IIT Bombay

Department of Physics

Ph.D. Autumn 2022 Admission

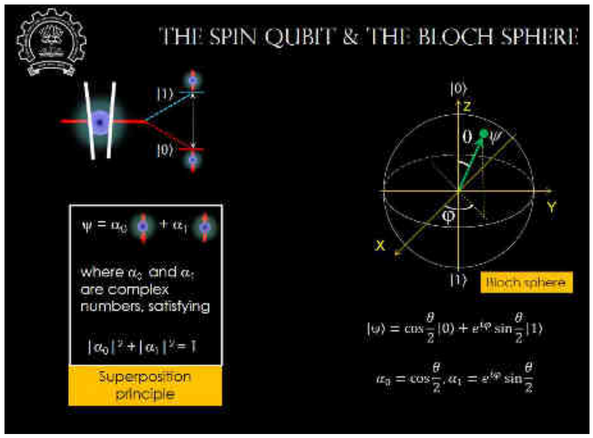
Research Write-ups

Condensed Matter Physics Experiment (CMP - E)	
1.	Prof. M. Aslam
2.	Prof. S. Mahapatra
3.	Prof. Sunita Srivastava
4.	Prof. Pramod Kumar
5	Prof. Maniraj M.
Condensed Matter Physics Theory (CMP –T) + Quantum Information Theory (QIT)	
1.	Prof. Gopal Dixit
1.	Prof. Himadri Dhar
2.	Prof. Siddhartha Santra
High Energy Physics Theory (HEP - T)	
1.	Prof. Asmita Mukherjee
2.	Prof. Vikram Rentala
High Energy Physics Experiments (HEP - E)	
1.	Prof. B. K. Nandi
2.	Prof. Sadhana Dash
Optics and Photonic	
1.	Prof. Parinda Vasa
2.	Prof. Anshuman Kumar
Soft Matter Physics Theory/ Biophysics (SMP)	
1.	Prof. Mithun Mitra
2.	Prof. Raghunath Chelakkot
3	Prof. Amitabha Nandi
Astronomy and Cosmology	
1.	Prof. Archana Pai
2.	Prof. Varun Bhalerao

Quantum Computing with Spin Qubits in Silicon

Silicon Quantum Computing Laboratory, Physics Department, IIT Bombay (Prof. S. Mahapatra)

In 1982, the Nobel prize-winning physicist, Richard Feynman, envisaged the idea of a 'quantum computer'- a computer that harnesses the power of quantum mechanics to perform information processing tasks billions of times faster than any state-of-the-art silicon-based computer. From a purely mathematical dream forty years ago, we have now reached an era where prototypes of quantum information processing systems are already in use.



As a part of a long-term national mission to develop quantum computing (QC) capabilities within the next 10 years, our laboratory in IIT Bombay is the first platform established for fabrication of a silicon-based spin QC architecture. To be a part of this exciting but extremely demanding project, you will be expected to have a sound understanding of quantum mechanics, electronics, and solid-state physics, together with an aptitude for nano-fabrication and measurements at cryogenic temperatures.

PI Short Bio

Name: Sunita Srivastava
Weblink: http://www.phy.iitb.ac.in/en/content/sunita-srivastava

Associate Professor: Physics
PhD (2004-2010): Indian Institute of Science, Bangalore, India.
Postdoctoral Fellow (2010 -2013): Brookhaven National Laboratory, New York, USA.
Postdoctoral Research Associate (2013 -2014): Stony Brook University, New York, USA.
Guest Researcher (2014 -2016): National Institute of Standards and Technology, Maryland, USA.

Research Area: My research work is in the interdisciplinary area of physics; at the interface of soft condense matter and nanoscience. Broadly, we focus towards creation of nanoscale systems with designed architectures and programmable physical properties through self-assembly and understanding structure-function correlations. Based on the nano-building block as well as the assembly guide, the assemble structure exhibits novel dynamic, mechanical and optical properties.
The student(s) will be involved in one of the problems mentioned below.

