{\pm} \to W^{\pm}\phi$ for both small and large leptonic Yukawa coupling cases. We find that via these associated production processes at the HL-LHC, the prospects of doubly-charged scalar $H^{\pm\pm}$ can reach up to 800 (500) GeV and 1.1 (0.8) TeV at the 2σ (5σ) significance for small and large Yukawa couplings, respectively. A future 100 TeV hadron collider will further increase the mass reaches up to 3.8 (2.6) TeV and 4 (2.7) TeV, at the 2σ (5σ) significance, respectively. We also demonstrate that the mass of ϕ can be determined at about 10% accuracy at the LHC for the large Yukawa coupling case even though it escapes as missing energy from the detectors.

In **arXiv:2203.06705 [hep-ph]**, we consider the model of heavy neutral leptons (HNLs) as an example to explore the potential of new physics searches at the Electron-Ion Collider (EIC). We propose two broad categories of search strategies depending on the HNL lifetime: direct searches for the prompt decay of HNLs with a short lifetime and displaced vertex searches for long-lived ones. After identifying the most promising signals and the corresponding backgrounds, we perform a detailed simulation to estimate the sensitivity of the EIC to HNLs, accounting for detector thresholds, resolutions, and geometric acceptance. We derive projections for the EIC reach to the HNL squared mixing angle as a function of the HNL mass under the electron fla-

vor mixing dominance hypothesis. Our findings indicate that the EIC can provide comparable sensitivity to the existing constraints for the prompt searches, while the displaced vertex searches can cover substantial new ground for HNLs in the 1-10 GeV mass range. Our proposed strategies are generally applicable to other new physics scenarios as well and motivate additional phenomenological exploration and dedicated future searches at the EIC.

In a different direction, in **arXiv:2203.08107 [hep-ph]**, We review simplified models in which a singlet Majorana dark matter candidate couples to Standard Model (SM) fermions through interactions mediated by scalar fermion partners. We summarize the two primary production mechanisms in these scenarios: dark matter annihilation mediated by first or second generation scalar fermion partners with significant left-right chiral mixing and co-annihilation with scalar fermion partners nearly degenerate in mass with the dark matter. We then highlight the most interesting phenomenological aspects of charged mediator models relevant for current and future searches for new physics. We describe precision measurements of SM fermion dipole moments, including models with scalar muon partners that can account for $g_\mu - 2$. We discuss new search strategies for charged mediators at the LHC and the projected sensitivity of future lepton colliders. We summarize constraints from direct detection and demonstrate how next generation experiments might probe QCD-charged mediators at mass scales beyond the sensitivity of the LHC. We also review the prospects for indirect detection of models with scalar lepton partners, focusing on the sensitivity of gamma-ray searches to internal bremsstrahlung emission.

Publications:

1. **Leptonic scalars and collider signatures in a UV-complete model**
   P.S.B. Dev, B. Dutta, T. Ghosh, T. Han, H. Qin, Y. Zhang;
   JHEP 03 (2022) 068 [arXiv: 2109.04490 [hep-ph]

Preprints:

1. **Neutrino Self-Interactions: A White Paper**
   J. Berryman *et. al.*
   arXiv: 2203.01955 [hep-ph]

2. **Heavy Neutral Lepton Searches at the Electron-Ion Collider: A Snowmass Whitepaper**
   B. Batell, T. Ghosh, K. Xie
   arXiv: 2203.06705 [hep-ph]

3. **Simplified dark matter models with charged mediators**
   T. Ghosh, C. Kelso, J. Kumar, P. Sandick, P. Stengel
   arXiv: 2203.08107 [hep-ph]

Conference/Workshops Attended:

1. **Anomalies 2021** (10-12 November,2021)
   An online conference organized by the IIT, Hyderabad
   Co-chaired a plenary session

2. **Phenomenology 2021 Symposium** (24-26 May, 2021)
   An online conference organized by the University of Pittsburgh, USA
   Chaired a parallel session

Invited Lectures/Seminars:

1. **Phenomenology of Lepton Number Charged Scalars**
   Invited seminar talk in the online *Majorana-Raychaudhuri international seminar series* (A joint initiative by various Italian and Indian research institutes)

Dileep P. Jatkar

Research Summary: (Technical)

We use massive spinor helicity formalism to study scattering amplitudes in $\mathcal{N} = 2^*$ super-Yang-Mills theory in four dimensions. We compute the amplitudes at an arbitrary point in the Coulomb branch of this theory. We compute amplitudes using projection from $mathcal N = 4$ theory and write three point amplitudes in a convenient form using special kinematics. We then compute four point amplitudes by carrying out massive BCFW shifts of the amplitudes. We find some of the shifted amplitudes have a pole at $z = \infty$. Taking the residue at $z = \infty$ into account ensures little group covariance of the final result.

Research Summary: (Non-Technical)

In the last year I have been looking at the problem of generalising spinor helicity formalism to massive field theories. I am also looking at aspects of 2D CFT at fraction levels of the Kač-Moody algebra.

Publications:

1. M. Abhishek, S. Hegde, D. P. Jatkar and A. P. Saha, "Scattering Amplitudes and BCFW in $\mathcal{N} = 2^*$ Theory," [arXiv:2202.12204 [hep-th]] SciPost Phys. 13, 008 (2022).

Conference/Workshops Attended:

1. *Strings 2021*, Online
2. *Indian Strings Meeting 2021*, Online..

Anshuman Maharana

Research Summary:

My Research in the last year has been focused in two directions, string phenomenology and cosmology. We highlight some of the interesting results.

In string phenomenology: We have pointed out that if the sector associated with the Standard Model degrees of freedom entered an open string Hagedorn phase in the early universe while the dark radiation sector was not part of this plasma, then this can lead to low values of the observable $\Delta N_{\rm eff}$ (number of additional neutrino-like species) from the dark radiation. For explicit analysis, we focused on warped string compactifications with the Standard Model degrees of freedom at the bottom of a warped throat. If the Hubble scale during inflation is above the warped string scale associated with the throat, then the Standard Model sector will enter the Hagedorn phase. In this scenario, bulk axions are no longer dangerous from the point of view of dark radiation. While the work focused on warped compactifications, the basic idea can be relevant to any scenario where the early universe entered a Hagedorn phase.

In cosmology: We presented a scenario for fast growth of cosmological perturbations; $\delta(t) \sim a(t)^s$, a(t) being the scale factor, with $s > 10$. The basic ingredients of the scenario are an early matter dominated era and the dark fermion which experiences a scalar mediated force during the epoch. Both of these arise in string/supergravity models. The fast growth occurs for sub-horizon density perturbations of the dark fermion. The fast growth has a rich set of phenomenological implications. We outline implications for the formation of primordial black holes and the production of gravitational waves. Primordial black holes in the sub-lunar mass range (which are ideal dark matter candidates) can be produced. Gravitational waves can be produced in a wide range of frequencies due to second order scalar perturbations and due to evaporation and merger of primordial black holes

Publications:

1. A. R. Frey, R. Mahanta and A. Maharana, *Dark radiation and the Hagedorn phase*, Phys. Rev. D **105** (2022) no.6, 066007
2. S. Das, A. Maharana, V. Poulin and R. K. Sharma, *Nonthermal neutrino-like hot dark matter in light of the S8 tension*, Phys. Rev. D **105** (2022) no.10, 103503
3. I. Broeckel, M. Cicoli, A. Maharana, K. Singh and K. Sinha, *Moduli stabilisation and the statistics of axion physics in the landscape*, JHEP **08** (2021), 059
4. Koushik Dutta and Anshuman Maharana, *Models of accelerating universe in supergravity and string theory* , Invited Review for Eur. Phys. J. Spec. Top. (2021).

Preprints:

1. I. Broeckel, M. Cicoli, A. Maharana, K. Singh and K. Sinha, *On the Search for Low W_0*, arXiv:2108.04266 [hep-th], (accepted for publication in Fortschritte der Physik/Progress of Physics)

2. S. Das, A. Maharana and F. Muia, *A Faster Growth of Perturbations in an Early Matter Dominated Epoch: Primordial Black Holes and Gravitational Waves*, arXiv:2112.11486 [astro-ph.CO]

3. A. Banerjee, S. Das, A. Maharana and R. Kumar Sharma, *Signatures of Light Massive Relics on nonlinear structure formation*, arXiv:2202.09840 [astro-ph.CO]

Conference/Workshops Attended

1. Indian Strings Meeting (2021), IIT Roorkee (December 2021)

2. Trends in String Theory and Related Topics (October 2021)

Invited Lectures/Seminars:

1. Indian Strings Meeting (2021), IIT Roorkee (December 2021)

Other Activities:

1. Member HBNI Board of Studies for Physical Sciences

2. Chief Vigilance Officer, HRI

3. Chief Patent Officer, HRI

4. Co-organisation of the conference: Trends in String Theory and Related Topics (October 2021)

Pinaki Majumdar

Research Summary:

I continue to work on non equilibrium correlated systems, and independently the effect of geometric frustration. The non equilibrium work uses in part the Langevin method, to probe the steady state of a driven system in a thermal environment. The other approach is to study purely quantum systems - decoupled from any environment - responding to an energy pulse, as in pump-probe experiments. We have completed a study of the dynamics in a charge ordered electron-phonon system using this framework. It can be generalised to study the response of any kind of order parameter in a correlated system, including the effect of competing orders. The frustration work focuses on the Kagome lattice, attempting to study how Hubbard physics modifies results that are well known in the Heisenberg limit.

Publications:

1. Sauri Bhattacharyya and Pinaki Majumdar, *Dynamics of magnetic collective modes in the square and triangular lattice Mott insulators at finite temperature,* Phys. Rev. B 104, 235124 (2021).

2. Arijit Dutta and Pinaki Majumdar, *Nonequilibrium thermal state of a voltage-biased Mott insulator*, Phys. Rev. B 105, 075149 (2022).

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*, Phys. Rev. B 105, 054501 (2022).

Preprints:

1. *Nonequilibrium dynamics of suppression, revival, and loss of charge order in a laser pumped electron-phonon system*, Sankha Subhra Bakshi, Debraj Bose, Arijit Dutta and Pinaki Majumdar, arXiv:2205.14710v1

Other Activities:

1. Taught Statistical Mechanics.

T P Pareek

Research Summary:

I have been making progress to study topological behaviours of matter using density matrices. Specifically a density matric scattering theory and using bruce distance in the space of density matrics we are able to relate various manifold os topological aspect of matter. This work is under progress.

Preprints:

1. 1 Bruce distanec and topological aspec of density matrix scattering theory and its relation to topological state of matter

Other Activities:

1. I have been member of various commities and have participated in the entrance exam and interview process of the institute.

Arun Kumar Pati

Research Summary: (Technical)

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.

Greenberger-Horne-Zeilinger States: Their Identifications and Robust Violations : The N-qubit Greenberger-Horne-Zeilinger (GHZ) states are the maximally entangled states of N qubits, which have had many important applications in quantum information processing, such as quantum key distribution and quantum secret sharing. Thus how to distinguish the GHZ states from other quantum states becomes a significant problem. In this work, by presenting a family of the generalized Clauser-Horne-Shimony-Holt (CHSH) inequality, we show that the N-qubit GHZ states can be indeed identified by the maximal violations of the generalized CHSH inequality under some specific measurement settings. The generalized CHSH inequality is simple and contains only four correlation functions for any N-qubit system, thus has the merit of facilitating experimental verification. Furthermore, we present a quantum phenomenon of robust violations of the generalized CHSH inequality, in which the maximal violation of Bell's inequality can be robust under some specific noises adding to the N-qubit GHZ states

Remote state preparation by multiple observers: We consider a scenario of remote state preparation of qubits where a single copy of an entangled state is shared between Alice and several Bobs who sequentially perform unsharp single-particle measurements. We show that a substantial number of Bobs can optimally and reliably prepare the qubit in Alice's lab exceeding the classical realm. There can be at most 16 Bobs in a sequence when the state is chosen from the equatorial circle of the Bloch sphere. In general, depending upon the choice of a circle from the Bloch sphere, the optimum number of Bobs ranges from 12 for the worst choice, to become remarkably very large corresponding to circles in the polar regions, in case of an initially shared maximally entangled state. We further show that the bound on the number of observers successful in implementing remote state preparation is higher for maximally entangled initial states than that for non-maximally entangled initial states

Quantum speed limits for information and coherence: The quantum speed limit captures the maximal evolution speed of the quantum system under arbitrary dynamical evolution. In this work, we derive speed limit bounds for informational measures, namely the von Neumann entropy, information, and coherence for arbitrary quantum dynamics. These speed limits ascertain the fundamental limitations on the evolution time required by the quantum systems for the changes in their informational measures. In the case of coherence, we have obtained the speed limit bounds on the change for both basis-dependent and basis-independent measures. As an application of our work, we use the speed limit on the information to obtain minimum time required to erase the information of given quantum state.

Publications:

1. Sk Sazim, M. Sedlak, K. Singh, and A. K. Pati, Classical communication with indefinite causal order for N completely depolarizing channel, Phys. Rev. A **103**, 062610 (2021).

2. M. Vempati, N. Ganguly, I. Chakrabarty, and A. K. Pati, Witnessing negative conditional entropy, Phys. Rev. A **104**, 012417 (2021).

3. P. Chowdhury, A. K. Pati, J. L. Chen, Wave and particle properties can be spatially separated in a quantum entity, Photonics Research **9**, 1379 (2021).

4. X. Y. Fan, J. Zhou, H. X. Meng, C. Wu, A. K. Pati, J. L. Chenai, Greenberger-Horne-Zeilinger States: Their Identifications and Robust Violations, Modern Physics Letters A**36**, 2150223 (2021).

Preprints:

1. B. Mohan, S. Das, A. K. Pati, Quantum speed limits for information and coherence, arXiv:2110.13193.

2. S. Datta, S. Mal, A. K. Pati, A. S. Majumdar, Remote state preparation by multiple observers using a single copy of a two-qubit entangled state, arXiv:2109.03682.

3. Sahil, Sohail, S. Modak, S. Ghosh, A. K. Pati, Extraction of Product and Higher Moment Weak Values: Applications in Quantum State Reconstruction, arXiv:2107.00573.

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

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

Invited Lectures/Seminars:

1. Invited Talk at Symposium on Quantum information and Computation (QUANTUM TALKS) dated from June 29 to July 3, 2021 at IIIT, Hyderabad.

2. Invited Visionary Speaker for ASSOCHAM 2nd Annual International Conclave India Quantum Technology Conclave IQTC202, Unlocking the Potential of Quantum in India, 25th May 2021.

3. Invited Keynote talk for ATAL-faculty development program (ATAL-FDP) sponsored by AICTE, New Delhi on Quantum Computing (QC-2021) during 4-8 Oct, 2021 at ABV-Indian Institute of Information Technology and Management, (ABV-IIITM), Gwalior (MP).

4. Invited talk at the "International Conference on Quantum Information and Foundations (ICQIF-2022)" during 14-24 February, 2022 organised by the Physics & Mathematics Unit, Indian Statistical Institute, Kolkata.

Academic Highlights:

- Ranked as Top 2% scientist in the World in the area of Quantum Information by Stanford University in 2021.
- Wave and Particle can be separated in a quantum entity was highlighted in the Cover page of PHOTONIC RESEARCH Journal.
- Scientific Social Responsibility: To spread and educate Quantum Computing and Quantum Technology among Female students, I have been invited to join as an Advisory Board of She Quantum organization.
- An Interview for general public on Quantum Computing: Link at https://www.youtube.com/watch?v=oe4nY32BJQ4

Other Activities:

1. Six students are working for PhD in the area of Quantum Information.
2. Two students have joined as Research Assistant under QUEST project, DST, India.
3. One Research Associate has joined under QUEST project initiated by DST, India.

Santosh Kumar Rai

Research Summary:

My research over the last year has focused on aspects of non-observation of any distinct and clear signatures of models beyond the Standard Model (SM) of particle physics. The common and hopeful perception in the particle physics community was that the Large Hadron Collider (LHC) would be able to observe new phenomena very early and give us hints of BSM physics. Although the experiment has proved to be a huge success, quickly establishing the SM by observing the Higgs boson as early as in 2012, it has been unable to detect any signals which may be inconsistent with SM predictions or hint towards any of the new physics proposals one would have expected to see. We proposed and studied new BSM models which are consistent with SM predictions and still provide solutions to the unresolved problems in SM but can remain effectively hidden in experimental searches. The proposed models encompass additional discrete symmetries and/or extensions of the SM symmetry group structure. We studied the phenomenology of the new proposed models and propose ways to observe its feeble signatures at LHC and future linear colliders.

In a couple of works we studied a 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 found that the DM is compatible with the current relic density data as well as satisfies all direct and indirect dark matter search constraints. We then show a detailed analysis at LHC and ILC through multi-lepton and multi-jet signals along with missing transverse energy in the final state that highlights how the model which could very easily evade observation at LHC could have a more robust and promising signature at ILC. The analysis was done using both cut-based and multivariate methods to compare the role of *machine learning* techniques in improving signal strengths.

In another set of work we consider a simple abelian extension to the SM. We consider a neutrinophilic $U(1)$ extension 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'. The new symmetry has minimal interaction with the SM sector. We study 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 show 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 show that a direct Z' signal is observable through multilepton final states provided there is a possibilty of significant Z-Z' mixing invoked in the gauge structure of the model, which could be crucial in discovering such a neutrinophilic gauge boson lying in a mass range of 200–500 GeV. We further establish that in the absence of any Z-Z' mixing which allows it to be light and below the SM gauge boson masses, the Z' can

be completely hidden in direct interactions and we show how a sub-100 GeV Z' can emerge through Higgs mediated channels at the LHC. . Interestingly such a light Z' is very difficult to observe in the standard production modes. We show that it is possible to observe such a gauge boson via scalar mediators that are responsible for the symmetry breaking mechanism of the model. The model also provides a dark matter candidate whose compatibility with the observed relic density is established due to the light Z'. We also comment on other interesting possibilities such a light Z' may present for other observables.

In a separate work we have looked at dark sector possibilities in an extended left-right symmetric model and point out their role in signals for a doubly-charged Higgs at experiments. We find that although such a model is compatible with relic density observations and be consistent with direct and indirect search of dark matter, hints of the model can still be quite elusive at experiments such as the LHC. We comment on the most likely avenues of observation of such a model.

Publications:

1. Indrani Chakraborty, Dilip Kumar Ghosh, Nivedita Ghosh, Santosh Kumar Rai, *Dark Matter and Collider Searches in S_3-Symmetric 2HDM with Vector Like Lepton*, European Physics Journal **C 81 7**, 679, (2021).

2. Waleed Abdallah, Anjan Kumar Barik, Santosh Kumar Rai, Tousik Samui, *Search for a light Z' at LHC in a neutrinophilic $U(1)$ model.* Physical Review **D 104 9**, 095031, (2021).

Preprints:

1. Waleed Abdallah, Anjan Kumar Barik, Santosh Kumar Rai, Tousik Samui, *An emergent Z' from the Higgs shadow*, [arXiv:2109.07980 [hep-ph]].

2. Indrani Chakraborty, Dilip Kumar Ghosh, Nivedita Ghosh, Santosh Kumar Rai, *Signals for vector-like leptons in a S_3-Symmetric 2HDM at ILC*, [arXiv:2201.11646 [hep-ph]].

3. Shyamashish Dey, Purusottam Ghosh, Santosh Kumar Rai, *Confronting dark fermion with a doubly charged Higgs in the left-right symmetric model*, [arXiv:2202.11638 [hep-ph]].

Conference/Workshops Attended:

1. *Anomalies 2021 (online)*, November 2021, IIT Hyderabad, India.

2. *Hunting SUSY @ HL-LHC (online)*, November 2021, International Centre for Theoretical Sciences (ICTS), India.

3. *ILC Workshop on Potential Experiments (ILCX2021) (online)*, October 2021, Tokyo, Japan.

4. *The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021) (online)*, August 2021, Shanghai, China.

Invited Lectures/Seminars:

1. "What's in a hidden U(1)?"; *Anomalies 2021*, November 2021, IIT Hyderabad, India. (Plenary Session - online)
2. "What's in a hidden U(1)?"; Invited seminar (online), January 2022, Ravenshaw University, Cuttack, Odisha, India.

