1.) **A study of quantum correlations: Squeezing and its various facets**

**P.I : Subhashish Banerjee**
**Co-PI : V. Narayanan**

**Funding Agency CSIR, New Delhi**

Brief description:

***Here the aim is to study the role of quantum correlations such as squeezing in the context of open quantum systems.***

Outcome:

Quantum correlations occupy a central position in the quest for understanding and harvesting the power of quantum mechanics. Here, we study quantum correlations in nonclassical states such as multiphoton squeezed state, from the prospective of a practical interface between quantum optics and quantum information processing. One of the principle tasks of the project is to study quantum correlations in non-classical states from the prospective of an interface between quantum optics and quantum information. Further, the effect noise on these systems needs to be understood. This is addressed here by a careful investigation of non-classical features in a physical system comprised of a cavity with two ensembles of two-level atoms. Noise causes the transition from quantum to classical behavior and manifest itself in the form of irreversible processes such as decoherence and dissipation. From the perspective of the implementation of any quantum information task, it is important to consider the role of noise on the chosen task. We study the contribution of decoherence to quantum cryptographic tasks. Further, a number of features of quantum information processing including quantum correlations, are studied using non-Markovian noise channels, i.e., channels endowed with memory, are used.

**Publications:**

(1) Decoherence can help quantum cryptographic security, Vishal Sharma, U. Shrikant, R. Srikanth and Subhashish Banerjee, Quantum Inf. Process. 17, 207 (2018).
(2) Lower- and higher-order nonclassical properties of photon added and subtracted displaced Fock states, Priya Malpani, Nasir Alam , Kishore Thapliyal, Anirban Pathak, V. Narayanan and Subhashish Banerjee, Ann. Phys. (Berlin) DOI: 10.1002/andp.201800318.
(3) Non-Markovian dephasing and depolarizing channels, U. Shrikant, R. Srikanth, Subhashish Banerjee, Phys. Rev. A 98, 032328 (2018).

**2.) Probing the Foundations of Quantum Mechanics in Neutrino Oscillations**

**P.I Subhashish Banerjee**

**Co-PI A. K. Alok**

**Funding Agency DST, New Delhi**

Brief description:

***The aim is to test the foundations of quantum mechanics in high energy physics experiments, such as those probing various facets of neutrino oscillations. This is aimed at exploring and expanding the territory at the interface between Quantum Information and Particle Physics with advantageous implications for both the fields.***

Outcome:

The foundations of quantum mechanics are usually studied in optical or electronic systems. In such systems, the interplay between the various measures of quantum correlations is well known. Due to the technical advances in high energy physics experiments, such as the short and long baseline neutrino experiments, it will be fruitful to test the foundations of quantum mechanics in such systems. The phenomenology of neutrinos from a quantum information point of view is studied. The project brings together distinct expertise such as the one on quantum foundations in the meson and hyperon system (Austria) and quantum foundations in the neutrino system (India). The aim of this collaboration is to come up with concrete proposals on how to probe the foundations of quantum mechanics at the current and planned accelerator facilities in addition to theoretical insights into the phenomenology of these fascinating particles. This is particularly timely since the newly built accelerator facilities are designed to look for these effects. It is proposed to probe the foundations of quantum mechanics in neutrinos, by studying the relation between a numbers of measures of quantum correlations in the context of neutrino oscillations, for natural as well as man-made experimental scenarios

**Patent or Publications (Generated from Project; Put best three)**

(i) Legget-Garg-Type Inequalities and the neutrino mass-degeneracy problem": arXiv: 1710.05562: Javid Naikoo, Ashutosh Kumar Alok, Subhashish Banerjee, S. Uma Sankar, Giacomo Guarnieri, Beatrix C. Hiesmayr.