Other Activities:

1. Taught M.Sc. course (shared) titled *Particle Physics*, Feb-May, 2022.
2. Taught M.Sc. course titled *Mathematical Methods-II*, August 2021-January, 2022.
3. Supervising Ph.d. of Mr. Anjan Kr. Barik and Mr. Shyamashish Dey.
4. Stand-in Supervisor of Ph.d. students Ms. Atri Dey and Mr. Deepak Raikwal.
5. External Referee, Ph.d. Thesis by Mr. Manas Kumar Mohapatra, IIT Hyderabad.
6. External member in the Doctoral Committee of Mr. Rameswar Sahu, Institute of Physics (IOP), Bhubaneswar.
7. Member of the Doctoral Committee for around 10 students at HRI.
8. Referee for journals Physical Review D, EPJC.
9. Co-ordinator, Regional Centre for Accelerator-based Particle Physics (RECAPP).
10. Member, HPC Cluster, Computer Committee, Faculty Appointment Committee, Endowment Committee.
11. Convener, Security Committee.

Debraj Rakshit

Research Summary:

I have been working on investigating quantum features in quantum many-body systems, which include the study of entanglement, topology, dynamical quantum phase transition, quantum Zeno effect. Apart from that I am working on various aspects related to quantum technology, e.g. quantum sensing, designing quantum simulators via ultracold atoms. Moreover, I am also developing/incorporating newly emerging numerical techniques, such as solving quantum many-body systems via artificial neural networks.

Publications:

1. J. Fraxanet, U. Bhattacharya, T. Grass, D. Rakshit, M. Lewenstein, and A. Dauphin, *Topological properties of the long-range Kitaev chain with Aubry-André-Harper modulation*, Phys. Rev. Research **3**, 013148 (2021).

2. R Modak and D Rakshit, *Many-body dynamical phase transition in quasi-periodic potential*, Phys. Rev. B **103**, 224310 (2021).

Preprints:

1. R. Modak, D. Rakshit and U. Sen, *Finite-size scalings in measurement-induced dynamical phase transition*, arXiv:2107.14647.

Conference/Workshops Attended:

1. *National Quantum Science and Tech Symposium*, IIT Hyderabad, July 2021

Invited Lectures/Seminars:

1. *Dynamical phase transitions in quantum many-body systems*, NQSTS - IIIT Hyderabad, July 2021.

2. *Ultracold quantum simulators*, IPA Colloquium - BHU Varanasi, March 2022

Other Activities:

1. Taught an advanced course on Ultracold Atoms during the Jan-May Semester, 2022.

2. Served as Referee in physics journals.

Prasenjit Sen

Research Summary:

We continued with our research on materials for alternative, renewable energy; and understanding and design of magnetic materials. We explored hydrogen evolution reaction (HER) in alkali media in collaboration with the experimental group of Dr. T. N. Narayanan at TIFR-Hyderabad. An explanation for the decrease in HER rate with increasing concentration of alkaline electrolyte is offered. Increasing alkali concentration increases the fraction of tetrahedrally coordinated water. Tetrahedrally coordinated water has larger barrier to dissociation, making the process slower, and thus decreases HER rate.

We designed a battery of Machine Learning models which can screen a set of materials for stable magnets with large magnetic moment and magnetic anisotropy energy. We tested this on a data set of two dimensional materials. Machine Learning predictions were tested with density functional calculations with good success.

Publications:

1. *Machine learning assisted hierarchical filtering: A strategy for designing magnets with large moment and anisotropy energy*, A. Dutta and P. Sen, J Mater. Chem. C **10**, 3404 (2022).

2. *Exploring a low temperature glassy state, Exchange Bias effect, and high magnetic anisotropy in Co_2C nanoparticles*, N. Roy, Md. A. Ali, A. Sen, D. T. Adroja, P. Sen and S. Banerjee, J Phys. Cond. Mat. **33**, 375804 (2021).

3. *Extending the Cyclability of Alkaline Zinc-Air Batteries: Synergistic Roles of Li^+ and K^+ Ions in Electrodics*, P. Thakur, K. Alam, P. Sen and T. N. Narayanan, ACS Appl. Mater. Interf. **13**, 33112 (2021).

4. *Probing active sites on $MnPSe_3$ and $FePSe_3$ tri-chalcogenides as a design strategy for better hydrogen evolution reaction catalysts*, T. Das, K. Alam, S. Chakraborty and P. Sen, Int. J Hydrogen Energy **46**, 37928 (2021).

5. *Finding the catalytically active sites on the layered tri-chalcogenide compounds $CoPS_3$ and $NiPS_3$ for hydrogen evolution reaction*, K. Alam, T. Das, S. Chakraborty and P. Sen, Phys. Chem. Chem. Phys. **23**, 23967 (2021).

Preprints:

1. *Ionization Energies and Ground State Structures of Neutral La_n ($n = 2 - 14$) Clusters: A Combined Experimental and Theoretical Investigation*, S. Bhattacharyya, D. Bandyopadhyay, S. Mukund, P. Sen and S. Nakhate (Accepted in J Phys. Chem. A).

2. *Complementary Effects of External Strain, Functionalization and Vacancy Defects Towards Enhanced HER Activity in Transition Metal Phosphorous based Tri-chalcogenide Monolayers*, T. Das, S. Chakraborty and P. Sen (submitted).

3. *Role of Water Structure in Alkaline Water Electrolysis*, A. Guha, M. Sahoo, K. Alam, D. K. Rao, P. Sen and T. N. Narayanan (submitted).

Conference/Workshops Attended:

1. International Online Conference on Nano Materials (ICN 2021), April 2021, Mahatma Gandhi University, Kottayam, Kerala, India (online).

2. International Conference on Materials Genome organized by the Asian Consortium for Computational Materials Science, March 24-25, 2022, SRM University, Andhra Pradesh, India (online).

Invited Lectures/Seminars:

1. "Machine Learning assisted hierarchical screening: A strategy for designing novel magnetic materials" ACCMS International Conference on Materials Genome, March 24-25, 2022, SRM University, Andhra Pradesh, India (online mode).

2. "Computational Design and Screening of Materials for Energy Applications", National-lecture organized under *Azadi ka Amrut Mahotsav* on 75 years of India's independence, June 2021, at the Indian Institute of Nano Science and Technology, (INST), Mohali, India.

3. "Screening layered ternary transition metal tri-chalcogenides as electrocatalysts", International Online Conference on Nano Materials (ICN 2021), April 2021, Mahatma Gandhi University, Kottayam, Kerala, India.

Other Activities:

1. Editorial Board Member of *Physica Scripta*.

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

3. Dean Academic till March 2022.

4. Teaching courses: Condensed Matter Physics 1.

Ujjwal Sen

Research Summary:

In the last academic year, I have been working on different aspects of quantum information and computation devices and its efficiencies in the presence of noise and disorder. In particular, we have shown that it is possible to isolate noise and amplify signal using the concept of the quantum Cheshire cat. In another work, we have analyzed the effect on the efficiency of the quantum phase estimation algorithm - an important element of Shor factorization - of glassy disorder in the circuit elements. We have also looked at the invariance properties of the success probability in the Grover quantum search algorithm under local noise with memory. We have also characterized the response to glassy disorder in the quantum coin on spread of a quantum walker. We have also shown that it is possible to witness entanglement by arbitrarily many independent observers by recycling a local quantum shared state. We also devised a method for closing loopholes of measurement-device-independent nonlinear entanglement witnesses. In another work, we have analyzed the spread and asymmetry of typical quantum coherence and their inhibition in response to glassy disorder.

Other works during the academic year include finding a relation between unextendible entangled bases and the phenomenon of more nonlocality with less entanglement, showing that quantum information can remain without physical body in volatile form, analyzing the inhibition of spread of typical bipartite and genuine multiparty entanglement in response to quenched disorder, proving the existence of measurement-device-independent nonlinear entanglement witnesses, analyzing finite-size scalings in a measurement-induced dynamical phase transition, characterizing Separability and entanglement in superpositions of quantum states, defining quantum coherence with incomplete set of pointers and analyzing the corresponding wave-particle duality, finding a convolution algebra of quantum superoperators and using it to understand nonseparability witnesses for quantum operations, uncovering a correlation between different resource-generating capacities - viz. entanglement and quantum coherence - of quantum gates, providing a steering inequality for pairs of particle-number-superselection-rule restricted quantum states, recycled entanglement detection by arbitrarily many sequential and independent pairs of observers, analyzing local PT-symmetric evolutions on separable states and showing that it violates the no-signaling principle, and assessing shared purity and concurrence of a mixture of ground and low-lying excited states as indicators of quantum phase transitions.

Publications:

1. George Biswas, Anindya Biswas, Ujjwal Sen, *Inhibition of spread of typical bipartite and genuine multiparty entanglement in response to quenched disorder*, New J. Phys. **23**, 113042 (2021).

2. Saronath Halder, Ujjwal Sen, *Unextendible entangled bases and more nonlocality with less entanglement*, Phys. Rev. A (Letter) **105**, L030401 (2022).

3. Ahana Ghoshal, Ujjwal Sen, *Heat current and entropy production rate in local non-Markovian quantum dynamics of global Markovian evolution*, Phys. Rev. A **105**, 022424 (2022).

4. Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, *Noisy quantum input loophole in measurement-device-independent entanglement witnesses*, Phys. Rev. A **104**, 012429 (2021).

5. Ahana Ghoshal, Sreetama Das, Amit Kumar Pal, Aditi Sen De, Ujjwal Sen, *Three qubits in less than three baths: Beyond two-body system-bath interactions in quantum refrigerators*, Phys. Rev. A **104**, 042208 (2021).

6. Arun Sehrawat, Chirag Srivastava, Ujjwal Sen, *Equilibrium and dynamical phase transitions in fully connected quantum Ising model: Approximate energy eigenstates and critical time*, Phys. Rev. B **104**, 085105 (2021).

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

8. Asmitha Mekala, Ujjwal Sen, *All entangled states are quantum coherent with locally distinguishable bases*, Phys. Rev. A (Letter) **104**, L050402 (2021).

9. Saronath Halder, Ujjwal Sen, *Local indistinguishability and incompleteness of entangled orthogonal bases: Method to generate two-element locally indistinguishable ensembles*, Annals of Physics **431**, 168550 (2021).

10. Asmita Kumari, Ujjwal Sen, *Local preservation of no-signaling in multiparty PT-symmetric evolutions*, J. Phys. A: Math. Theor. **55**, 185302 (2022).

11. 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).

12. 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).

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

14. Kornikar Sen, Ujjwal Sen, *Local passivity and entanglement in shared quantum batteries*, Phys. Rev. A (Letter) **104**, L030402 (2021).

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

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

17. Sreetama Das, Sudipto Singha Roy, Samyadeb Bhattacharya, Ujjwal Sen, *Nearly Markovian maps and entanglement-based bound on corresponding non-Markovianity*, J. Phys. A: Math. Theor. **54**, 395301 (2021).

18. Saptarshi Roy, Anindita Bera, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, , *Recycling the resource: Sequential usage of shared state in quantum teleportation with weak measurements*, Phys. Lett. A **392**, 127143 (2021).

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

20. Sunho Kim, Longsuo Li, Asutosh Kumar, Chunhe Xiong, Sreetama Das, Ujjwal Sen, Arun Kumar Pati, Junde Wu, *Protocol for unambiguous quantum state discrimination using quantum coherence*, QIC **21**, 0931 (2021).

Preprints:

1. Kornikar Sen, Chirag Srivastava, Ujjwal Sen, *Closing loopholes of measurement-device-independent nonlinear entanglement witnesses*, arXiv:2203.07192.

2. George Biswas, Santanu Sarkar, Anindya Biswas, Ujjwal Sen, *Spread and asymmetry of typical quantum coherence and their inhibition in response to glassy disorder*, arXiv:2203.03025.

3. Soham Sau, Ahana Ghoshal, Debmalya Das, Ujjwal Sen, *Isolating noise and amplifying signal with quantum Cheshire cat*, arXiv:2203.00254.

4. George Biswas, Anindya Biswas, Ujjwal Sen, *Shared purity and concurrence of a mixture of ground and low-lying excited states as indicators of quantum phase transitions*, arXiv:2202.03339.

5. Asmita Kumari, Ujjwal Sen, *Local PT-symmetric evolutions on separable states and violation of no-signaling*, arXiv:2202.02744.

6. Mahasweta Pandit, Chirag Srivastava, Ujjwal Sen, *Recycled entanglement detection by arbitrarily many sequential and independent pairs of observers*, arXiv:2201.02594.

7. Asmita Kumari, Ujjwal Sen, *Steering inequality for pairs of particle-number-superselection-rule restricted states*, arXiv:2112.10452.

8. Soubhadra Maiti, Kornikar Sen, Ujjwal Sen, *Quantum phase estimation in presence of glassy disorder*, arXiv:2112.04411.

9. Sheikh Parvez Mandal, Ahana Ghoshal, Chirag Srivastava, Ujjwal Sen, *Invariance of success probability in Grover quantum search under local noise with memory*, arXiv:2112.02640.

10. Priya Ghosh, Kornikar Sen, Ujjwal Sen, *Response to glassy disorder in coin on spread of quantum walker*, arXiv:2111.09827.

11. Aparajita Bhattacharyya, Ahana Ghoshal, Ujjwal Sen, *Correlation between resource-generating capacities of quantum gates*, arXiv:2110.13839.

12. Chirag Srivastava, Mahasweta Pandit, Ujjwal Sen, *Entanglement witnessing by arbitrarily many independent observers recycling a local quantum shared state*, arXiv:2109.10310.

13. Sohail, Ujjwal Sen, *Convolution algebra of superoperators and nonseparability witnesses for quantum operations*, arXiv:2108.08776.

14. Ingita Banerjee, Kornikar Sen, Chirag Srivastava, Ujjwal Sen, *Quantum coherence with incomplete set of pointers and corresponding wave-particle duality*, arXiv:2108.05849.

15. Saronath Halder, Ujjwal Sen, *Separability and entanglement in superpositions of quantum states*, arXiv:2108.02260.

16. Ranjan Modak, Debraj Rakshit, Ujjwal Sen, *Finite-size scalings in measurement-induced dynamical phase transition*, arXiv:2107.14647.

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

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

Conference/Workshops Attended:

1. *International Conference on Quantum Information and Foundations (online)*, India, February 2022.

Other Activities:

1. Supervising Masters theses of Ingita Banerjee (ISM Dhanbad), Deepesh Khushwani (IISER Pune), Soubhadra Maiti (IISER Pune), Sheikh Parvez Mondal (IISER Pune), Soham Sau (Central Uni of Rajasthan). (Mostly online.)

2. Mentored/-ing the visiting students, Riddhi Ghosh (IIT Delhi), Shubhalakshmi S (IISER Pune), Asmitha Mekala (IIT BHU), Adithi Ajith (IISER Thiruvananthapuram), Murali Krishna Kurmapu (IIT Chennai), Ayushi Dubal (BITS Goa), Jayanth Jayakumar (IIT Roorkee), C S Sudheer Kumar (IISER Pune), Shashaank Khanna (IIT Indore), Samannay Bhuyan (IISER Mohali), Indrasen Ghosh (IIT Kharagpur), Arshid Lone (NIT Srinagar), Soumik Mahanti (IISER Kolkata), Priyankar Banerjee (IIT Guwahati), Subhra Priyadarshini Behura (Maulana Azad National institute of technology Bhopal, through science academies), Sangita Bera (Presidency Uni), Shilpa Mahato (ISM Dhanbad), Varad Pande (IISER Pune), Sayanwita Biswas (IIT Kharagpur), Arunava Majumder (IIT Kharagpur), Soumya Roy (IIT Kharagpur). (Often partly/fully online.)

3. Courses taken: Quantum mechanics 2, Quantum information and computation 1, Quantum information and computation 2.

4. Mentored numerical analysis projects of several HRI students.

5. Convener of computer committee, HRI; Member of visiting students and outreach committee, HRI.

6. Editorial boards/committees of Quantum, J. Phys. B, IOP SciNotes, Frontiers of Physics.

7. PI of QuEST project of DST, GoI.

Jayanta Dutta

Research Summary:

With Sukalpa, we have worked to develop a model using radiative feedback technique that incorporates the Bondi-Hoyle accretion flow in a rotating collapsing gas clumps in order to produce an upper bound on the final mass of the accreting primordial stars. It is a highly challenging task. We have prepared the manuscript for re-submission in The ApJ (impact factor 5.874). A second manuscript is on the way for submission.

With Shubham, we present the result of 3D simulations of gravitational collapse of primordial gas clumps with various degrees of initial solid-body rotation using SPH with a modified version of Gadget-2 code. The non-linear collapse is studied using a piecewise polytropic equation of state in order to approximate the various heating and cooling processes, and to reduce the computation cost. This Numerical experiment is important to investigate the survival possibility of primordial stars (We have prepared a LETTER and a journal. LETTER is ready for submission next week).

A Postdoc and three more students are working together on the survival probability of Pop III stars using a semi-analytical method.

Preprints:

1. Sukolpo Kundu, Jayanta Dutta, Sharanya Sur and Jasjeet Singh Bagla *Effect of Radiative feedback in Bondi-Hoyle accretion of Pop III stars* (in preparation for ApJ journal)

2. Shubham Raghuvanshi and Jayanta Dutta
Effects of rotation on survival rate of the Pop III stars (ApJ LETTER)

3. Shubham Raghuvanshi and Jayanta Dutta
Effects of rotation on fragmentation with polytropic equation of state and survival possibility (ApJ Journal)

Conference/Workshops Attended:

1. *Cosmic Cartography 2022 - Exploring the cosmic web and large scale structure*, Kavli IPMU, Kashiwa, Japan, 7-11 March 2022.

Invited Lectures/Seminars:

1. *Expert Lecture "The very first source of light in the universe*,
Medi-Caps University, Zoom India, February, 2022.

TEACHING:

1. Cosmology (February 2022 - May 2022)

2. Numerical Methods (February 2021 - May 2021

3. Numerical Methods (October 2021 - January 2022)
4. Astrophysics (February 2021 - May 2021)
5. Astrophysical Fluid Dynamics (February 2021 - May 2021)

Other Activities:

I have also supervised the following projects (each involved one PhD student):

1. Primordial star with radiative feedback effect (January 2021 - April 2021)
2. Self similar solution in primordial gas collapse (January 2021 - April 2021)

Arindam Bhattacharjee

Research Summary:

Since joining HRI on December 2021, the main focus of our research has been three dimensional gravity and its relation with two dimensional field theories. The asymptotic symmetry algebra of the gravity theory can be used to write a classical dual 2D theory. We have constructed a matrix model with the asymptotic symmetry algebra of 3D flat spaces (BMS_3) as its loop equation. This model would be further investigated to understand the integrability structures of BMS invariant field theories.

Apart from this, we have been exploring the behaviour of characters of Wess-Zumino-Witten models at complex levels. These play huge role in understanding lower dimensional de-Sitter gravity.

Publications:

1. Arindam Bhattacharjee, Neetu, *Matrix model with 3D BMS constraints*, Phys.Rev.D **105** (2022) 6, 066012, DOI: 10.1103/PhysRevD.105.06601

Tisita Das

Research Summary:

During the last year, I have worked on a number of projects in catalytic materials, battery and hybrid perovskite systems. Firstly, I have explored the possibility of employing atomic functionalization, vacancy induced defect and external bi-axial strain to enhance the hydrogen evolution reaction (HER) activity of single layer iron phosphosulfide ($FePS_3$) compound. A three-fold approach has been taken into account to improve the HER performance on the basal plane of $FePS_3$ in its monolayer phase. With the help of first principles electronic structure calculations, we have systematically investigated the HER activity of the pristine, functionalized, and vacancy induced defective monolayers. We have further applied bi-axial tensile and compressive strain in selected functionalized systems, through which the relevant adsorption free energy could be improved further as compared to the other possibilities. The manuscript in under revision. In addition, currently I am working on a few other transition metal based tri-chalcogenide monolayers to investigate oxygen evolution and oxygen reduction reaction bifunctional activity to be used for rechargable metal air batteries.

Apart from pure theoretical works I have also worked on a few other projects in collbaoration with experimental groups where using first-principles DFT calculations I have validated the experimental outcomes along with a more profound understanding at the electronic level. These projects not only include exploring catalytic acitivity and catalytic pathway in different 2D or quassi 2D materials but also involves determination of ion migration in battery and perovskite materials to study their stability as well as efficiency for sustainble energy production.

Publications:

1. Tisita 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,* International Journal of Hydrogen Energy, **46**, 37928-37938, (2021).

2. K. Alam, Tisita 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,* Phys. Chem. Chem. Phys., **23**, 23967, (2021).

3. P. Kour, M. C. Reddy, S. Pal, S. Sidhik, Tisita Das, P. Pandey, S. Mukherjee, S. Chakraborty, A. D. Mohite, S. B. Ogale *An Organic-Inorganic Conducting Perovskitoid with Zwitterion Cysteamine Linker and Its Crystal-Crystal Transformation to Ruddlesden-Popper Phase,* Angew. Chem. Int. Ed., **60**, 18750 (2021).

4. S. Sarkar, A. Rawat, Tisita Das, M. Gaboardi, S. Chakraborty, C. P. Vinod, and S. C. Peter, *Structure-Tailored Non-Noble Metal-based Ternary Chalcogenide Nanocrystals for Pt-like Electrocatalytic Hydrogen Production,* ChemSusChem **14**, 1-11, (2021).

5. S. Parmar, Tisita Das, B. Ray, B. Debnath, S. Gosavi, G. Shanker, S. Datar, S. Chakraborty, S. B. Ogale, *N, H Dual-doped Black Anatase TiO_2 Thin Films towards*

Significant Self-Activation in Electrocatalytic Hydrogen Evolution Reaction in Alkaline Media, Adv. Energy Sustainability Res., **3**, 2100137, (2022).

6. S. Mondal, S. Sarkar, D. Bagchi, Tisita Das, R. Das, A. Singh, P. K. P., C. Vinod, S. Chakraborty, S. Peter, *Morphology Tuned Pt_3Ge Accelerates Water Dissociation to Industrial Standard Hydrogen Production over a wide pH Range*, Advanced Materials, Accepted (2022).

Preprints:

1. Tisita Das, S. Chakraborty, P. Sen, *Competing Effect of External Strain, Functionalization and Vacancy Defect Towards Enhanced HER Activity in Transition Metal Phosphorous based Trichalcogenide Monolayers,* (in preparation).

2. A. Karmakar, Tisita Das, K. Karthick, S. Kumaravel, S. Sankar, R. Madhu, S. Chakraborty, S. Kundu, *Tuning the electronic structure of Ni vacancy enriched AuNi spherical nanoalloy via electrochemical etching for water oxidation study in alkaline and neutral medium,* (in preparation).

3. S. Singh, A. Neveu, K. Jayanthi, Tisita Das, S. Chakraborty, A. Navrotsky, V. Pralong, P. Barpanda, *Facile Synthesis and Phase Stability of Cu-based $Na_2Cu(SO_4)_2.xH2O$ (x = 0-2) Sulfate Minerals as Conversion type Battery Electrodes,* (in preparation).

4. N. Sethulakshmi, S. Nellaiappan, P. K. P., Tisita Das, S. Chakraborty, S. Sharma, *Hydrazine Assisted Water Oxidation and its Mechanism over Nanocoral $CuCo_2S_4$,* (in preparation).

5. D. Gupta, A. Kafle, S. Kaur, P. P. Mohanty, Tisita Das, S. Chakraborty, R. Ahuja, T. Nagaiah, *High Yield Selective electrochemical conversion of N_2 to NH_3 via morphology controlled silver phosphate under ambient conditions,* (in preparation).

6. D. Gupta, A. Kafle, P. P. Mohanty, Tisita Das, S. Chakraborty, R. Ahuja, T. Nagaiah, *Self-powered NH_3 synthesis by trifunctional Co_2B based high power density Zn-air batteries,* (in preparation).

Conference/Workshops Attended:

1. Virtually attended *Flagship Workshop "GPAW 2021: Users and Developers Meeting"*, organized by CECAM, in June 1-4, 2021.

Other Activities:

1. I was involved in Teaching Assistantship for the course of Advanced Quantum Mechanics (QM-III) to the HRI students of M.Sc. 2nd year, during October - January, 2021.

Nivedita Ghosh

Research Summary:

In this academic year 2020-2021, *i.e*, 1st April 2021 to 31st March 2022, 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. To explain the observed muon anomaly and simultaneously evade bounds from lepton flavor violation in the same model parameter space is a long-cherished dream. In view of a generalized Two Higgs Doublet Model, with a Yukawa structure as a perturbation of Type-X, we are able to get substantial parameter space satisfying these criteria. In this work, we focus on a region with "wrong-sign" lepton Yukawa coupling which gives rise to interesting phenomenological consequences. Performing a simple cut-based analysis, we show that at 14 TeV run of the LHC with 300fb-1 integrated luminosity, part of the model parameter space can be probed with significance $\geq 5\sigma$ which further improves with Artificial Neural Network analysis. [Nivedita Ghosh and Jayita Lahiri, European Physics Journal C 81 12 1074 ,(2021)]

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, trilepton 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, Indrani Chakraborty, Dilip Kumar Ghosh, Santosh Kumar Rai, European Physics Journal C 81 7 679 ,(2021)]

Publications:

1. Nivedita Ghosh, Jayita Lahiri, *Generalized 2HDM with wrong-sign lepton Yukawa coupling, in light of $g_\mu - 2$ and lepton flavor violation at the future LHC,* European Physics Journal C 81 **12 1074 ,(2021)**.

2. Nivedita Ghosh, Indrani Chakraborty, Dilip Kumar Ghosh, Santosh Kumar Rai, *Dark Matter and Collider Searches in S_3-Symmetric 2HDM with Vector Like Lepton*, European Physics Journal C 81 **7 679 ,(2021)**.

Preprints:

1. Nivedita Ghosh, Indrani Chakraborty, Dilip Kumar Ghosh, Santosh Kumar Rai, *Signals for vector-like leptons in a S_3-symmetric 2HDM at ILC*, Arxiv:2201.11646.

Visits to other Institutes:

1. Visited Dr. Rahul Srivastava, IISER Bhopal, Bhopal, India, February 21- March 7, 2022.

Subramanya Hegde

Research Summary:

In the academic year 2021-2022, I have worked on the following problems.

Scattering amplitudes in supersymmetric theories display rich mathematical structures which have deepened our understanding of amplitudes. Spino-helicity formalism to represent kinematic variables for scattering amplitudes plays a key role in this. In 2017, massive spinor helicity formalism was introduced which has since then been extended to supersymmetric theories, to compute the scattering amplitude in the Coulomb branch of $N = 4$ SYM theory. We consider a close cousin of this theory where we study the Coulomb branch of $N = 2^*$ theory. In this theory there is a massive $N = 2$ SYM multiplet and a massive $N = 2$ hypermultiplet, which remains massive even at the origin of the moduli space. We utilised the close relationship of this theory with $N = 4$ SYM to write the $N = 2^*$ amplitudes using projection. We also performed the BCFW analysis within $N = 2^*$ theory which provides interesting lessons on BCFW in massive theories. This work was done in collaboration with Md. Abhishek, Dileep P Jatkar, Arnab Priya Saha.

Along with Madhu Mishra, Debangshu Mukherjee and Bindusar Sahoo, we are constructing the higher derivative matter coupled action for $N = 3$ supergravity in four dimensions. We employ the superconformal approach, where we use $N = 3$ conformal supergravity theory, which was recently developed by some of us.

Publications:

1. Subramanya Hegde, Madhu Mishra and Bindusar Sahoo, $N = 3$ *conformal supergravity in four dimensions* JHEP **04** 001, (2022)

Preprints:

1. Md. Abhishek, Subramanya Hegde, Dileep P. Jatkar and Arnab Priya Saha, *Scattering Amplitudes and BCFW in* $N = 2^*$ *theory*, 2104.07453 [hep-th]

Conference/Workshops Attended:

1. *Amplitudes 2021*, Copenhagen, Denmark (Online), August 2021
2. *Indian Strings Meeting*, India (Online), January 2021.
3. *Frontier Symposium in Physics*, IISER Thiruvananthapuram, India, April 2022.

Visits to other Institutes:

1. NIT Calicut, March 10th to April 1st 2022.
2. IISER Thiruvananthapuram, April 2nd 2022 to May 4th 2022.
3. IIT Ropar, May 5th to June 2nd 2022.
4. IISER Mohali, June 2nd to June 4th 2022.

Invited Lectures/Seminars:

1. *One-loop polytope from generalized scattering equations*, Poster presentation in Amplitudes 2021, Niels Bohr Institute, Copenhagen (Online), August 2021.
2. *Scattering amplitudes from symmetries*, Institute seminar at NIT Calicut, March 2022.
3. *Lectures on basics of scattering amplitudes*, IISER Thiruvananthapuram, April 2022.
4. *Lectures on basics of scattering amplitudes*, IIT Ropar, May 2022.
5. *Scattering amplitudes from spinor-helicity formalism*, Institute seminar at IISER Mohali, June 2022.

Som Kanjilal

Research Summary:

- Unsharp measurement gives us the ability to re-utilize a quantum object (state) multiple times in the context of a information processing task. We considered a scenario involving multiple independent pairs of observers acting with unbiased inputs on a single pair of spatially separated qubits sequentially. In this scenario, we address whether more than one pair of observers can demonstrate quantum advantage in some specific $2 \xrightarrow{p} 1$ and $3 \xrightarrow{p} 1$ random access codes. Interestingly, we not only address these in the affirmative but also illustrate that unbounded pairs can exhibit quantum advantage. Furthermore, these results remain valid even when all observers perform suitable projective measurements and an appropriate separable state is initially shared.

- Random Access Codes are one of the most primitive information processing tasks. Just like any standard communication tasks it consists of four steps (1)classical encoding, (2)quantum encoding, (3)quantum decoding and (4)classical decoding. A $n \xrightarrow{p} m$ RAC is a two party information theoretic task where a sender/encoder (Alice) is in possession of a bit string of length n. It is a two step process, involving a communication step and a guessing step. In communication step, Alice sends to a receiver/decoder (Bob) another bit string of length m ($m < n$), encoding the information about n bit string. In the guessing step, Bob guesses any of the n bits correctly with probability at least p. In other words, p is the worst case success probability corresponding to the RAC task. In this context, we compare the $n \xrightarrow{p} 1$ random access code assisted with a shared bit and qubit source. We show that,

  - for $n > 3$, the necessary number of quantum decoding-encoding strategies (measurements) to achieve quantum advantage does not exist,
  - for $n = 2$, given a particular classical decoding strategy, the invertibility of the correlation matrix along with a condition on the lowest eigenvalue tells us when there exists a set of encoding measurements such that quantum advantage can be obtained for all pairs of orthogonal decoding measurements (quantum decoding strategies),
  - for $n = 3$, given a particular classical strategy, the invertibility of the correlation matrix ensures that there exists a classical decoding strategy and a set of encoding measurements such that quantum advantage can be obtained for all triplets of non-collinear decoding measurements

Publication:

1. Debarshi Das, Arkaprabha Ghosal, Ananda G. Maity, Som Kanjilal, and Arup Roy, *Ability of unbounded pairs of observers to achieve quantum advantage in random access codes with a single pair of qubits*, Phys. Rev. A **104**, L060602 (2021)

Preprints:

1. Surya Narayan Sahoo, Sanchari Chakraborti, Som Kanjilal, Dipankar Home, Alex Matzkin, and Urbasi Sinha, *Unambiguous joint detection of spatially separated properties of a single photon in the two arms of an interferometer*, arXiv:2201.11425 (2022)

2. Simanraj Sadana, Som Kanjilal, Dipankar Home, Urbasi Sinha, *Relating an entanglement measure with statistical correlators for two-qudit mixed states using only a pair of complementary observables*, arXiv:2201. 06188(2022)

3. Som Kanjilal, Chellasamy Jebarathinam, Tomasz Paterek, and Dipankar Home, *On quantum advantage in the random access code protocols with two-qubit states*, arXiv: 1912.09900 (2022)

Deepak Singh Kathyat

Research Summary:

We identify a mechanism to convert skyrmions and antiskyrmions into their antiferromagnetic (AFM) counterparts via interface engineering. The key idea is to combine properties of an antiferromagnet and a spin-orbit (SO) coupled metal. Utilizing hybrid Monte Carlo (HMC) simulations for a generic microscopic electronic Hamiltonian for the interfacial layers, we explicitly show the emergence of AFM skyrmions and AFM antiskyrmions. We further show that an effective spin Hamiltonian provides a simpler understanding of the results. We discuss the role of electronic itinerancy in determining the nature of magnetic textures, and demonstrate that the mechanism also allows for a tuning of antiskyrmion size without changing the SO coupling. The anisotropic interactions of the Dzyaloshinskii-Moriya (DM) and pseudo dipolar form emerge naturally in addition to the standard isotropic term in the derived effective spin Hamiltonian from Dresselhaus SOC modified double exchange model.

I have learned the stochastic Langevin dynamics approach and implemented the scheme for spin dynamics study of Heisenberg model and Mott insulating phase of half-filled Hubbard model for various lattice geometries. For a system of interacting spins described by a Hamiltonian $\mathcal{H}(\mathbf{S}_1, \mathbf{S}_2, ..., \mathbf{S}_N)$, The Langevin equation of motion for an individual spin $\mathbf{S}_i$ has the form

$$\frac{d\mathbf{S}_i}{dt} = \frac{1}{\hbar}[\mathbf{S}_i \times (\mathbf{H}_i + \boldsymbol{\xi}_i) - \gamma \mathbf{S}_i \times (\mathbf{S}_i \times \mathbf{H}_i)],$$

where $\mathbf{S}_i = \mathbf{S}_i(t)$ is a spin vector, $\mathbf{H}_i(t) = -\mathcal{H}/\partial \mathbf{S}_i$ is the effective field acting on the spin $\mathbf{S}_i$, and γ is a dimentionless damping parameter. The fluctuating thermal noise, $\boldsymbol{\xi}_i$ allow us to study the finite temperature effects. A robust and numerically stable algorithm based on Suzuki-Trotter decomposition is implemented for integrating the stochastic Langevin spin dynamics equations. For spin dynamics in Hubbard model, we first decouple the interaction term to obtain the spin fermion model.

Given that the diamagnetic response in some spin-orbit coupled systems can turn out to be anomalously large, the coupling of the external magnetic field to the orbital motion of electrons becomes relevant. The main focus of this project is to study the competition between two distinct aspects of coupling of electrons to the external magnetic field in skyrmion-host magnetic metals. Including the Peierls phase experienced by itinerant electrons because of the presence of external magnetic field in the spin-orbit coupled system adds new aspects to the study. Purpose of the project is to understand theoretically the experimental observations on enhanced stability of antiskyrmions over skyrmion states.

Currently working on a microscopic electronic mechanism for co-existence of distinct topological magnetic textures in centrosymmetric materials. Studying the minimal microscopic lattice model describing the geometrically frustrated metallic magnet. The spin-fermion model is relevant for material like Gd_2PdSi_3 which is a metallic magnet composed of a triangular-lattice arrangement of Gd atoms in the centrosymmetric hexagonal structure. Its crystal structure suggests there is strong coupling between conduction electrons and localized magnetic moments formed by *4f* orbitals of Gd atoms. Since Gd^{3+} ions carry a large moment (S = 7/2), the localized spins can be

treated as classical vectors. We observe that the competeing exchange interactions give rise to emergence of skyrmions or antiskyrmions but the interactions mediated by the itinerant electrons is responsible for the presence of skyrmions and antiskyrmions on same lattice.

Publications:

1. A. Mukherjee, D. S. Kathyat, and S. Kumar, *Engineering antiferromagnetic skyrmions and antiskyrmions at metallic interfaces*, Phys. Rev. B **105**, 075102 (2022).

Preprints:

1. D. S. Kathyat, "Co-existence of distinct topological magnetic textures in centrosymmetric Hund's metals", (*manuscript in preparation*).

Conference/Workshops Attended:

1. "International Conference on Strongly Correlated Electron Systems (SCES) 2020/21 -Brazil Online", 27 September - 2 October, 2021.

Arghya Maity

Research Summary:

In the previous year, my research was primarily focused on quantum information theory, with particular emphasis on the theory of entanglement. Quantum entanglement is one of the most functional resources in quantum information tasks. It is important to develop a procedure to manipulate entanglement in quantum states, so that they may be brought into a useful form to fulfill a particular task. Entanglement transformation plays a crucial role in the manipulation process, by which a potentially less applicable state is turned into a more useful one, by some non-resource generating operations, say, local operations and classical communication (LOCC). When transformation between a given pair of states is not possible via LOCC, an additional entangled state known as the catalyst, is introduced to assist the protocol, which remains unaltered after the transformation just like in a chemical process. Catalysts are also shown to make a correlation with the states and enhance the transformation probability and power. Over the years, several results are obtained which characterize the state transformation.

The distribution of typical bipartite pure states is studied by us within the framework of state transformation via local operation and classical communication (LOCC). We report the statistics of comparable and incomparable states in different dimensions for single- and multi-copy regimes and establish a connection between state transformation and the difference between the entanglement contents of the initial and the target states. From the analysis of catalyst resources, required to further otherwise impossible LOCC transformations between pairs, we demonstrate a universal pattern in the average and minimum entanglement of the randomly generated catalysts. Furthermore, we introduce a concept of hierarchy between different kinds of catalysts and show how they can not only aid in the conversion of incomparable states but can also act as a less costly resource towards this goal. We confirm the existence of catalysts, referred to as *strong catalysts*, which can activate LOCC transformation between pairs at the single-copy level, when it is initially impossible even with multiple copies.

I also woked on Structural Analysis of DNA molecule in a confined shell. We have studied the DNA molecule that is confined in a cylindrical shell. In genetic engineering, the DNA is encapsulated in a shell. Motivated by these experiments, we have considered a DNA molecule of different lengths and confined it in a cylinder. Using the statistical model, we first study the thermodynamics of the molecule and then study the effect of confinement on the structural parameters of the molecule. Probably, this is the first simulation-based study in which details of the structural parameters have been calculated.

Preprints:

1. Rivu Gupta, Arghya Maity, Shiladitya Mal, Aditi Sen De, *Statistics of Entanglement Transformation with Hierarchies among Catalysts*, arXiv:2202.01540.

2. Arghya Maity, Neha Mathur, Petra Imhof, Navin Singh, *Structural Analysis of DNA molecule in a confined shell*, arXiv:2202.02084 .

Conference/Workshops Attended:

1. International Conference on Quantum Information and Foundations **(ICQIF-2022)**, Physics and Applied Mathematics Unit, Indian Statistical Institute, Kolkata, India

Asmita Kumari

Research Summary:

In the previous academic year, I have worked on aspects of PT-symmetric quantum theory and Steering inequality for pairs of particle-number-superselection-rule restricted states.

We consider violations of a Clauser-Horne-Shimony-Holt-type steering inequality for quantum states of systems of indistinguishable particles restricted by a particle-number-superselection rule. We check for violations in non-interacting Bose-Einstein condensate and N00N states, by using two copies of the states for bypassing the superselection rule. The superselection rule prevents the states from maximally violating the steering inequality.

We show that local PT-symmetric evolutions can lead to violation of the no-signaling principle for separable and even classically correlated bipartite shared quantum states. For classically correlated states, specially chosen PT-symmetric operations from a set of zero volume can also preserve the principle. The violations can be removed by using a CPT inner product instead of the traditional one.

Next, We have studied the quantum violations of Leggett-Garg inequalities (LGIs) while system evolves under qubit channel and PT symmetric Hamiltonian. We first show for both the evolutions the quantum violations of LGIs beat the respective Luders bounds (unitary case) and even approach algebraic maximum of the inequalities. we demonstrate a hitherto unexplored feature that, for the case of variant of LGI and PT symmetric evolution, the quantum violation can even be obtained when only the arrow-of-time is violated but no-signaling in time condition is satisfied.