(ii) Study of coherence and mixedness in meson and neutrino systems, Khushboo Dixit, Javid Naikoo, Subhashish Banerjee, Ashutosh Kumar Alok, Eur. Phys. J. C (2019) 79: 96

(iii) Leggett-Garg inequality in the context of three flavour neutrino oscillation, Javid Naikoo, Ashutosh Kumar Alok, Subhashish Banerjee, S. Uma Sankar, arXiv:1901.10859 (To appear in Phys. Rev. D)

## 3. Graph Theoretical aspects in Quantum Information Processing

**P.I Subhashish Banerjee**

**Funding Agency CSIR, New Delhi**

Brief description:

***The aim of this project was to provide a graph theoretical dictionary to quantum mechanics.***

Outcome:

Quantum mechanics deals with states living in the Hilbert space, allowing for linear superposition to be built up, a facility of immense importance for harnessing the power of quantum mechanics, but at the same time making it computationally a formidable task. This can be most easily appreciated by considering entanglement in higher dimensions as well as in multi-partite systems, all mathematically and computationally very formidable tasks. Any tool that would aid in this regard would be very welcome. The theory of graphs is a well-developed mathematical theory that has found many applications in diverse areas. Graphs have, by their very construction, the inbuilt feature of visualization. A pertinent question to ask is whether graphical representation of quantum states can be made? This would enable the incorporation of the mathematical machinery of graphs into the problems of quantum mechanics and at the same time bring in the attractive feature of visualization of quantum states.

**Publications:**

(i) Bibhas Adhikari, Subhashish Banerjee, Satyabrata Adhikari, and Atul Kumar. Laplacian matrices of weighted digraphs represented as quantum states. Quantum information processing, 16(3):79, 2017.

(ii) Supriyo Dutta, Bibhas Adhikari, and Subhashish Banerjee. A graph theoretical approach to states and unitary operations. Quantum Information Processing, 15(5):2193–2212, 2016.

(iii) Supriyo Dutta, Bibhas Adhikari, Subhashish Banerjee, and R Srikanth. Bipartite separability and nonlocal quantum operations on graphs. Physical Review A, 94(1):012306, 2016.

**4. Hunting of new physics through b → s transitions**

**P.I A. K. Alok**

**Co-PI Subhashish Banerjee**

**Funding Agency CSIR, New Delhi**

Brief description:

**This project is aimed at finding novel signatures to deviations from the Standard model. Further, a study was made of various facets of quantum correlations in meson systems.**

Outcome:

The Standard Model (SM) of High Energy Physics is a theory concerning the electromagnetic, weak, and strong interactions, which mediate the dynamics of the known subatomic particles. While almost all predictions of this model are consistent with data, it is surely not a complete theory of fundamental interactions. Just a few of the many reasons for this statement: that it does not comprehend gravity; it includes no dark matter candidate particles; and it fails to account for the matter-antimatter asymmetry of the Universe. Therefore we need to look for the physics beyond the SM, which we call new physics. Flavor physics, the detailed understanding of the relationship between three families of quarks and leptons and the comparison between properties of matter and antimatter, is one of the most promising ways to explore new physics, quite complementary to the energy frontier research most notably pursued at the Large Hadron collider (LHC). It is a rich laboratory which can probe physics beyond the SM by precision measurements that can look for the virtual production of new particles in quantum loops. In this project, we studied observables in various new physics models such as vector quark models, Z′ models, and models with extended Higgs sector. Special emphasis will be on following observables and finding out important correlations between them. We also made a study of various facets of quantum correlations in meson systems.

**Publications:**

(i) "Quantum correlations in two-flavor neutrino oscillations", Nucl. Phys. B 909, 65 (2016); Eprint:arXiv: 1411.5536: A. K. Alok, S. Banerjee and S. U. Sankar.

(ii) "New-physics signals of a model with a vector-singlet up-type quark", Phys. Rev. D 92, 013002 (2015): Ashutosh Kumar Alok, Subhashish Banerjee, Dinesh Kumar, S. Uma Sankar and David London.

(iii) "Re-examining sin(2beta) and Delta m(d) from evolution of B(d) mesons with decoherence", Phys. Lett. B 749, 94 (2015): Ashutosh Kumar Alok, Subhashish Banerjee, S. Uma Sankar.