Publications:

1. Ann. Phys. (Berlin) 2100401 (2022).
2. Asmita Kumari and A K Pan, *Quantum violations of Lüders bound Leggett-Garg inequalities for non-unitary quantum channel*, J. Phys. A: Math. Theor. 55 135301 (2022)
3. Asmita Kumari and Ujjwal Sen, *Local preservation of no-signaling in multiparty PT-symmetric evolutions*, J. Phys. A: Math. Theor. 55 185302

Preprints:

1. arXiv:2202.02744, arXiv:2112.10452

Conference/Workshops Attended:

1. QUEST Symposium
2. ICQIF-2022

Visits to other Institutes:

1. Visited S. N. Bose National Centre for Basic Sciences during the period 22-28 May 2022.

Arpan Krishna Mitra:

Research Summary:

1. Low angular momentum, general relativistic, axially symmetric accretion of hydrodynamic fluid onto Schwarzschild black holes may undergo more than one critical transition. To obtain the stationary integral solutions corresponding to such multi-critical accretion flow, one needs to employ numerical solutions of the corresponding fluid dynamics equations. In the present work, we develop a completely analytical solution scheme which may be used to find several trans-critical flow behaviours of aforementioned accretion, without explicitly solving the flow equations numerically. We study all possible geometric configurations of the flow profile, governed by all possible thermodynamic equations of state. We use Sturm's chain algorithm to find out how many physically acceptable critical points the accretion flow can have, and discuss the transition from the mono to the multi-critical flow profile, and related bifurcation phenomena. We thus illustrate, completely analytically, the application of certain aspects of the dynamical systems theory in the field of large scale astrophysical flow under the influence of strong gravity. Our work may possibly be generalized to calculate the maximal number of equilibrium points certain autonomous dynamical systems can have in general (submitted in GRG. Reference no. - GERG-D-22-00024).

2. Anomaly, a generic feature of relativistic quantum field theory, is shown to be present in non-relativistic classical ideal fluid. A new result is the presence of anomalous terms in current algebra, an obvious analogue of Schwinger terms present in quantum field theory. We work in Hamiltonian framework where Eulerian dynamical variables obey an anomalous algebra (with Schwinger terms) that is inherited from modified Poisson brackets, with Berry curvature cor- rections, among Lagrangian discrete coordinates. The divergence anomaly appears in the Hamiltonian equations of motion. A generalized form of fluid velocity field can be identified with the "anomalous velocity" of Bloch band electrons appearing in quantum Hall effect in condensed matter physics. We finally show that the divergence anomaly and Schwinger terms satisfy well known Adler consistency condition. Lastly we mention possible scenarios where this new anomalous fluid theory can impact (submitted in PRL. Reference no. - LL17718).

3. For general relativistic black hole accretion in the Kerr metric, linear pertur- bation of the axially symmetric matter flow leads to the emergence of black hole like acoustic spacetime. For different parameters characterizing the flow, the characteristic of the phase portrait of flow can be constructed. For such flow, the fluid equations may be perturbed and the corresponding emergent spacetime can be obtained such that the propagation of first order perturba- tion in these spacetimes can be analyzed in a way similar to the propagation of light as analyzed in a spacetime using causal structure. We present the Penrose Carter formalism to analyze the emergent metric and the aforemen- tioned propagation. Certain special flows with parameters at the boundary of the parameter space are also studied in this context. Analogue spacetime corresponding to accretion flow with shock is shown to be endowed with one white hole like sonic horizon flanked by

two black hole like acoustic horizons. The problem of separation of two regions in the Penrose Carter diagram of this flow, and thus the inconclusive presence of white hole is solved by consid- ering the extremely thin but finite width of shock. The shock is established to be the acoustic white hole. The resemblance of such a special kind of space- time with a wormhole is established (Ongoing with Tapas Kumar Das from HRI, Susovan Maity from HRI, Subir Ghosh from ISI).

4. We are investigating the effects on flow variables of transonic advection dominated accretion flows (ADAfs) for different outer boundary locations with a changing energy constant (E) of the flow. We have investigated a general power index rule ($v_r \propto r^{-p}$) of a radial bluk velocity with different boundary location (Ongoing with Rajiv Kumar from University of Science $\&$ Technology of China).

5. The bifurcation phenomenon that we observe in the parameter space plots of axisymmetric accretion on a spherically symmetric black hole is pitch fork bifurcation. Bifurcation of such kind is found in physical systems which bear a symmetry. The normal form of the supercritical pitchfork bifurcation is $\dot{x} = rx - x^3$. Though we get polynomial equations for different disc geometries those apparently bear no resemblance with the aforementioned form. We are trying, through a canonical transformation, to establish a connection between the polynomial equations those represent the axisymmetric accretion for the respective disc geometries with this normal form of the p-f bifurcation. Our main goal is to understand the underlying symmetry of these systems that gives rise to the similar kind of bifurcation phenomenon for all the available disc geometries (Ongoing with Tapas Kumar Das from HRI, Pratik Tarafdar from IMSC, and Pathikrith Banerjee from The University of Manchester).

6. We are dealing with a model inspired by extra dimensions that is built on the DGP brane - world scenario. We consider a Chaplygin gas with generalized equation of state as the dark energy component on the brane. Then we have studied a holographic model of the Chaplygin gas in the framework of DGP cosmology. Earlier for simplest possible model it has been shown that holographic Chaplygin gas can mimic a phantom fluid. We , after incorporating the generalization, are trying to find the new features of the system and trying to fix possible ranges of the parameters defining the generalized model (Ongoing with Souvik Ghose from HRI).

7. The evolution of collapsing metal-free protostellar clouds is investigated for various masses and initial conditions. Recent numerical simulations have suggested the probability of a fraction of the primordial stars being ejected from the cluster of their origin. I have been exploring the semianalytical models consistent with the results of cosmological simulations to study the functional dependence of the mass accretion on the original stellar mass and other pa- rameters like angular momentum and gravitational drag due to ambient gas by these protostars (With Jayanta Dutta from HRI).

Preprints:

1. Arpan Krishna Mitra, Subir Ghosh, *Chiral Anomaly in Ideal Fluid*, arXiv: 2111.00473

2. Arpan Krishna Mitra, Aishee Chakraborty, Pratik Tarafdar, Tapas Kumar Das, *Multi-criticality and related bifurcation in accretion discs around non-rotating black holes – an analytical study*, arXiv:2111.13592.

Conference/Workshops Attended:

1. ASI -2022 (25-29 March, 2022): Poster Presentation: 'Multi-criticality and related bifurcation in accretion discs around non-rotating black holes – an analytical study'

Visits to other Institutes:

1. Indian Statistical Institute, Kolkata (4th Feb - 20 th march).

Invited Lectures/Seminars:

1. Non-Commutative fluids, a Hamiltonian description and NC effects in cosmology: Cosmic Ray Group of Astronomy(CRAGA), High Energy $\&$ Cosmic ray Research Centre, University of North Bengal, 23rd May, 2021.

Other Activities:

1. Mentored a BSc. final year student from Asutosh College in a project on analytical study of multitransonicity that is observed in axisymmetric ac- crition around black holes and submitted the results for publication (arXiv: 2111.13592).

Rafiqul Rahaman

Research Summary:

During the academic year 2021-2022, i.e., from 1st April 2021 to 31st March, I have worked on the following projects.

I completed work on the spin correlation of a pair of spin-full particles in collaboration with Dr. Ritesh K. Singh and submitted to journal for publication. 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 the 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.

I worked on studying anomalous couplings in the leptonic $t\bar{t}Z$ production at the Large Hadron Collider using the polarizations of top quarks and Z boson, the two-body and three-body spin correlations. I showed how the reconstruction of two neutrinos at the detector level affects the angular distributions corresponding to polarizations and spin correlations compared to the parton level distributions. The sensitivity of the couplings to polarizations and spin correlations are studied in the form of χ^2 for a luminosity of $\mathcal{L} = 3$ ab^{-1}. The improvements of limits on the couplings are studied over the cross section by successively including the polarization and spin correlation asymmetries. The 95% C.L. limits are obtained on the anomalous couplings a few set of luminosity. The manuscript is submitted to a journal for publication.

I am involved in work to identify the spin of exotic charged particles and their neutral partner, which are possible dark matter candidates in the future e^+e^- collider in collaboration with Dr. Santosh Kumar Rai and Anjan Kumar Barik. We choose two well motivated existing models, such as Inert Doublet Model (IDM) and Minimal supersymmetric SM (MSSM), having potential dark matter candidates of type scalar (spin-0) and fermionic (spin-1/2), respectively, for this study. We use the potential of beam polarization (longitudinal and transverse) of an e^+e^- collider to discriminate between the two models by looking at various angular distributions in the $l^{\pm}jj + MET$ final states. The manuscript of this work is almost prepared, and we hope to communicate this work very soon.

I am also involved in work to search for fatjets originating from boosted particles decayed from heavy resonance in a left-right symmetric extension of SM accompanied by heavy leptons, heavy quarks and heavy neutrinos in collaboration with Dr. Santosh Kumar Rai and Atri Dey. The fatjets, which include non-isolated leptons, originates from heavy neutrino (in GeV range) decayed from heavier (few TeV range) right-handed gauge boson. We employ substructure based variables lepton soft jet fraction (LSF) and lepton mass drop (LMD) together with hard kinematic cuts to search for fatjet with associated leptons and reduce SM background while keeping enough statistics for the signals. The manuscript of this work is almost prepared, and we hope to communicate this work very soon.

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. Since Z_d couples to SM particles via the interactions, 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 polarization observables of Z_d constructed from the decay of $Z_d \to \ell^+\ell^-$. The manuscript of this work is under preparation.

Publications:

1. P. Konar, B. Mukhopadhyaya, R. Rahaman and R. K. Singh, *Probing non-standard $b\bar{b}h$ interaction at the LHC at $\sqrt{s} = 13$ TeV*, Phys. Lett. B **818**, 136358 (2021)

Preprints:

1. R. Rahaman and R. K. Singh, *Breaking down the entire spectrum of spin correlations of a pair of particles involving fermions and gauge bosons*, [arXiv:2109.09345 [hep-ph]].

2. R. Rahaman, *On two-body and three-body spin correlations in leptonic $t\bar{t}Z$ production and anomalous couplings at the LHC*, [arXiv:2204.12152 [hep-ph]].

3. Anjan Kumar Barik, Rafiqul Rahaman, Santosh Kumar Rai *Determining spin of exotic charged particles at the future e^+e^- collider,* manuscript under preparation.

4. Atri Dey, Rafiqul Rahaman, Santosh Kumar Rai *Fatjet signatures of heavy neutrinos and heavy leptons in a left-right symmetric Model with Universal Seesaw at the HL-LHC,* manuscript under preparation.

5. Ashok Kumar Goyal, Mukesh Kumar, Satendra Kumar, Rafiqul Rahaman, *Exploring Dark Z-boson in electron-proton collisions,* manuscript under preparation.

Pratim Roy

Research Summary:

The main direction of my research over the past year has been to study entanglement in field theories. Primarily, a measure of mixed state entanglement called logarithmic negativity has been studied. The main advantage to studying logarithmic negativity over other measures of mixed state entanglement is that it does not require any optimisation over different configurations. The system chosen is a scalar field theory with a fractional Laplacian. The physical significance of the fractional Laplacian is that it incorporates long-range interactions, via a tunable parameter which is the exponent of the fractional Laplacian. The logarithmic negativity has been calculated numerically for both static and time-dependent scenario in a disjoint configuration, wherein two subsystems are separated by a finite distance. For the static scenario, it is found that the negativity decays slower as the range of interactions is increased (by changing the tunable parameter). For the time-dependent scenario, a quantum quench is considered, in which a parameter of the Hamiltonian (specifically, the mass) is changed abruptly. The time evolution of the negativity after the change is studied and shows the "revivals" after a certain time period. This phenomenon is one of the main results of the work. To provide stronger evidence, the entanglement entropy is also investigated numerically. This is a much simpler measure of entanglement and has the advantage that it is easily calculated according to the quasiparticle picture, which intuitively describes quantum quenches. Both the direct numerical results and the quasiparticle results for entanglement entropy show "dips" at the same temporal values as logarithmic negativity, confirming that this is a generic feature.

It has been conjectured in the literature that the revivals/dips indicate scrambling, which is a phenomenon which has previously been investigated in other long-range systems. A quantity which has been used in the literature for probing scrambling and chaos is out-of-time-ordered correlators. Consequently, these are also calculated in this system. They reveal that although scrambling in indicated in the logarithmic negativity and entanglement entropy, fast scrambling is absent.

In addition to the above work, an attempt is being made to investigate scrambling in conformal field theories. The scenario under consideration is that a conformal field theory is perturbed away from the fixed point by an operator. The model is then investigated by means of conformal perturbation theory. It is hoped that this approach will provide further insight to revivals in non-conformal theories.

Publications:

1. Aspects of entanglement in non-local field theories with fractional Laplacian (accepted in Journal of High Energy Physics)

Shalini Tomar

Research Summary:

I am working as a Research Associate with Dr. Sudip Chakraborty under DST-NSM project since 29 June 2021. My research work focused on the theoretical prediction of Layered Materials for hydrogen production. Mainly, I have done work on the transition metal dichalcogenides layered materials such as VX_2 and ZrX_2 type layered structures. I have done theoretical study of catalytic properties of these pristine and doped layered structure using Density functional theory based code.

Preprints:

1. S. Tomar, P. Sen, S. Chakraborty, "Theoretical Investigation on the Hydrogen Evolution, Oxygen Evolution, and Oxygen Reduction Reactions Performances of Zirconium Dichalcogenide Monolayers" (in preparation)

2. S. Tomar, P. Sen, S. Chakraborty, "Single Atom Functionalization in Vanadium Dichalcogenide Monolayers: Towards Enhanced Catalytic Activity". (in preparation)

Faruk Abdulla

Research Summary:

Over the past year I have been working on two different problems. One of them is involving topological insulator, Weyl semimetal and other involves the double bilayer graphene.

In the first problem I, with my collaborator Ankur Das and Ganpathy Murthy, study models which live in the CII class of topological insulators and superconductors. Models with time reversal, particle-hole and chiral symmetries fall in the CII class. We have classified all the time reversal and inversion broken but chiral symmetric perturbations. We add such perturbations and study the gapless, gapped phases and the associated surface states of the resulting chiral model (which is in AIII class after breaking time reversal).

In the second problem, I with my collaborator Ankur Das, study correlated phases in double bilayer quantum Hall graphene. We take two AB stacked bilayers, placed in high magnetic field, which are separated by a distance d which we can tune. There is no tunnelling but only the Coulomb interaction between the two bilayers. There exists an important parameter d/ℓ_B, where ℓ_B is the magnetic length, in the problem. We are doing a Hartree-Fock study to find the possible correlated phases as a function of the tunnable parameter d/ℓ_B.

Publications:

1. Faruk Abdulla, Ankur Das, Sumathi Rao, and Ganpathy Murthy, *Time reversal broken Weyl semimetal in the Hofstadter regime,* Scipost Phys. Core 5, 014 (2022)

Preprints:

1. Faruk Abdulla and Ankur Das, *Layer correlated phases in double bilayer graphene* (in preparation).

Conference/Workshops Attended:

1. Participated in *Topological aspects of strong correlations and gauge theories* (online), ICTS, Bangalore, Sep 2021
2. Participated in *Young investigators meet on quantum condensed matter theory* (YIMQCMT, online), NISER Bhubaneswar, Nov 2021
3. Participated in *APS March Meeting* (online), American Physical Society, Chicago, USA, March 2022.

Presentation in School/Conferences:

1. Poster presentation in *Young investigators meet on quantum condensed matter theory* (YIMQCMT), (online conference), NISER Bhubaneswar, Nov 2021

2. Oral presentation in *APS March Meeting* (online conference), American Physical Society, Chicago USA, March 2022.

Other Activities:

1. Attended an online course *Quantum phases of matter* by Subir Sachdev.
2. Co-supervised (with Sumathi Rao) Krishna Prahalad (IISER Bhopal) for his Master thesis.
3. Co-supervised (with Sumathi Rao) Kishore Iyer (IISER TVM) for his MSc summer intern project.
4. Visited ICTS from October-February 2021-2022.

Md. Abhishek

Research Summary:

During the academic year 2021-2022, in the collaboration with Dileep P. Jatkar, Arnab Priya Saha, and Subramanya Hegde, have studied the scattering amplitudes of $\mathcal{N} = 2^*$ theory using massive spinor-helicity variables and the BCFW recursion.

With Dileep P. Jatkar, Sachin Grover, and Kajal Singh, we have been studying some problems related to the two-dimensional conformal field theory (2d CFT).

Publications:

1. Md. Abhishek, S. Hegde, and A. P. Saha, *One-loop integrand from generalised scattering equations,* JHEP. **05**, 012, (2021).

Preprints:

1. Md. Abhishek, S. Hegde, D. P. Jatkar, and A. P. Saha, *Scattering Amplitudes and BCFW in $\mathcal{N} = 2^*$ Theory,* arXiv: 2202.12204.

Conference/Workshops Attended:

1. *Amplitudes 2021*, Niels Bohr Institute, Copenhagen, Denmark, 16–20 August, 2021.

2. *Trends in String Theory and Related Topics*, HRI, Allahabad, India, 9th October 2021.

Invited Lectures/Seminars:

1. *Double soft theorem for generalised bi-adjoint scalar amplitudes* (Poster presentation), Amplitudes 2021, Niels Bohr Institute, Copenhagen, Denmark, 16–20 August, 2021.

2. *Scattering amplitudes and cluster algebras*, Trends in String Theory and Related Topics, HRI, Allahabad, India, 9th October 2021.

Other Activities:

1. Teaching Assistant, 'Quantum Field Theory-II' Course, February 2022 - June 2022.

Sankha Subhra Bakshi

Research Summary:

Recent developements in probing correlated matters open up the possibility to understand the non-equilibrium behaviors of strongly-correlated system and experiments show they differ very much in non-intuitive ways from their equilibrium counter-parts. An electron-phonon system at commensurate filling often displays charge order (CO) in the ground state. Such a system subject to a laser pulse shows a wide variety of behaviour. A weak pulse sets up low amplitude oscillations in the order parameter, with slow decay to a slightly suppressed value. A strong pulse leads to the destruction of the charge order with the order parameter showing rapid, oscillatory, decay to zero. The regime in between, separating the weak pulse CO sustained state from the strong pulse CO destroyed state, shows complex dynamics characterised by multiple, pulse strength dependent, time scales. It involves an initial rapid decay of the order parameter, followed by a low amplitude quiescent state, and the power-law rise to a steady-state over a timescale τ_{cr}.

Accesssing these meta-stable states via non-equilibrium routes requires a method that not only can caprture the slow real-time dynamics of the phonons but the true genuine ultra-fast dynamics of the electrons as well. Our work shows a simple method that is numerically way less costly than other current methods and yetcan capture true long time rich dynamics.

We are also trying to adept this method to the case where spin and phonon both are present which can give rise to multiple transient phase transitions cause by a single laser pump.

Preprints:

1. Sankha Subhra Bakshi, Debraj Bose, Arijit Dutta, Pinaki Majumdar, *Nonequilibrium dynamics of suppression, revival, and loss of charge order in a laser pumped electron-phonon system*, arXiv:2205.14710

Conference/Workshops Attended:

1. Statphys-Kolkata XI (online) meeting, IISER-Kolkata, India, 21-25 March, 2022
2. Emerging Trends in Physical Sciences (ETPS-2021), ICFAI Universirty Tripura, India, 27th September - 1st October, 2021

Other Activities:

1. Tutor for Research Methodology Course offered at HRI, February-May, 2022

Anjan Kumar Barik

Research Summary:

In this academic year, I worked on three projects under the supervision of Prof. Santosh Kumar Rai . Two projects namely "Search for a light Z' at LHC in a neutrinophilic U(1) model" and "Emergent new symmetry from the Higgs shadow", I did with Dr. Waleed Abdallah, Prof. Santosh Kumar Rai and Dr. Tousik Samui.

The third project was named "Determining the spin of exotic charged particles at future e^+ e^- collider", I did with Dr. Rafiqul Rahaman and Prof. Santosh Kumar Rai. Soon it will be in arXiv preprint .

Publications:

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,* PhysRevD. **104. 095031** (2021).

Preprints:

1. Waleed Abdallah, Anjan Kumar Barik, Santosh Kumar Rai and Tousik Samui *An emergent Z′ from the Higgs shadow*, arXiv:2109.07980 [hep-ph].
2. Anjan Kumar Barik, Rafiqul Rahaman and Santosh Kumar Rai *Determining the spin of exotic charged particles at future e^+ e^- collider* .(In Preparation)

Conference/Workshops Attended:

1. *Invisibles21 School*, Online, April 12th to May 7th, 2021.
2. *The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)* , Online, 23rd to 27th Aug 2021.
3. *VIRTUAL SCHOOL ON FLAVOR STRUCTURE OF THE STANDARD MODEL*, Online, 31th August to 12th September 2021.
4. *Iwate Collider School (ICS2022)*, Online, March 21 to 26, 2022.

Invited Lectures/Seminars:

1. *Search for a light Z′ at LHC in a neutrinophilic U(1) model*, The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021), Institute of Theoretical Physics, Chinese Academy of Sciences, 25 August 2021.

2. *Search for a light Z' at LHC in a neutrinophilic U(1) model*, Virtual School on Flavour Stucture of the Standard Model, IISc, IITK, IOP and IITKGP (All the organising institutes), 12th September 2021.

Nirnoy Basak

Research Summary:

I did a work with Pritam Chatterjee, Arijit Saha, Ruchi Saxena and Sumathi Rao on Weyl-semimetal superconductor heterojunction. We took an inversion symmetry broken Weyl-semimetal and make a heterostructure with a superconductor. We investigated the thermal response of the system by using Landuer-Buttiker formalism. Furthermore, we inserted a thin insulator in between the WSM and the superconductor to investigate how the barrier length and barrier potential affect the thermal response. Apart from thermal conductivity we calculate thermal power response and Figure of merit of the system to speculate if one can make a thermal device from it. We calculate the ratio between thermal conductivity and electrical conductivity to see if the Weidemann-Franz law of metal is being violated or not. We found that if we go further from the Weyl nodes the more the system acts as a metal.

I am currently doing another work with Arijit Kundu, Rohit Mukherjee and Ritajit Kundu from IIT Kanpur on electrical transport in a thin slab of Weyl Semimetal. We are calculating the electrical conductivity in presence of disorder using the standard Kubo formula of conductivity. By making the system to be a thin slab we are concentrating on the unusual surface states of Weyl Semimetal called Fermi arcs and investigating how they can contribute to the conductivity. We are also including a few bulk states in order to get the effect of surface and bulk correspondence. The existence of a Drude peak ensures the behaviour of the material as a metal at low frequency and we are investigating the behaviour of the peak with temperature. We are on the final part of our work and expect to write the paper soon.

I have started another work with Dibya Kanti Mukherjee from University of Indiana on Volkov-Pankratov states of Weyl Semimetal. We are now progressing on this work.

Preprints:

1. Ruchi Saxena, Nirnoy Basak, Pritam Chatterjee, Sumathi Rao and Arijit Saha, *Thermoelectric properties of inversion symmetry broken Weyl semimetal-Weyl superconductor hybrid junctions*, arXiv: 2202.10237 (2022).

Visits to other Institutes:

1. I visited IIT Kanpur on March, 2022.

Aparajita Bhattacharyya

Research Summary:

Quantum information and computation constitutes a broad area of research in Physics. The formulation of resource theory, within quantum information science, was initiated by the theory of entanglement. Since then, quantifying entanglement for pure and mixed states, with and without auxiliary systems, and the generation of maximal entanglement using global unitaries have been extensively studied in literature. Similarly, various aspects of the quantum theory of coherence have also been uncovered.

In my work, I have analyzed the optimal product basis for generating the maximum relative entropy of quantum coherence by an arbitrary gate on a two-qubit system. The optimal basis is not unique, and the high quantum coherence generating gates are also typically high entanglement generating ones and vice versa. However, the profile of the relative frequencies of Haar random unitaries generating different amounts of entanglement for a fixed amount of quantum coherence is different from the one in which the roles of entanglement and quantum coherence are reversed, although both follow the beta distribution.

Preprints:

1. Aparajita Bhattacharyya, Ahana Ghoshal, Ujjwal Sen, *Correlation between resource-generating powers of quantum gates*, arXiv:2110.13839.

Swapnil Bhowmick

Research Summary:

I have worked on some aspects of capacity of entanglement in the past months. Currently I am working on self testing using non linear Bell inequalities.

Conference/Workshops Attended:

1. QuEST 2022

Other Activities:

1. Statistical Mechanincs Tutorial January- May 2022

Debraj Bose

Research Summary:

I am studying the phonon and electron dynamics in the Holstein model using Von-Neumann equation. The initial conditions are generated using Langevin equation. The coupling constant, filling and temperatures are varied and the dynamics have been studied. The temperature enters the system from the initial condition. We are also trying to calculate the optical conductivity.

Preprints:

1. Sankha Subhra Bakshi, Debraj Bose, Arijit Dutta, Pinaki Majumdar, *Nonequilibrium dynamics of suppression, revival, and loss of charge order in a laser pumped electron-phonon system*, arXiv:2205.14710.

Conference/Workshops Attended:

1. Statphys-Kolkata XI (online) meeting, 21-25 March 2022.

Other Activities:

1. Tutor for Research Methodology, February-May 2022

Leela Ganesh Chandra Lakkaraju

Research Summary:

During last year, I have worked in two directions – 1) connecting non-Hermitian exceptional point with Hermitian factorization point and 2) design of novel quantum batteries using non-Hermitian chargers.

In the traditional quantum theory, one-dimensional quantum spin models possess a factorization surface where the ground states are fully separable and have vanishing bipartite as well as multipartite entanglement. We report that in the non-Hermitian counterpart of these models, these factorization surfaces either can predict the exceptional points where the unbroken-to-broken transition occurs or can guarantee the spectrum to be real, thereby suggesting a procedure to reveal the unbroken phase. We first analytically demonstrate it for the nearest-neighbor rotation-time-($\mathcal{RT}$) symmetric XY model with uniform and alternating transverse magnetic fields, referred to as the $iATXY$ model. Exact diagonalization techniques are then employed to establish this fact for the $\mathcal{RT}$-symmetric XYZ model with short- and long-range interactions as well as for the long-range $iATXY$ model. Moreover, we show that although the factorization surface prescribes the unbroken phase of the non-Hermitian model, the bipartite nearest-neighbor entanglement at the exceptional point is nonvanishing.

We propose a design of a quantum battery exploiting the non-Hermitian Hamiltonian as a charger. In particular, starting with the ground or the thermal state of the interacting (non-interacting) Hamiltonian as the battery, the charging of the battery is performed via $\mathcal{PT}$ - ($\mathcal{RT}$)-symmetric Hamiltonian to store or extract energy. We report that such a quenching with a non-Hermitian Hamiltonian leads to an enhanced power output compared to a battery with a Hermitian charger. We identify the region in the parameter space which provides the gain in performance. We also demonstrate that the improvements persist with the increase of system size both in the battery having $\mathcal{PT}$- and $\mathcal{RT}$-symmetric charger. In the $\mathcal{PT}$-symmetric case, although the anisotropy of the XY model does not help in the performance, we show that the XXZ model as a battery with a non-Hermitian charger performs better than that of the XX model having certain interaction strengths. We also exhibit that the advantage of non-Hermiticity remains valid even at finite temperatures in the initial states.

Publications:

1. Leela Ganesh Chandra Lakkaraju and Aditi Sen (De), *Detection of an unbroken phase of a non-Hermitian system via a Hermitian factorization surface,* Physical Review A 104, 052222 (2021).

2. Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Saptarshi Roy, Aditi Sen (De), *Distribution of entanglement with variable range interactions,* Physics Letters A 418, 127703 (2021).

Preprints:

1. Keshav Das Agarwal, Leela Ganesh Chandra Lakkaraju, Aditi Sen (De), *Predicting Critical Phases from Entanglement Dynamics in XXZ Alternating Chain*, arXiv:2112.12099.

2. Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen (De), *Quantum Battery with Ultracold Atoms: Bosons vs. Fermions* , arXiv:2109.06816.

3. Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Aditi Sen (De), *Quantum Battery with Non-Hermitian Charging*, arXiv:2203.09497.

Conference/Workshops Attended:

1. Asian Quantum Information Science Conference, Tokyo, Japan. September 1 – 4, 2021 - *Poster Presentation on Randomness Amplification under Simulated $\mathcal{PT}$-symmetric Evolution*.

2. Quantum Information Processing 2022, California, USA. March 7-11, 2022 - *Poster Presentation on Detection of an unbroken phase of a non-Hermitian system via a Hermitian factorization surface*.

Suman Jyoti De

Research Summary:

The research work that I have done during the academic year "2021-2022", is given below

The first part of my research work is related to the effect of interaction induced superconductivity on $2d$ Quantum Spin Hall(QSH) insulator. In presence of finite Zeeman field along the spin quantization axes the ground state of the QSH system do carry a finite persistent current. We have investigated the fate of this current when we introduce the superconductivity on the edge. Although the effective low energy model of QSH insulator is well described by the $1d$ gapeless Dirac theory but our findings are non-trivial due to the presence of finite bulk in realistic $2d$ system.

The second part of my research work is dedicated to study the effect of linear background potential on Graphene quantum hall system in presence of electron-electron interaction using hatree-fock(HF) approximation . It was found earlier that at charge neutral Graphene($\nu = 0$) there are plethora of symmetry broken states in the bulk which do have non-trivial conductance signature on the edge. In this scenario we have studied the case near the interface of $\nu = -1$ and $\nu = +1$ where both $\nu = \pm 1$ are spin polarized in presence of finite Zeeman field. As we tune the width of the interface we found that we have two region one with filled $\nu = 0$ region prefers to be spin canted(CAF) phase and in other the filled $\nu = 0$ region prefers to be spin ferromagnet(FM) phase. Going beyond HF approximation we found using time dependent hartree-fock(TDHF) calculation that in the spontaneously broken $U(1)$ spin-symmetry CAF phase there are two counter propagating gapeless Goldstone modes, which will have non-trivial transport signature.

I am also working in another project where we want to find the most general $\nu = 0$ phase diagram in Graphene Quantum Hall system in presence valley anistropic interactions and in presence of spin and valley Zeeman field.

Publications:

1. 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,* (Accepted in PRB).

Preprints:

1. Suman Jyoti De,Aabir Mukhopadhyay, Vivekananda Adak, Udit Khanna, Sumathi Rao, Sourin Das, *Boost driven spatially modulated superconducting order parameter at the edge of Quantum Spin Hall insulator* , (In preparation).

2. Suman Jyoti De,Sumathi Rao,Ganpathy Murthy,*Low energy excitations between two Graphene Quantum Hall Ferromagnet,* (In preparation).

Conference/Workshops Attended:

1. Participated in *Topological aspects of strong correlations and gauge theories* (online), ICTS, Bangalore, Sep 2021.

2. Participated in *Young investigators meet on quantum condensed matter theory* (YIMQCMT, online),NISER, Bhubaneswar, Nov 2021.

3. Participated in *APS Satellite March Meeting* (hybrid), ICTS, Bangalore, March 2022.

Visits to other Institutes:

1. Visiting ICTS from December 2021.

Shyamashish Dey

Research Summary:

In last academic year, I have done two projects. First of which is with Prof. Santosh Kumar Rai and Dr. Purusottam Ghosh, the title of this project is Confronting dark fermion with a doubly charged Higgs in the left-right symmetric model. In this model we considered the Left-Right symmetric standard model and extended it with dark sector vector-like fermionic doublets charged under both $SU(2)_L$ and $SU(2)_R$ and a discrete Z_2 symmetry, which satisfy current relic density, direct and indirect detection bounds of dark matter. We have also studied possible collider signatures of double charged higgs in presence of dark matter in context of this model. This paper in currently under review process for publication in European Physical Journal C.

My second work, which is under work in progress, is with Prof. Satosh Kumar Rai and Dr. Sarif Khan, we are studying possible collider features of the model considered in the paper Common origin of baryon asymmetry, dark matter and neutrino mass(arXiv:1812.06122v2).

Preprints:

1. Shyamashish Dey, Purusottam Ghosh, Santosh Kumar Rai, *Confronting a dark fermion with a doubly charged Higgs in the left-right symmetric model*, arXiv:2202.11638

Srijon Ghosh

Research Summary:

In the last one year, my reserach work was mainly focused on application based quantum thermodynamics, precisley on the quantum thermal devices. The modelling of such devices to acheive a better performance than its classical counterparts and the existing quantum mechanical models is of a great challenge. Towards this aim, going beyond the usual convention, I tried to model the thermal devices like battery, refrigertaor by using higher dimensional quantum systems.

I along with my collaborator, show that the average power output of a quantum battery based on a quantum interacting spin model, charged via a local magnetic field, can be enhanced with the increase of spin quantum number, thereby exhibiting dimensional advantage in quantum batteries. we demonstrate such increment in the power output when the initial state of the battery is prepared as the ground or canonical equilibrium state of the spin-j XY model and the bilinear-biquadratic spin-j Heisenberg chain (BBH) in presence of the transverse magnetic field and a weak value of interaction strength between the spins in the former model. Interestingly, we observe that in the case of the XY model, a tradeoff relation exists between the range of interactions in which the power increases and the dimension, while for the BBH model, the improvements depend on the phase in which the initial state is prepared. Moreover, we exhibit that such dimensional advantages persist even when the battery Hamiltonian has some defects or when the initial battery state is prepared at finite temperature.

On the other hand, we have also designed quantum refrigerators based on spin-j quantum XYZ and bilinear-biquadratic models with individual spins attached to bosonic thermal baths. By considering both local and global master equations, we illustrate an enhancement in the performance of the refrigerators with an increase in the spin dimension irrespective of the choice of the spin models. To assess the performance of the refrigerators, we introduce a distance-based measure to quantify the local temperature of a particle with arbitrary spin quantum number j. Interestingly, we find that the local temperature quantifier, defined via minimizing the distance between a spin-j thermal state and the evolved state of the spin-j particle in the steady state, coincides with the population-based definition of local temperature known in the literature for spin-$\frac{1}{2}$ particles. We further observe by computing local master equation that the quantum refrigerator consisting of a spin-$\frac{1}{2}$ and a spin-j particle can lead to a lower local temperature compared to a refrigerator with two identical spin-j particles following the XYZ interactions.

Publications:

1. Distribution of entanglement with variable range interactions, Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Saptarshi Roy, Aditi Sen(De), Phys. Lett. A **418**, 127703 (2021).

2. Fast charging of a quantum battery assisted by noise, Srijon Ghosh, Titas Chanda, Shiladitya Mal, and Aditi Sen(De), Phys. Rev. A **104**, 032207(2021).

3. Designing robust quantum refrigerators in disordered spin models, Tanoy Kanti Konar, Srijon Ghosh, Amit Kumar Pal, and Aditi Sen(De), Phys. Rev. A **105**, 022214(2022).

4. Dimensional enhancements in a quantum battery with imperfections, Srijon Ghosh and Aditi Sen(De), Phys. Rev. A **105**, 022628(2022).

Preprints:

1. Quantum Battery with Ultracold Atoms: Bosons vs. Fermions,
Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen(De), arXiv:2109.06816.

2. Circulating Genuine Multiparty Entanglement in Quantum Network,
Pritam Halder, Ratul Banerjee, Srijon Ghosh, Amit Kumar Pal, Aditi Sen(De), arXiv:2112.10122.

3. Beyond Qubits: Building Quantum Refrigerators in Higher Dimensions,
Tanoy Kanti Konar, Srijon Ghosh, Amit Kumar Pal, Aditi Sen(De), arXiv:2112.13765.

Priya Ghosh

Research Summary:

Quantum random walk, quantum version of classical random walk, has a standard deviation of the position distribution of the walker that is linear in the number of steps whereas position distribution of the walker is Gaussian for classical case. We analyze the response to incorporation of glassy disorder in the coin operation of a discrete-time quantum walk in one dimension. We find that the ballistic spread of the disorder-free quantum walker is inhibited by the insertion of disorder, for all the disorder distributions that we have chosen for our investigation, but remains faster than the dispersive spread of the classical random walker. Beyond this generic feature, there are significant differences between the responses to the different types of disorder. In particular, the falloff from ballistic spread can be slow (Gaussian) or fast (parabolic) for different disorders, when the strength of the disorder is still weak. The cases of slow response always pick up speed after a point of inflection at a mid-level disorder strength. The disorder distributions chosen for the study are Haar-uniform, spherical normal, circular, and two types of spherical Cauchy-Lorentz.

Preprints:

1. Priya Ghosh, Kornikar Sen, Ujjwal Sen, Response to glassy disorder in coin on spread of quantum walker, arXiv:2111.09827.

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, properties of quantum resources, Grover quantum search algorithm, weak measurements etc.

In the first work, we analyze the optimal product basis for generating the maximum relative entropy of quantum coherence by an arbitrary gate on a two-qubit system. The optimal basis is not unique, and the high quantum coherence generating gates are also typically high entanglement generating ones and vice versa. However, the profile of the relative frequencies of Haar random unitaries generating different amounts of entanglement for a fixed amount of quantum coherence is different from the one in which the roles of entanglement and quantum coherence are reversed, although both follow the beta distribution.

In another work, we establish a lower bound on the quantum coherence of an arbitrary quantum state, possibly nonpure and in arbitrary dimension, using a noncommutativity estimator of an arbitrary observable, where the estimator is 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.

In the other direction, we analyze the robustness of Grover's quantum search algorithm under a local unitary noise with memory effects. For a multi-qubit register of the Grover circuit, we model the noise as originating from arbitrary but fixed unitary rotations in an arbitrary number of qubits of the register. We derive a restricted set of unitaries for which the success probability of the algorithm remains invariant with respect to the "noise strength" in the multi-qubit register. Precisely, we show that only when the unitary operator is either of two specific Pauli matrices, the algorithm's success probability stays unchanged when increasing or decreasing the nontrivial number of noisy qubits. When the third Pauli matrix acts as the noise unitary on an even number of noise sites, the success probability at all times will be unaltered as long as the total number of noise sites is changed to another even number. Likewise happens when the total number of noise sites stays odd. This asymmetry between the Pauli operators stems from the inherent symmetry-breaking existing within the Grover circuit. We further show that the positions of the noisy sites are irrelevant in the case of any of the Pauli matrices as noise. Our results hold true irrespective of the presence of time-correlations in the noise. The results are exemplified in a situation where the noise is Markovian-correlated in time.

In the direction of weak measurement, we propose a thought experiment, similar to this phenomenon, with an interferometric setup, where a property (a component of polarization) of an object (photon) can be separated from the object itself and can simultaneously be amplified when it is already decoupled from its object. We further show that this setup can be used to dissociate two complementary properties, e.g. two

orthogonal components of polarization of a photon and identified with the grin and the snarl of a cat, from each other and one of them can be amplified while being detached from the other. Moreover, we extend the work to a noisy scenario, effected by a spin-orbit coupling -like additional interaction term in the Hamiltonian for the measurement process, with the object in this scenario being identified with a "confused Cheshire cat". We devise a gedanken experiment in which such a "confusion" can be successfully dissociated from the system, and we find that the dissociation helps in amplification of signals.

Publications:

1. Ahana Ghoshal, Sreetama Das, Amit Kumar Pal, Aditi Sen(De), and Ujjwal Sen, *Three qubits in less than three baths: Beyond two-body system-bath interactions in quantum refrigerators*, Phys. Rev. A **104**, 042208 (2021).

2. Ahana Ghoshal and Ujjwal Sen, *Heat current and entropy production rate in local non-Markovian quantum dynamics of global Markovian evolution*, Phys. Rev. A **105**, 022424 (2022).

3. Tanaya Ray, Ahana Ghoshal, Arun Kumar Pati, and Ujjwal Sen, *Estimating quantum coherence by noncommutativity of any observable and its incoherent part*, Accepted in PRA (2022).

Preprints:

1. Aparajita Bhattacharyya, Ahana Ghoshal, Ujjwal Sen, *Correlation between resource-generating capacities of quantum gates*, arXiv:2110.13839.

2. Sheikh Parvez Mandal, Ahana Ghoshal, Chirag Srivastava, Ujjwal Sen, *Invariance of success probability in Grover quantum search under local noise with memory*, arXiv:2112.02640.

3. Soham Sau, Ahana Ghoshal, Debmalya Das, Ujjwal Sen, *Isolating noise and amplifying signal with quantum Cheshire cat*, arXiv:2203.00254.

Sachin Grover

Research Summary:

In the academic year 2021-2022, various aspects of two-dimensional conformal field theory (CFT) were explored in the following directions.

Fractional level $su(2)_k$ CFT are an interesting class of theories with applications in three-dimensional gravity which we are exploring with Dileep Jatkar and Arindam Bhattacharjee. In particular the recently found dS/CFT correspondence between Einstein gravity in dS_3 and $su(2)_k$ CFT, where the level is pure imaginary. With Dileep Jatkar we have closely looked at the modules of the highest weight representations of the affine Lie algebra. We have found interesting results which we will report shortly. A draft is under preparation. We are using results from our analysis of real fractional level $su(2)_k$ CFTs to better understand the dS/CFT correspondence.

With Dileep Jatkar, Md Abhishek and Kajal Singh we continue to look for the correspondence between certain special non-unitary and unitary CFT viewed from the context of four-dimensional SCFT's map to the two-dimensional CFTs. We will report our findings in the near future.

In another collaboration with Dileep Jatkar and Subramanya Hegde, we studied some single character CFTs and also, defects in CFT. To this end we studied lie algebraic root and weight lattices and corresponding lattice vertex operator algebra (LVOA).

Conference/Workshops Attended:

1. *Trends in String Theory & Related Topics (Online)*, HRI Prayagraj, U.P., India, October 2021.

2. *INYAS Prayojan workshop, (Online) 23rd-24th April 2022*

Other Activities:

1. Teaching Assistant for Quantum Field Theory-2. *Instructor: Prof. Anshuman Maharana*. February-June 2022.

2. Student Representative to HBNI for the term January 2020-December 2021.

Rivu Gupta

Research Summary:

In the previous year, my research was primarily focused on continuous variable quantum information theory, with particular emphasis on the theory of quantum metrology, continuous variable quantum communication protocols and quantum correlations. Besides this, I also worked on the theory of state transformation and catalysis in the paradigm of random quantum states. In this respect, me and my collaborators studied the performance of target detection in the presence of noisy environment and imperfect apparatus. Furthermore, we investigated the catalytic properties of random quantum states with respect to the state transformation protocol. Finally, we worked on the dense coding and teleportation protocols designed for continuous variable systems, both in the presence and absence of system disorders. Most of the research was based on the framework of quantum optics with the help of multimode entangled states of photons.

Quantum illumination is a method to detect a weakly reflecting target submerged in a thermal background. Entangled states like two-mode squeezed vacuum states are known to give quantum advantage in the illumination protocol. In the first work, we studied the performance of non-Gaussian photon-added and subtracted states as probes for the single shot quantum illumination both in the presence and absence of noise. Based on the difference between the Chernoff bounds obtained with the coherent state and the non-Gaussian state having equal signal strengths, whose positive values are referred to as a quantum advantage in illumination, we classified the performance of non-Gaussian states, when photons are added or subtracted in a single mode or in both the modes. We highlighted the hierarchy among Gaussian and non-Gaussian states obtained via this method, which is compatible with correlations per unit signal strength. Interestingly, such hierarchy is different when comparisons are made only using the Chernoff bounds. The entire analysis was performed in presence of different noisy apparatus like faulty twin-beam generator, imperfect photon addition or subtraction as well as with noisy non-Gaussian probe states.

In the quantum illumination protocol, the target is typically modelled by a partially reflecting beam splitter. In our second work, we analyzed the performance of quantum illumination when the target absorbs part of the light that falls on it, thereby making the scenario more realistic. We presented an optical setup that modeled a target with these characteristics and explored its detectibility in the quantum domain in terms of the Chernoff bound. For an idler-free setup, we used the coherent state for illumination while the two mode squeezed vacuum state was employed in the signal-idler scheme. In both the cases, we reported an absorption-induced enhancement of the detection efficiency indicated by a lowering of the Chernoff bound with increasing amounts of absorption. Interestingly, we showed that in the presence of absorption, a more intense thermal background can lead to target detection with enhanced efficiency. Moreover, we observed that the quantum advantage persists even for finite amounts of absorption. However, we found that the quantum advantage offered by the two mode squeezed Gaussian state decreases monotonically with absorption, and becomes vanishingly small in the high absorption regime. We also demonstrated the optimality of both the coherent and the two mode squeezed vacuum states in their

respective setups (idler-free and signal-idler) in the limit of low reflectivity and absorption.

Publications:

1. Rivu Gupta, Shashank Gupta, Shiladitya Mal, and Aditi Sen(De), *Constructive feedback of non-Markovianity on resources in random quantum states*
   Physical Review A **105**, 012424 (2022)

Preprints:

1. Rivu Gupta, Saptarshi Roy, Tamoghna Das, Aditi Sen De, *Quantum illumination with noisy probes: Conditional advantages of non-Gaussianity*
   arXiv:2107.02774

2. Rivu Gupta, Saptarshi Roy, Tamoghna Das, Aditi Sen De, *Quantum illumination with a light absorbing target*
   arXiv:2111.01069

3. Rivu Gupta, Arghya Maity, Shiladitya Mal, Aditi Sen De, *Statistics of Entanglement Transformation with Hierarchies among Catalysts*
   arXiv:2202.01540

4. Ayan Patra, Rivu Gupta, Saptarshi Roy, Aditi Sen De, *Significance of Fidelity Deviation in Continuous Variable Teleportation*
   arXiv:2203.06684

5. Ayan Patra, Rivu Gupta, Saptarshi Roy, Tamoghna Das, Aditi Sen De *Quantum Dense Coding Network using Multimode Squeezed States of Light*
   arXiv:2204.14147

Conference/Workshops Attended:

1. Quantum Information Processing 2022, California, USA. March 7-11, 2022 - *Poster Presentation on Quantum Illumination with imperfections*

Pritam Halder

Research Summary:

In the last one year, my research work have been mainly focused in the direction of designing quantum network. The entire development of a quantum network demands a systematic creation and detection of multipartite entangled states which is one of the current challenges in quantum information science. We proposed a measurement-based protocol for producing multipartite entangled states which we call "multipartite entanglement inflation". The basic unit of operation was weak entangling measurement on two parties to create entanglement between more parties starting from an entangled state with a lesser number of parties and auxiliary systems. In the context of inflating bipartite entanglement to more number of parties, surprisingly, maximally entangled states as inputs turned out to be worse than that of the nonmaximally entangled states, Haar uniformly generated pure states having a moderate amount of entanglement and the Werner state with a certain threshold noise. We also observed that for Haar uniformly generated pure states, unentangled auxiliary systems are sometimes more advantageous than the protocol with multiple copies of the initial entangled states.

On the other hand, I am also working on the creation of genuine multipartite entangled states by unitary dynamics with quantum gates.

Publications:

1. Pritam Halder, Shiladitya Mal, Aditi Sen(De), *Measurement-based multipartite entanglement inflation*, Phys. Rev. A **104**, 062412 (2021).

Preprints:

1. Pritam Halder, Ratul Banerjee, Srijon Ghosh, Amit Kumar Pal, Aditi Sen(De), *Circulating Genuine Multiparty Entanglement in Quantum Network*, arXiv: 2112.10122.

2. Pritam Halder, Ratul Banerjee, Shiladitya Mal, Aditi Sen(De), *Limits of network nonlocality probed by time-like separated observers*, arXiv: 2203.05353.

Tanoy Kanti Konar

Research Summary:

During last year, I have mainly worked in two directions, (1) implementation of quantum refrigeartor in spin system. (2) design of a quantum battery with indistinguishable particles. Let us discuss them in detail,

We explore a small quantum refrigerator in which the working substance is made of paradigmatic nearest-neighbor quantum spin models, the XYZ and the XY model with Dzyaloshinskii-Moriya interactions, consisting of two and three spins, each of which is in contact with a bosonic bath. We identify a specific range of interaction strengths which can be tuned appropriately to ensure a cooling of the selected spin in terms of its local temperature in the weak-coupling limit. Moreover, we report that in this domain, when one of the interaction strengths is disordered, the performance of the thermal machine operating as a refrigerator remains almost unchanged instead of degrading, thereby establishing the flexibility of this device. However, to obtain a significant amount of cooling via ordered as well as disordered spin models, we observe that one has to go beyond the weak-coupling limit and compute the figures of merit by using global master equations.

We design a quantum battery made up of bosons or fermions in an ultracold atom setup, described by Fermi-Hubbard (FH) and Bose-Hubbard (BH) models respectively. We compare the performance of bosons as well as fermions and check which can act more efficiently as a quantum battery for a given on-site interaction and temperature of the initial state. We report that when the initial battery state is in the ground state, fermions outperform bosons in a certain configuration over a large range of on-site interactions which are shown analytically for a smaller number of lattice sites and numerically for a considerable number of sites. Bosons take the lead when the temperature is comparatively high in the initial state for a longer range of on-site interaction. We perform the study of a number of up and down fermions as well as the number of bosons per site to find the optimal filling factor for maximizing the power of the battery. We also introduce disorder in both on-site and hopping parameters and demonstrate that the maximum power is robust against impurities. Moreover, we identify a range of tuning parameters in the fermionic as well as bosonic systems where the disorder-enhanced power is observed.

Publications:

1. Tanoy Kanti Konar, Srijon Ghosh, Amit Kumar Pal, Aditi Sen(De) *Designing robust quantum refrigerators in disordered spin models,* Phys. Rev. A 105, 022214 (2022)

Preprints:

1. Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Srijon Ghosh, Aditi Sen(De), *Quantum Battery with Ultracold Atoms: Bosons vs. Fermions,* arXiv:2109.06816.

2. Tanoy Kanti Konar, Srijon Ghosh, Amit Kumar Pal, Aditi Sen(De), *Beyond Qubits: Building Quantum Refrigerators in Higher Dimensions,* arXiv:2112.13765.

3. Tanoy Kanti Konar, Leela Ganesh Chandra Lakkaraju, Aditi Sen(De), *Quantum Battery with Non-Hermitian Charging*, arXiv:2203.09497.

Conference/Workshops Attended:

1. *QTD 2021*, University of Geneva, Switzerland, October, 2021.
2. *TIQuR 2021*, University of Exeter, UK, July, 2021

Susovan Maity

Research Summary:

For general relativistic black hole accretion in the Kerr metric, linear perturbation of the axially symmetric matter flow leads to the emergence of black hole like acoustic spacetime. For different parameters characterizing the flow, the characteristic of the phase portrait of flow can be constructed. For such flow, the fluid equations may be perturbed and the corresponding emergent spacetime can be obtained. The propagation of first order perturbation in the emergent metric of the accreting fluid corresponding to a particular flow line can be analyzed in a way similar to the propagation of light as analyzed in a spacetime using causal structure. We present the Penrose Carter formalism to analyze the emergent metric and the aforementioned propagation. Certain special flows with parameters at the boundary of the parameter space are also studied in this context. Analogue spacetime corresponding to accretion flow with shock is shown to be endowed with one white hole like sonic horizon flanked by two black hole like acoustic horizons. The problem of separation of two regions in the Penrose Carter diagram of this flow, and thus the inconclusive presence of white hole is solved by considering the extremely thin but finite width of shock. The shock is established to be the acoustic white hole. The resemblance of such a special kind of space-time with a wormhole is established, where two different parts of certain manifold is joined by this black hole white hole pair.

Preprints:

1. Fernandes, Karan., Maity, Susovan., & Das, Tapas K., *Dynamical analogue spacetimes in non-relativistic flows*, Physical Review D, **To Appear**, `Manuscript Number DP12655`, (**2022**).

2. Fernandes, Karan., Maity, Susovan., & Das, Tapas K., *Dynamical spacetimes from nonlinear perturbations*, Physical Review Letters, **Under Review**, `Manuscript Number LP17166`, (**2022**).

3. Maity, Susovan.,Shaikh, Md. Arif., Tarafdar, Pratik., & Das, Tapas K., *Carter-Penrose diagrams for emergent spacetime in axisymmetrically accreting black hole systems*, Physical Review D, **Under Review**, `Manuscript Number DS13186`, (**2022**).

Conference/Workshops Attended:

1. Annual Meeting of Astronomical Society of India (ASI) 2022

Sourav Mal

Research Summary:

In this academic year I am working on the problem of designing new permanent magnets without rare-earth elements. I have trained machine learning models on a dataset of bulk magnetic materials, taken from publicly available databases, for different classification and regression tasks on formation energy, magnetic moment and magnetocrystalline anisotropy energy to screen stable materials with high moment and high anisotropy.

Brij Mohan

Research Summary:

In the the academic year "2021-22", which is defined from 1st April 2021 to 31st March 2022, I mainly worked on quantum speed limit for information, coherence and observable.

The quantum speed limit indicates the maximal evolution speed of the quantum system. In this work, we determine speed limits on the informational measures, namely the von Neumann entropy, maximal information, and coherence of quantum systems evolving under dynamical processes. These speed limits ascertain the fundamental limitations on the evolution time required by the quantum systems for the changes in their informational measures. Erasing of quantum information to reset the memory for future use is crucial for quantum computing devices. We use the speed limit on the maximal information to obtain the minimum time required to erase the information of quantum systems via some quantum processes of interest.

In the Schrödinger picture, the state of a quantum system evolves in time and the quantum speed limit describes how fast the state of a quantum system evolves from an initial state to a final state. However, in the Heisenberg picture the observable evolves in time instead of the state vector. Therefore, it is natural to ask how fast an observable evolves in time. This can impose a fundamental bound on the evolution time of the expectation value of quantum mechanical observables. We obtain the quantum speed limit time-bound for observable for closed systems, open quantum systems and arbitrary dynamics. Furthermore, we discuss various applications of these bounds. Our results can have several applications ranging from setting the speed limit for operator growth, correlation growth, quantum thermal machines, quantum control and many body physics.

Publications:

1. Brij Mohan and Arun K. Pati, *Reverse quantum speed limit: How slowly a quantum battery can discharge*, Phys. Rev. A **104**, 042209 (2021).

Preprints:

1. Brij Mohan, Siddhartha Das, and Arun Kumar Pati, *Quantum speed limits for information and coherence*, arXiv:2110.13193.

2. Brij Mohan and Arun Kumar Pati, *Quantum speed limits for Observable*, arXiv:2112.13789.

Conference/Workshops Attended:

1. *ICQIF-2022*, India, 14 - 24th February, 2022 (Online). (Presented a talk on 'Quantum speed limits for information and coherence')

Academic recognition/Awards:

1. INFOSYS scholarship, 2021-22

Tanmoy Mondal

Research Summary:

In the last academic year, I have studied the effect of frustration on on magnon dynamics through Hubbard model in kagome lattice using the Langevin equation.

I have investigated the effect of frustration on equilibrium dynamics of magnetic moments of the Hubbard model on the Kagome lattice. I have used the Langevin scheme to study the dynamics after recasting the interaction term of Hubbard model in term of auxiliary vector field. I have benchmarked our result with Heisenberg spin Kagome lattice for strong coupling. My main focus have been in the moderate and weak coupling regime. I have looked into the effects of increasing amplitude fluctuation of the magnetic modes with coupling strength on the static and dynamical properties of the system. I have observed the static and dynamical structure factor to track these effects. I have found that the presence of a cross over coupling strength below which there is a drastic changes in the dynamical structure factor of the system from two peak behaviour to one peak behaviour. My result will help to understand the properties of the growing number of kagome materials.

I plane to study the above mentioned frustrated model more meticulously also look into the effects of external probing in the systems.

Conference/Workshops Attended:

1. STATPHYS KOLKATA XI (ONLINE), arranged by DPS, IISER Kolkata .

Kalyanbrata Pal

Research Summary:

Matter accretion onto compact astrophysical objects (BH, Neutron Stars etc.) is a non-linear process. These nonlinear behaviors can be observed in their observational data. At present I am trying to explore these features by studying the corresponding light curve produced by the multi-wavelength photons emergering out as a consequence of accretion phenomena. Here I am using different techniques such as delay embedding technique with computation of correlation dimension(CD), wavelet analysis etc. I am also studying Self-organized Criticality (SOC) phenomena for accretion disk.

Conference/Workshops Attended:

1. Workshop : Online Workshop On High Performance Computing For Astrophysics And Astronomy. Conducted by SKA-India and IIT Kharagpur, September 2021.

Visits to other Institutes:

1. Physics Department, Ramakrishna Mission Vivekananda Centenary College, Rahara, West Bengal, India. March 2022.

Vivek Pandey

Research Summary:

In the last academic year 2021-2022, I have mainly studied quantum speed limit and quantum thermodynamics in detail. Along with this, I have also studied indefinite causal order, Page-Wootters formalism and continuous variable quantum information in detail.

Conference/Workshops Attended:

1. *Quantizing Time 2021*, Perimeter Institute, Canada, 14-18 June, 2021.
2. *Vienna Quantum Foundation Conference 2021*, IQOQI Vienna, 7-10 September, 2021.

Other Activities:

1. Tutor MM-1 course, October-January, 2022.

Ayan Patra

Research Summary:

In academic year $2021-22$, I have worked on three projects – (1) constructing nonlinear witness for non-absolutely separable states with possible loophole analysis; (2) quantification of non-locality in orthogonal product ensembles using coherence-based measures; (3) significance of fidelity deviation in continuous variable quantum teleportation. I will discuss the first one which has already been completed. The other two are ongoing.

Entangled states are undoubtedly an integral part of various quantum information processing tasks. On the other hand, absolutely separable states which cannot be made entangled under any global unitary operations are useless from the resource theoretic perspective, and hence identifying non-absolutely separable states can be an important issue for designing quantum technologies.

In this project, we find that nonlinear witness operators provide significant improvements in detecting non-absolutely separable states over their linear analogs, by invoking examples of states in various dimensions. We also address the problem of closing detection loophole and find critical efficiency of detectors above which no fake detection of non-absolutely separable (non-absolutely positive partial transposed) states is possible.

Publications:

1. Ayan Patra, Shiladitya Mal, and Aditi Sen(De), *Efficient nonlinear witnessing of non–absolutely separable states with lossy detectors,* Phys. Rev. A 104, 032427 (2021).

Preprints:

1. Ayan Patra, Shiladitya Mal, and Aditi Sen(De), *Coherence measure of ensembles with nonlocality without entanglement,* arXiv:2112.04430v1 (2021).

2. Ayan Patra, Rivu Gupta, Saptarshi Roy, and Aditi Sen(De), *Significance of Fidelity Deviation in Continuous Variable Teleportation,* arXiv:2203.06684v1 (2022).

Deepak Raikwal

Research Summary:

In the last one year span, I worked on many problems in neutrino physics, Which are in long-baseline neutrino experiments and INO. I combined different neutrino experiments to understand the BSM physics and standard oscillation physics in the neutrino sector.

I worked on mass hierarchy determination in INO, JUNO and T2HK and combined the data from all three experiments. The internal review committee of INO has reviewed this work. Now, we are preparing it for a journal.
I also worked on the Earth tomography aspect of the INO detector. I have modelled and analysed many scenarios, which are realistic and more accurate to the earth model. We have generated the tomography sensitivity limits for INO. This work is also in preparation for internal review.

I also worked on LIV study in INO, DUNE and T2HK. We have generated the primary results and working on the compilation of results for the internal review committee.

Preprints:

1. Sandhya Choubey, Monojit Ghosh, Deepak Raikwal, Determining Neutrino Mass Ordering with INO, JUNO and T2HK (in preparation)

Conference/Workshops Attended:

1. Poster Presented - Determining Neutrino Mass Ordering with INO, JUNO and T2HK in Neutrino 2022, XXX international conference on neutrino physics and astro physics, May 30 - June 4 2022.

Subhojit Roy

Research Summary:

During the academic year 2021-'22, I circulated one research paper on the arXiv (which subsequently got accepted in the Journal of High Energy Physics (JHEP)) where a detailed stock is taken of the viability of a strong First-Order ElectroWeak Phase Transition (FOEWPT) in the Z_3-NMSSM as a prerequisite to a successful Baryogenesis in the early Universe, in the light of the latest relevant results from the Large Hadron Collider (LHC) and various Dark Matter (DM) experiments. The work further studies the prospects of detecting the Stochastic Gravitational Waves (GWs), originating from a FOEWPT, at various (proposed) future experiments. This work was done in collaboration with Arindam Chatterjee and AseshKrishna Datta.

In a subsequent work with AseshKrishna Datta, Monoranjan Guchait and Arnab Roy, I am working in a project on the searches of lighter electroweakinos from heavy top squarks decays at the LHC. Here, we make use of conventional cut-based approach as well as machine learning techniques using ROOT-TMVA to distinguish the signal from the background. To check the current LHC constraints I recast one of the recent ATLAS experimental paper on the constraint of the top squark mass with the help of the popular package CheckMATE.

In another collaboration with Purushottam Ghosh and Tathagata Ghosh, I am working on a model, known as type-II Seesaw model extended with a complex singlet DM. The type-II Seesaw model has a few blind spots in the searches of doubly charged Higgs boson at the LHC. We focus on those regions and connect the parameter space to the upcoming GWs and DM experimentes to probe the same experimentally.

Another project from last year with Waleed Abdallah and AseshKrishna Datta has subsequently been published in JHEP.

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; JHEP 04 (2021) 122.

Preprints:

1. Subhojit Roy with Arindam Chatterjee and AseshKrishna Datta, *Electroweak Phase Transition in the Z_3-invariant NMSSM Implications of LHC and Dark matter Searches and Prospects of Detecting the Gravitational Waves*, arXiv:2202.12476 [hep-ph].

Conference/Workshops Attended:

1. *New observational windows on the high-scale origin of matter-antimatter asymmetry, Kavli IPMU (online), January, 2022.*

2. *Hunting SUSY @ HL-LHC, ICTS-TIFR (online) November 2021.*

3. *Anomalies 2021, IIT-Hyderabad, India (online), November, 2021.*

4. *Higgs 2021, Stony Brook University, Simons Center for Geometry and Physics (online), October 2021.*

5. *LHCP 2021, CERN and IUPAP (online),June 2021.*

6. *Les Houches 2021 Summer School on Dark Matter (online), August 2021.*

7. *SUSY 2021, Beijing, China (online) August 2021.*

8. *Gravitational Waves Probes of Physics Beyond Standard Model workshop, (Online) July, 2021.*

Visits to other Institutes:

1. A month-long visit (March-2022) to Dept. of High Energy Physics, Tata Institute of Fundamental Research, Mumbai, INDIA

Invited Lectures/Seminars:

1. *A relatively light bino-like dark matter in the Z_3-symmetric NMSSM and its implications for the LHC*, SUSY 2021, August, 2021 (online).

2. *Electroweak Phase Transition in the Z_3-invariant NMSSM Implications of LHC and Dark matter Searches and Prospects of Detecting the Gravitational Waves*, DTP, TIFR, March, 2022.

Other Activities:

1. I was a teaching assistant of the Quantun Field Theory-I course under the instructor Prof. Anirban Basu.

Kornikar Sen

Research Summary:

Quantum coherence quantifies the amount of superposition in a quantum system, and is the reason and resource behind several phenomena and technologies. It depends on the natural basis in which the quantum state of the system is expressed, which in turn hinges on the physical set-up being analyzed and utilized. While quantum coherence has hitherto been conceptualized by employing different categories of complete bases, there do exist interesting physical situations, where the natural basis is an incomplete one, an example being an interferometric set-up with the observer controlling only a certain fraction of all the slits. We have introduced a quantification of quantum coherence with respect to an arbitrary incomplete basis for general quantum states, and developed the corresponding resource theory, identifying the free states and operations. Moreover, we have obtained a complementarity relation between the so-defined quantum coherence and the which-path information in an interferometric set-up with several slits, of which only a section is in control of the observer or is accessible to her. This therefore provided us with another face of the wave-particle duality in quantum systems, demonstrating that the complementarity is functional in more general set-ups than thus far considered.

We have analyzed the response to incorporation of glassy disorder in the coin operation of a discrete-time quantum walk in one dimension. We have found that the ballistic spread of the disorder-free quantum walker was inhibited by the insertion of disorder, for all the disorder distributions that we had chosen for our investigation, but remained faster than the dispersive spread of the classical random walker. Beyond this generic feature, there were significant differences between the responses to the different types of disorder. In particular, the falloff from ballistic spread could be slow (Gaussian) or fast (parabolic) for different disorders, when the strength of the disorder was still weak. The cases of slow response always picked up speed after a point of inflection at a mid-level disorder strength. The disorder distributions chosen for the study were Haar-uniform, spherical normal, circular, and two types of spherical Cauchy-Lorentz.

We have investigated the response to noise, in the form of glassy disorder present in circuit elements, in the success probability of the quantum phase estimation algorithm, a subroutine used to determine the eigenvalue - a phase - corresponding to an eigenvector of a unitary gate. We have considered three types of disorder distributions: Haar-uniform with a circular finite cut-off, Haar-uniform with a squeezed cut-off, and spherical normal. We have examined the behavior of the probability of estimating the correct phase in response to the inflicted disorder. There was generally a depreciation of the quenched averaged success probability in response to the disorder incorporation. Even in the presence of the disorder, increasing the number of auxiliary qubits helped to get a better precision of the phase, albeit to a lesser extent than that in the clean case. We have found a concave to convex transition in the dependence of probability on the degree of disorder when the distribution at hand was Haar-uniform, and a log-log dependence was witnessed between the strength of disorder at the point of inflection and the number of auxiliary qubits used.

The concept of entanglement witnesses form a useful technique to detect entangle-

ment in realistic quantum devices. Measurement-device-independent nonlinear entanglement witnesses (MDI-NEWs) are a kind of entanglement witnesses which eliminate dependence on the correct alignments of measurement devices for guaranteeing the existence of entanglement and also detect more entangled states than their linear counterparts. While this method guarantees entanglement independent of measurement alignments, they are still prone to serving wrong results due to other loopholes. We have studied the response of MDI-NEWs to two categories of faults occurring in experiments. In the first category, the detection loophole, characterized by lost and additional events of outcomes of measurements, have been investigated, and bounds which guarantee entanglement have been obtained in terms of the efficiency of measurement being performed. In the second category, we have studied noise associated with the sets of additional quantum inputs required in MDI-NEW scenarios. In this case, a type of noise has been identified which still allows the MDI-NEWs to guarantee entanglement. We have also showed that MDI-NEWs were less or equally robust in comparison to their linear counterparts under the same noise in additional quantum inputs, although the former group detects a larger volume of entangled states in the noiseless scenario than their linear cousins.

A pack of quantum measurements that cannot be measured simultaneously is said to form a set of incompatible measurements. Every set of incompatible measurements have advantage over the compatible ones in a quantum state discrimination task where one prepares a state from an ensemble and sends it to another party, and the latter tries to detect the state using available measurements. We have considered the local quantum state discrimination task where a sender prepares a bipartite state and sends the subsystems to two receivers. The receivers try to detect the sent state using locally incompatible measurements. We have analyzed the ratio of the probability of successfully guessing the state using incompatible measurements and the maximum probability of successfully guessing the state using compatible measurements. We have found that this ratio is upper bounded by a simple function of robustnesses of incompatibilities of the local measurements. Interestingly, corresponding to every pair of sets of incompatible measurements, there exists at least one local state discrimination task where this bound can be achieved. We have argued that the optimal local quantum state discrimination task does not present any "nonlocality", where the term have been used in the sense of a difference between the ratios, of probabilities of successful detection via incompatible and compatible measurements, in global and local state discriminations. The results have been generalized to the regime of multipartite local quantum state distinguishing tasks.

Publications:

1. Kornikar Sen and Ujjwal Sen, *Local passivity and entanglement in shared quantum batteries*, Phys. Rev. A **104**, L030402 (2021).

Preprints:

1. Ingita Banerjee, Kornikar Sen, Chirag Srivastava, Ujjwal Sen, *Quantum coherence with incomplete set of pointers and corresponding wave-particle duality* , arXiv:2108.05849.

2. Priya Ghosh, Kornikar Sen, Ujjwal Sen, *Response to glassy disorder in coin on spread of quantum walker*, arXiv:2111.09827.

3. Soubhadra Maiti, Kornikar Sen, Ujjwal Sen, *Quantum phase estimation in presence of glassy disorder*, arXiv:2112.04411.

4. Kornikar Sen, Chirag Srivastava, Ujjwal Sen, *Closing loopholes of measurement-device-independent nonlinear entanglement witnesses* , arXiv:2203.07192.

5. Kornikar Sen, Ujjwal Sen, *Incompatibility of local measurements provide advantage in local quantum state discrimination* , arXiv:2204.10948.

Other Activities:

1. Tutoriship in Electronics.

Divyansh Shrimali

Research Summary:

Extending the work based on determining spectra of given quantum system, a protocol was proposed for a general interacting composite system with the aim of extracting subsystems closest possible local Hamiltonian. The protocol is based on optimization on a Hilbert Schmidt space of operators and further through this technique a witness for the presence of nonlocal term of any bipartite Hamiltonian is also proposed.

Continuing from previous years project which undertook the study of scrambling for information as a no go result 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. This was further verified by utilizing loshmidt echo as a viable ansatz and realizing its analogous nature to OTOC(Out of Time ordered Correlator), the rate of spread of scrambling was also studied.

Another project undertaken was motivated from information theoretic counterpart of thermodynamic specific heat capacity which we term as Entanglement capacity. Study of rate of capacity for general two qubit hamiltonian and arbitrary dimensional self Inverse Hamiltonian was studied. Further more, through Entanglement capacity, a bound on rate of entanglement and its speed limit was evaluated. The definition of capacity for pure state was further generalized to mixed state case. Finally speed limit for various quantum correlations in bipartite quantum systems were also evaluated.

Preprints:

1. Divyansh Shrimali, Vivek Pandey, Swapnil Bhowmick and Arun Kumar Pati, *Capacity of Entanglement for Non-Local Hamiltonians* (In preparation)
2. Vivek Pandey, Divyansh Shrimali, Brij Mohan, Siddhartha Das and Arun Kumar Pati, *Speed limits on correlations in bipartite quantum systems* (In preparation)
3. Divyansh Shrimali, Sohail, Ujjwal Sen and Arun Kumar Pati, *Witnessing Non-Local Hamiltonians* (In preparation)

Conference/Workshops Attended:

1. Summer School on Quantum Information and Quantum Technology (QIQT - 2022)

Other Activities:

1. Internal arxiv flashbacks arranged on weekly basis.

Kajal Singh

Research Summary:

During the academic year 2021-2022, I mainly studied the explicit construction of KKLT vacua. 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 year we focused on developing algorithm for finding perturbatively flat vacua in KKLT construction. In later part of year, we started working on the combined distributions of cosmological constant and gravitino mass in 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 axion physics in the landscape*, JHEP 08 (2021) 059 .

2. Igor Broeckel, Michele Cicoli, Anshuman Maharana, Kajal Singh, Kuver Sinha, *On the Search for Low W_0*, Fortschritte der Physik 70 (2022) 06, 2200002.

Conference/Workshops Attended:

1. *XIV International Workshop on Interconnections between Particle Physics and Cosmology (Online)*, University of Oklahoma, USA, May 2021.

2. *Trends in String Theory & Related Topics (Online)*, HRI Prayagraj, U.P., India, October 2021.

Invited Lectures/Seminars:

1. "*Statistics of Low Energy Physics in the String Landscape*", Conference Talk, Trends in String Theory & Related Topics, HRI Prayagraj, U.P., India, October 2021.

2. "*Moduli Stabilisation and Statistics of Low Energy Physics in String Landscape*", HEP Seminar, Department of Physics and Astronomy, University of Oklahoma, USA, October 2021.

3. "*Exploring Aspects of the String Landscape*", String Pheno Seminar Series, Jointly organized by theoretical physics groups from all over the world, January 2022.

Other Activities:

1. Tutored General Theory of Relativity, Instructor- Prof. Dileep Jatkar. (Aug-Dec 2021)
2. Tutored Quantum Field Theory-II, Instructor- Prof. Anshuman Maharana. (Jan-Jun 2022)

Sohail

Research Summary:

In the academic year 2021-2020, I have worked on convolution algebra of superoperators and nonseparability witnesses for quantum operations, extraction of product and higher moment weak values and monogamy inequality for entanglement. In the work "convolution algebra of superoperators and nonseparability witnesses for quantum operations ", we define a product between quantum superoperators which is preserved under the Choi-Jamiołkowski-Kraus-Sudarshan channel-state isomorphism. We then identify the product as the convolution on the space of superoperators, with respect to which the channel-state duality is also an algebra isomorphism. We find that any witness operator for detecting nonseparability of quantum operations on separated parties can be written entirely within the space of superoperators with the help of the convolution product. The brief overview of the work " extraction of product and higher moment weak values" is the following, Weak measurements introduced by Aharonov, Albert and Vaidman (AAV) can provide informations about the system with minimal back action. Weak values of product observables (commuting) or higher moments of an observable are informationally important in the sense that they are useful to resolve some paradoxes,realize strange quantum effects, reconstruct density matrices, etc. In this work, we show that it is possible to access the higher moment weak values of an observable using weak values of that observable with pairwise orthogonal post-selections. Although the higher moment weak values of an observable are inaccessible with Gaussian pointer states, our method allows any pointer state. We have calculated product weak values in a bipartite system for any given pure and mixed pre selected states. Such product weak values can be obtained using only the measurements of local weak values (which are defined as single system weak values in a multi-partite system). As an application, we use higher moment weak values and product weak values to reconstruct unknown quantum states of single and bipartite systems, respectively. Further, we give a necessary separability criteria for finite dimensional systems using product weak values and certain class of entangled states violate this inequality by cleverly choosing the product observables and the post selections. By such choices, positive partial transpose (PPT) criteria can be achieved for these classes of entangled states. Robustness of our method which occurs due to inappropriate choices of quantum observables and noisy post-selections is also discussed here. Our method can easily be generalized to the multi-partite systems. In the work "monogamy inequality for entanglement", we prove a tight monogamy relation in the product form for the concurrence of pure tripartite systems. We illustrate our relation with several examples,including the canonical three qubit states, where this monogamy relation is saturated.

Publications:

1. Sohail and Ujjwal Sen, *Convolution algebra of superoperators and nonseparability witnesses for quantum operations,* Accepted at Journal of Physics A.

Preprints:

1. Sahil, Sohail, Subhrajit Modak, Sibasish Ghosh, Arun Kumar Pati, *Extraction of Product and Higher Moment Weak Values: Applications in Quantum State Reconstruction and Entanglement Detection,* arXiv:2107.00573.

2. Ida Mishra, Arun K Pati, Sohail, *Tight Product Monogamy Inequality for Entanglement,* arXiv:2205.01160.

Conference/Workshops Attended:

1. 42^{nd} *International Conference on Quantum Probability and Infinite Dimensional Analysis (QP-42)*, India, January, 2022.

2. *International Conference on Quantum Information and Foundations (ICQIF-2022)* , India, February, 2022.

Abhay Srivastav

Research Summary:

In the last academic year 2021-2022, I studied quantum speed limit using time energy uncertainty relation. Also, I studied LOCC distinguishability of unextendible product basis(UPB) states.

Conference/Workshops Attended:

1. *Quantizing Time*, Perimeter Institute, June 14-18, 2021.
2. *Vienna Quantum Foundation Conference 2021*,IQOQI Vienna, September 7-10, 2021.

Chirag Srivastava

Research Summary:

In the previous academic year, I have worked on some of recently studied areas of quantum information like recycled detection of entanglement and genuine entanglement, measurement-device-independent entanglement witnesses (MDI-EWs), resource theory of quantum coherence and wave-particle duality. I have also explored areas like dynamical quantum phase transitions and Grover's quantum search algorithm. In a specific work, we studied quantum coherence in an interesting set-up. Quantum coherence quantifies the amount of superposition in a quantum system, and is the reason and re-source behind several phenomena and technologies. It depends on the natural basis in which the quantum state of the system is expressed, which in turn hinges on the physical set-up being analyzed and utilized. While quantum coherence has hitherto been conceptualized by employing different categories of complete bases, there do exist interesting physical situations, where the natural basis is an incomplete one, an example being an interferometric set-up with the observer controlling only a certain fraction of all the slits. We introduced a quantification of quantum coherence with respect to an arbitrary incomplete basis for general quantum states, and develop the corresponding resource theory, identifying the free states and operations. Moreover, we obtained a complementarity relation between the so-defined quantum coherence and the which-path information in an interferometric set-up with several slits, of which only a section is in control of the observer or is accessible to her. This therefore provides us with another face of the wave-particle duality in quantum systems, demonstrating that the complementarity is functional in more general set-ups than thus far considered. In the next set of works, we constructed a nonlinear version of the standard MDI-EWs and studied the cases of detection loophole and noisy quantum input loophole. Entanglement witnesses are one of the most effective methods to detect entanglement. It is known that non-linear 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 entangle-ment 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 certify 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. In another set of works, my aim was to study the sequential detection property of entanglement and genuine entanglement under different scenarios. We investigated the scenario where an observer, Alice, shares a two-qubit state with an arbitrary number of observers, Bobs, via sequentially and independently recycling the qubit in possession of the first Bob. It is known that there exist entangled states which can be used to have an arbitrar-

ily long sequence of Bobs who can violate the Clauser-Horne-Shimony-Holt (CHSH) Bell inequality with the single Alice. We showed that there exist entangled states that do not violate the Bell inequality and whose entanglement can be detected by an arbitrary number of Bobs by suitably choosing the entanglement witness operator and the unsharp measurement settings by the Bobs. This proves that the set of states that can be used to witness entanglement sequentially is larger than those that can witness sequential violation of local realism. There exist, therefore, two-party quantum correlations that are Bell "classical", but whose entanglement "nonclassicality" can be witnessed sequentially and independently by an arbitrarily large number of observers at one end of the shared state with the single observer at the other end. We also considered a scenario where spatially separated observers share a genuinely multiparty entangled quantum state with each local observer possessing a single qubit. A particular qubit is acted upon by sequential and independent observers. We studied the recycled detection of genuine multipartite entanglement of multiqubit states by any one of the sequential observers and the rest of the spatially separated parties. We showed that it is possible to sequentially detect genuine multiparty entanglement, arbitrarily many times for an arbitrarily large number of parties. Modified genuine multiparty entanglement witness operators for unsharp measurements by sequential observers are deduced, which are then employed to show that an arbitrary number of observers can sequentially detect genuine multisite entanglement of Greenberger-Horne-Zeilinger and cluster states of an arbitrary number of parties. Extensions to multiparty generalized Greenberger-Horne-Zeilinger states and a class of mixed states were also shown to be achievable. In the work on Grover's quantum search algorithm,

we analyzed the robustness of Grover's quantum search algorithm under a local unitary noise with memory effects. For a multi-qubit register of the Grover circuit, we modeled the noise as originating from arbitrary but fixed unitary rotations in an arbitrary number of qubits of the register. We derived a restricted set of unitaries for which the success probability of the algorithm remains invariant with respect to the "noise strength" in the multi-qubit register. Precisely, we showed that only when the unitary operator is either of two specific Pauli matrices,the algorithm's success probability stays unchanged when increasing or decreasing the nontrivial number of noisy qubits. When the third Pauli matrix acts as the noise unitary on an even number of noise sites, the success probability at all times will be unaltered as long as the total number of noise sites is changed to another even number. Likewise happens when the total number of noise sites stays odd. This asymmetry between the Pauli operators stems from the inherent symmetry-breaking existing within the Grover circuit. We further showed that the positions of the noisy sites are irrelevant in the case of any of the Pauli matrices as noise. Our results hold true irrespective of the presence of time-correlations in the noise. The results were exemplified in a situation where the noise is Markovian-correlated in time.

Publications:

1. Entanglement witnessing by arbitrarily many independent observers recycling a local quantum shared state, Chirag Srivastava, Mahasweta Pandit, and Ujjwal Sen, Phys. Rev. A **105**, 062413 (2022).

2. Equilibrium and dynamical phase transitions in fully connected quantum Ising model: Approximate energy eigenstates and critical time, Arun Sehrawat, Chirag Srivastava, and Ujjwal Sen, Phys. Rev. B **104**, 085105 (2021).

3. Noisy quantum input loophole in measurement-device-independent entanglement witnesses, Kornikar Sen, Chirag Srivastava, Shiladitya Mal, Aditi Sen De, Ujjwal Sen, Phys. Rev. A **104**, 012429 (2021).

Preprints:

1. Recycled detection of genuine multiparty entanglement of unlimitedly stretched array of parties and arbitrarily long series of sequential observers, Chirag Srivastava, Mahasweta Pandit, and Ujjwal Sen, arXiv:2205.02695[quant-ph].

2. Closing loopholes of measurement-device-independent nonlinear entanglement witnesses, Kornikar Sen, Chirag Srivastava, and Ujjwal Sen, arXiv:2203.07192[quant-ph].

3. Invariance of success probability in Grover quantum search under local noise with memory, Sheikh Parvez Mandal, Ahana Ghoshal, Chirag Srivastava, and Ujjwal Sen, arXiv:2112.02640[quant-ph].

4. Recycled entanglement detection by arbitrarily many sequential and independent pairs of observers, Mahasweta Pandit, Chirag Srivastava, and Ujjwal Sen, arXiv:2201.02594[quant-ph].

5. Measurement-device-independent nonlinear entanglement witnesses, Kornikar Sen, Chirag Srivastava, and Ujjwal Sen, arXiv:2106.05796[quant-ph].

6. Quantum coherence with incomplete set of pointers and corresponding wave-particle duality, Ingita Banerjee, Kornikar Sen, Chirag Srivastava, and Ujjwal Sen, arXiv:2108.05849[quant-ph].

7. Quantum information can remain without physical body in volatile form, Brij Mohan, Sohail, Chirag Srivastava, Arun K. Pati, and Ujjwal Sen, arXiv:2105.03250[quant-ph].

Conference/Workshops Attended:

1. *International Conference on Quantum Information and Foundations (ICQIF-2022)*, organized by Physics and Applied Mathematics Unit, Indian Statistical Institute jointly with Uni- versity of Calcutta, S. N. Bose National Centre for Basic Sciences and Bose Institute, Kolkata, India, February 2022.

2. *Quantum Information Processing 2022*, hosted by the California Institute of Technology (Caltech) in Pasadena, CA, USA, March 2022.

Other Activities:

1. Presented a talk on "Recycled entanglement detection by arbitrarily many sequential and independent pairs of observers " in the international conference *ICQIF-2022*.

2. Presented a poster on "Entanglement witnessing by arbitrarily many independent observers recycling a local quantum shared state" in the international conference *Quantum Information Processing 2022*.

Mathematics Conferences/Workshops

1. *Group Theory Sangam Conference*, June 01-04, 2021, Virtual (jointly with other Indian colleagues)
2. *Workshop on Group Theory*, February 04-05, 2022, Virtual (jointly with other Indian colleagues)

Physics Conferences/Workshops

Recent Graduates

Mathematics

1. **Lalit Vaishya**
   Some problems on sign change and shifted convolution sums of Fourier coefficients of certain automorphic forms.

2. **Souvik Pal**
   On level zero Integrable modules over extensions of Lie tori.

3. **Mohit Mishra**
   Structure of the class groups of totally real number fields.

4. **Rishabh Agnihotri**
   Arithmetical properties of Fourier coefficients of Hilbert modular forms.

Physics

1. **Sauri Bhattacharyya**
   Finite temperature dynamics in strongly correlated systems.

2. **Arpita Sen**
   First-principles studies of Electronic and Magnetic properties of atomic clusters and surfaces of polar oxides.

3. **Arijit Dutta**
   Nonequilibrium response and dynamics in the Mott insulator.

4. **Arpan Kar**
   Indirect search for dark matter in current and upcoming radio observations.

5. **Avirup Ghosh**
   Phenomenology of feebly coupled dark sectors.

6. **Ratul Mahanta**
   Topics in Conformal Field Theory and String Theory.

7. **Saptarshi Roy**
   Implementation of quantum information protocols in physical Systems.

MSc Physics

1. Aman Chauhan
2. Ayan Sahoo
3. Harshit Rajgadia
4. Kaustubh Singhi
5. Sayan Mondal
6. Sukalpa Kundu
7. Manojit Das

Publications

Publications (Mathematics)

1. Aprameyo Pal, Gergely Zabradi, *Cohomology and overconvergence for representations of powers of Galois groups* , Journal of the Institute of Mathematics of Jussieu 20(2) (2021), 361-421.

2. Arpan Kanrar, *Wolstenholme's theorem revisited*, Elemente der Mathematik, DOI 10.4171/EM/457, (2021).

3. Chandan Singh Dalawat, *Congruent numbers, elliptic curves, and the passage from the local to the global: an update*, in *Resonance-75, Promoting Science Education*, vol. 1 (2022). See also arXiv:2201.11071.

4. Rishabh Agnihotri, *Lambert series associated to Hilbert modular forms*, Int Journal of Number Theory (2022) (To appear).

5. Rishabh Agnihotri, Kalyan Chakraborty, *On the Fourier coefficients of certain Hilbert modular forms*, Ramanujan J., 58(2022),no. 1, 167–182. 11F41 (11F30 11F66).

6. Rishabhn Agnihotri, Kalyan Chakraborty, *Sign changes of certain arithmetical function at prime powers*, Czechoslovak Math. J., 71(146)(2021), no. 4, 1221–1228.

7. Chiranjit Ray, Kalyan Chakraborty, *Certain eta-quotients and l-regular overpartitions*, Ramanujan J., 57(2022),no. 2, 453–470, 11F33 (05A17 11F11 11F20 11F25 11P81 11P83)

8. Kalyan Chakraborty, Azizul Hoque, *On the Diophantine equation* $dx2 + p2aq2b = 4yp$, Results Math., 77(2022), no. 1,Paper No. 18, 11 pp.

9. P. Agarwal, A. Shehata, S. I. Moustafa, Kalyan Chakraborty, *On some recursion relations for Horn's hypergeometric functions of three variables*, Proc. Jangjeon Math. Soc., 24(2021), no. 2, 231–247.

10. Kalyan Chakraborty, Takao Komatsu, *Generalized hypergeometric Bernoulli numbers*, Rev. R. Acad. Cienc. Exactas Fís. Nat. Ser. A Mat. RACSAM, 115(2021), no. 3, Paper No. 101, 14 pp.

11. Kalyan Chakraborty, Krishnarjun Krishnamoorthy, *On some symmetries of the base n expansion of $1/m$: The class number connection*, to appear in Pacific Journal of Mathematics.

12. Rishabh Agnihotri, Kalyan Chakraborty, Krishnarjun Krishnamoorthy, *Sign Changes in Restricted coefficients of Hilbert Modular Forms*, to appear in Ramanujan Journal.

13. Kalyan Chakraborty, Krishnarjun Krishnamoorthy, *On moments of non-normal number fields*, to appear in Journal of Number Theory **238** 183-196 (2022),

14. Krishnarjun Krishnamoorthy, *Generalized divisor problem for new forms of higher level*, Czech. Math. J. **72**, 259–263 (2022).

15. Valeriy Bardakov, Mikhail Neshchadim and Manoj K. Yadav, *On λ-homomorphic skew braces,* J. Pure Appl. Algebra **226**, Paper No. 106961, 37 pp., (2022).

16. M. Naik, R. P. Sarkar: *Asymptotic mean value property for eigenfunctions of the Laplace–Beltrami operator on Damek–Ricci space.* Annali di Matematica Pura ed Applicata.
https://doi.org/10.1007/s10231-021-01172-9

17. M. Naik: *Generalized mean value property in limit for eigenfunctions of the Laplacian on $\mathbb{R}^n$,* Colloq. Math. 169 (2022), no. 2, 255–267.

18. N. Bag, A. R. León and W. P. Zhang, *An explicit evaluation of 10-th power moment of generalized of quadratic Gauss sums and some applications*, Functiones et approximatio, 2021.

19. Priyanshu Chakraborty, S.Eswara Rao, *Partial clssification of irreducible modules for loop-Witt algebras* , Journal of Lie theory, (32) **(2022)**, 267-279.

20. Priyanshu Chakraborty, Punita Batra, *A class of irreducible modules for loop-Virasoro algebras*, to be appear in Journal of algebra and its application,
https://doi.org/10.1142/S0219498823501566

21. Ramesh Manna , P.K. Ratnakumar, *Global Fourier Integral Operators in the Plane and the Square Function*, Journal of Fourier Analysis and Applications, 28, no. 2, Paper No. 1-28, (2022)

22. Veekesh Kumar and R. Thangadurai, *On simultaneous approximation of algebraic numbers*, To appear in., Mathematika.

23. D. G. Bhimani and S. Haque, *Norm Inflation for Benjamin–Bona–Mahony Equation in Fourier Amalgam and Wiener Amalgam Spaces with Negative Regularity,* Mathematics **9**, 3145, (2021).

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Computer Centre

The computer centre provides the support to a very large community which includes academic and research Faculty, Administrative staff, Post-Doctoral Fellows, Ph.D. and M.Sc. students and visiting scientists. The computing facilities are available to users round the clock i.e. $24 \times 7 \times 365$ all over the campus. The entire HRI campus is connected with OFC based Gigabit backbone providing network and internet connectivity to each and every office, Engineering building, Library building, Hostels, Guest House, Pantry, Health Centre and Residences. The network is connected to the Internet through two ISPs.

The Computer Centre runs in-house developed Mail server, Web server, Directory server, Firewall servers and other important servers running on most secured OpenBSD and Linux Operating Systems with hand written firewall rules and are placed inside the DMZ.

The core of the network is the Computer Centre, which houses various servers, and several desktop computers for general use. File and authentication services are exported from the Computer Centre to a large chunk of the network through NFS and LDAP. Apart from the NFS and LDAP clients, users have independent machines running different flavours of Linux operating System and MS Windows that are not clients of the central servers.

The common operating systems used at computer centre are Unix clones like GNU/Linux, and Unix-like operating systems such as OpenBSD and FreeBSD. Most software packages, proprietary and open source that are necessary for research in mathematics and physics, are available to users. The computer centre, time-to-time, upgrades the operating systems and its associated software packages to meet user requirements and to enhance the security of the servers. The computer centre maintains high end UPS systems for providing continuous power supply to the servers and network of the institute.

The computer centre provides centralised printing facility to all the academic and administrative members of the institute and helps the accounts section in implementing the Public Financial Management System (PFMS). It also assists the staff in acquiring the Digital Certificates (DSC) to be used in PFMS and e-tendering on GeM portal and on NIC's Central Public Procurement Portal (CPPP). The various sections of the institute get its assistance in implementing e-tendering on the GeM portal and on NIC's Central Public Procurement Portal (CPPP).

The last two years were very challenging due to the Covid-19 as most of the activities were done in online mode. The computer centre provided the support to all in organising the online conferences and online interviews of Ph.D. and M.Sc. students and provided support in organising all academic and administrative meetings in online mode.

The computer centre had set up a facility to access the IP based online subscribed journals and books by the Institute members from the home during the work from home period of Covid-19.

The computer centre undertook a cleanliness drive with a spate of activities as in accordance to the nation-wide Swachh Bharat Cleanliness Campaign launched by the Hon'ble Prime Minister. The whole drive was quite inspiring and motivating for the staff. The CC staff realized that any work is best done when it is carried out by a person himself. It also made the CC staff aware of the dignity of labour.

Our centre's vision is to power the future of computing by advancing the foundation of computing facilities in novel ways to address society's most important computer related challenges. Our mission is holistic in its integration of multiple areas of computers and its associated services within the institute and the adoption of responsible computing as a guiding principle. The Computer Centre continues to grow and is trying to keep updated with latest technological support by the CC Project staff under the leadership of Mr. Sanjai Verma, Section Head.

All this has become possible by the great support from the Director, Registrar and our dedicated team of computer committee, CC project staff and very cooperative non-teaching staff and also well disciplined students. We are proud of our achievements and excited by new opportunities as we aspire to be among the top computer centre. The computer centre endeavour to provide the right environment for students, staff and faculty to flourish.

Library

In an academic or research institute a library plays an important role in the dissemination of knowledge. In fact, the **a**mbience of the library reflects the quality of the education/research imparted by the Institute. The Central Library plays a vital role in furthering the academic and research mission of HRI and facilitates creation and dissemination of knowledge. The range of services offered by the library are comparable to the best libraries in the country. 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. HRI's library serves as a knowledge hub containing resources in print and electronic form.

Glimpse of the Library:

Collection Development and Management:

Building a collection of reading materials is one of the important functions of the library that supports academic and research work of the students, faculty, staff and other users. Our Library collection comprises of all types of materials related to the Mathematics and Physics and is considered one of the best in the country and is its greatest asset. The total collection of library as on 31st March 2022 stands as follows:

Resources	Details
Total Collection: Books (Print)	**62012**
No. of Books	21831
No. of Bound Volumes	38292
Gratis	1889
Total Collection: Journals	**144**
International Journals :	**119**
Online	114
Print	05
National Journals :	**12**
Print	12
DAE-Elsevier Consortium Journals (online):	**12**
E-Books:	**2270** (Lecture Notes in Mathematics and Archives)

Subscribed E-Resources, Databases:		
MathScienet	Database of Reviews, Abstracts and Bibliographic Information	American Mathematical Society (AMS)
Project Euclid Journals	31 Journals Package	Duke University Press
JSTOR	102 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

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, Reference 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.

Other Resources and Facilities:

Theses	125
CD's/DVD's	101
Newspapers	07
Seating Capacity	43
Carpet Area	550 Sq. Mts
Computers for Users/OPAC	4 No's
Library Management Software	Koha 19.11 Version with RFID Technology

Newly added materials during April 2021 to March 2022:

Books	135
Gratis-Books	31
E-books	13

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: Scholarship and other fellowship information
Referral	Orientation for newly joined library members
Reprographic	Display of Faculty/PDF/Students Publications
New Arrivals service	Display of Institute Publications
Newspaper Clippings	Library Advisory Committee
Book Exhibition	Stock Verification
Theses Consultation Facilities	Book tracing service
Inter Library Loan	18 Hours uninterrupted Services

Library Advisory Committee:

Library Advisory Committee works towards continual improvement of the library activities, so that the library and its facilities achieve a fair degree of acceptability and appreciation amongst the users. This Committee, is chaired by a **Professor of the Institute 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.

Members

Details are as follows	
Prof. D. Surya Ramana	Convenor
Dr. Anirban Basu	Member
Dr. N. Raghavendra	Member
Mr. K.K. Suresh Kumar, Librarian	Member

LC recommendations:

The Library Advisory Committee Meeting held on 5th October 2021 and recommended to the renewal subscription of existing collections of journals, E-books, databases and other resources for the year 2022. Along with the existing materials, 11 new journals from American Chemical Society (ACS) and 02 journals from Royal Society of Chemistry (RSC) are subscribed for library users.

Library Team:

The day-to-day functions of the library at HRI is efficiently managed by a team headed by a Qualified Librarian with professional experience. He is supported by a SO "C" along with a team of well-trained library staff. The library staffs perform their duties exceptionally well, and are always appreciated by library users for their service mindedness, intelligence, enthusiasm and sincerity with which they serve them. In addition to their regular jobs, officers are involved in various committees and institute's other work.

The Library Staff with their names and designation:

Dr. K.K. Suresh Kumar	Librarian
Mrs. Anju Verma	SO "C"
Mr. Vivek Kumar	Junior Library Assistant
Mr. Kamta Prasad	Peon
Other contractual staff	05

Stock Verification:

Conducting the Stock verification every year is one the BEST PRACTICES of the HRI-Library. As per directions from the Administration, library has done stock verification of the library materials for the period 1st April 2021 to 31st Dec 2021 and we are happy to state that, "there is no missing" books or any other reading materials.

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 i s operational on Intranet. It can be accessed online to search more than 62012+ bibliographic records, available in the Library database.

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, finding 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 drastically changing the way the library and information services work. 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 meet the Library users expectations over the years and as per feedback from its patrons has been quite successful in this endeavor. HRI Library not only proactively works on its collection building and infrastructural augmentation, but also puts a 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.

Smart card facilities:

The Institute's members Identity Card has a chip which also serves as a Library card through which users can borrow books through the KIOSK/ Self issue-return process. This smart card facility has been given to students, researchers, PDFs, faculty, staff members and other members like Visitors and retired employees of t he Institute.

Major Initiatives:

The Central Library has taken various initiatives to improve the existing services, infrastructure, facilities, and procurement of bookshelves and reading chairs to increase the collections and user strength to provide strong and dynamic support to the academic, research programmes and policies of the institute. Some of these initiatives are described in the following sections.

- **Active participation:** Conducted Library Committee meetings, implemented policies and programs of the library, as adopted by the Library Committee, Registrar and the Director and whenever required provided the information and reports to the LC, Accounts Officer, Admin Officer, Registrar, and the Director and tried to building the library as a source for research activities.
- **Legal Agreement Procedure:** Introduced Legal Agreements (Stamp paper) process for the subscription of online and print journals, databases and e-book packages. Thereby cautioning Vendors/ Publishers to the consequences of misuse of the huge subscription amount.
- **Safe environment:** Regularly conducting discussions with Publishers and Vendors regarding invoices, currency conversion rates, price proof, discounts, Institute's subscription tier level and keep a safe environment for the library's spending budget.
- **Value Added Services:** Every year a marked budget of Rs. 2-3 Crores is spent for the library. Therefore to value the spends, made a continuous effort to facilitate the user community with value added services with the help of the library team
- **Best Practices:** In consultation with the Library Committee, Registrar and Director implemented BEST PRACTICES in the Library and strived to make HRI-Library one of the best research libraries in the DAE community and try to bring library standard to the National/IIT/IISER library level.
- **Trial Access & other Services:** Analyzing user expectations and communicating with publishers and providing different types of resources' Trial access to the users and grabbing their attention on new sources. Also analysing user needs and demands and fulfilling them in time and communicating to users related to the indents, articles, feedback, overdue, services and responding to user's queries.
- **Infrastructure APEX Project (Library component):** Successfully handled library related SIRD project (revised) with the help of the LC and Registrar and achieved 96.21% financial progress and 83% Physical progress. Also provided library plan and estimated amount for 2021-2024's new Infrastructure APEX Project (Library component).
- **DAE-Elsevier Consortium-2021:** Handled DAE-Elsevier Consortium-2021 for the institute and attended several online meetings. In this discussion suggested consortium related, access related, perpetual access related, special discount related information to the Coordinator and member libraries of the Consortium. The Consortium members recognized HRI's effort on matters pertaining to Consortium-2021.

- **Intra-mail Services:** We have individual, group e-mail services, whenever we find new information useful to the particular community, details are sent through e-mail. Also studied different matters/ subjects to curate necessary information for benefit of the research community in the Library. In this year, we have sent around 57 Informative e-mails to the Institute community related to Open Source resources, Scholarships, Library services, Newspaper clippings, about Scientists and their achievements, e-catalogues, different websites, Conferences/ Workshops, DST programs, and information on Bilateral exchange programs, interesting and noteworthy information on Science and other relevant news. Also made required changes in "library standards" and strove to upgrade library services to a faster and higher level of functioning.

- **Systematic re-shelving of books:** Experienced library staff members have been assigned to devote one to two hours daily in the morning in the stack areas to facilitate easy retrieval of books. This process is a continuous process throughout the year and it will give easy access to the books and other materials without any hurdles. This initiative has produced considerable satisfaction among users.

- **Reprographic and Spiral binding Facility:** Dedicated photocopier and spiral binding machines are made available in the library for the use of our students and faculty members. Access to this facility is available for students and faculty generally throughout the day.

- **Library Lounge/Collaboration learning space:** The library has created library lounge/ collaborative learning space in the entrance of the library near to the security check point. This space has been created to facilitate space to the users who wants to learn/ one-to-one discussions/ discuss together/in a group to solve problems, work on a project or have a meaningful discussion are allowed for limited time. Also newspapers are kept for users benefits. We provided comfortable furniture for the users. This area is quite popular for library users.

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.

Inter Library Loan Services/Sharing of Resources:

The library is a part of DAE family/libraries so the HRI library can help in obtaining articles and other materials that HRI library does not subscribe to and get it from other libraries all over the India. Also the library maintains excellent relations with a number of major institutions and libraries in India for exchange of journal articles etc., for the mutual benefit of the users.

Donation of Books and other materials:

HRI-Library welcomes donations of books and other materials including print and electronic materials that support the current teaching and research needs of the Institute. We are taking donation of new books, good condition used books, other relevant materials (print), and e-books related to Mathematics and Physics subject. Users may donate other subject books like novels, short stories, dictionaries, biographies, science literature, rare books, children literature, Hindi and other language books etc. In fact, from long time we have this practice in library and presently we have variety of collections of about 1889 donated books in library with proper documentation.

During COVID-19 pandemic:

The Library has been actively engaged in designing and delivering need-based information services. During the COVID-19 pandemic, library continued to stay connected with the user community and support their academics by providing off-campus access to e-resources through 'Remote Access Portal'.

Construction Activity

The works related to construction of buildings is hampered in campus due to order of Allahabad High Court in reference of PIL related to Ganga Pollution. Therefore no building construction work was carried out during last Financial Year 2021-22. Except routine mainteance works (Civil/Electrical/Air-conditioning/Horticulture) with repainting works in some flats/houses, no new work has been carried out during this period