1. Understanding self-assembly mechanism for superlattice nanostructure formation with functional properties for optical and biomedical applications.
2. Structure-property correlation of nanoscale materials confined at surfaces and interfaces.

The project will learn about sample characterization techniques such as SEM, TEM, AFM, UV-vis absorption spectroscopy. The student will also get opportunity to learn state of the art, advance x-ray scattering based techniques such as SAXS, GISAXS, for structure analysis and XPCS for dynamic studies. I collaborate at APS, ANL and NSLS I, II, BNL, NY for synchrotron measurements and Standford University for surface dynamic experiments.

Recent Publications: (Google Scholar link for complete publications: https://scholar.google.co.in/citations?hl=en&user=ZT26TGAAAAAJ&view_op=list_works&sortby=pubdate)

1. Sunita Srivastava*, Anuj Chabra and Gang O*; Effect of monovalent and divalent ionic environment on the in-lattice nanoparticle-grafted single-stranded DNA, *Soft Matter , 18, 526, 2022.*
2. Zaibudeen A. Wahith, S. Khawos and **Srivastava S***.; Understanding multiscale assembly mechanism in evaporative droplet of gold nanorods"; *Colloid and Interface Science Communications 44, 100492, 2021.*
3. Sunita Srivastava,* Zaibudeen A. Wahith, Oleg Gang, Carlos E. Colosqui, and Surita R. Bhatia*; Adv. Mater. Interfaces, 2020, 1901954.
4. Srivastava, S; Fukuto, M. and Gang, O.; Soft Matter, 2018; 14(19): 3929-3934.
5. Kishore, S.; Srivastava, S*.; Bhatia, S.R.; Polymer, 2016; 105: 461-471.

Prof. Pramod Kumar

Project 1: Development of bio-compatible piezo-electric haptic sensor for prosthesis

ZnO can be grown in many nano-shapes with the help of the hydrothermal process. The nanostructures show high piezoelectricity due to the c-axis orientation. Haptic devices can be synthesized with the ZnO nanostructures which can provide touch responses. In this project, the growth physics and effect of various shapes and sizes of nanostructures will be explored with simulation and various experimental measurement techniques for the development of bio-compatible haptic sensors, which will be used in the prosthesis.

Project 2: Study of charge carrier transport in hybrid vertical field-effect transistor

Organic semiconductors are well known for their low-cost processing techniques and can be combined with high bandgap semiconductor nanostructures for the development and understanding of the physics of charge carrier transport in hybrid vertical field-effect transistors. Vertical field-effect transistors are known for their faster response and ability to miniaturize. The study can shed light on the charge carrier exchange between the two semiconductors.

Prof. Maniraj Mahalingam

Condensed Matter Physics - Experiment

Current activity of the group member is focused on experimental investigation of material's electronic band structure using state of the art ultrahigh vacuum based surface science techniques, such as photoemission, inverse photoemission, scanning tunneling microscopy and spectroscopy, and electron diffraction. In a simplified version, these technique provide information about all quantum numbers and structure of the materials. Output of these measurements are widely employed to understand the physical properties such as optical, magnetic, and transport properties.

As a material system of choice, focus are on two dimensional materials with wide range of properties, suitable for technological application and fundamental research.

One of the topic is new family of graphene analogy materials, widely known as X-ene. Key activities are to grow them in-situ, and characterize using mentioned techniques to establish its predicted physical properties and support with theory.

Another topic of interest is oxide based quasicrystal. Key activities are designing/identifying a new composition out of wide range of available bulk oxide materials, and its in-situ growth and characterization.

Mostly likely activity at the beginning includes designing and constructions of components needed for the above research topics. Additionally, implementing and establishing the electron diffraction and spectroscopy methods are expected to be a primary activity in the laboratory.

Prof. Gopal Dixit

Light Tailored Topological Properties of Quantum Materials for Quantum Technologies

Discoveries of quantum materials, such as topological insulators, Dirac and Weyl semimetals, have revolutionized contemporary physics. Moreover, these materials hold promises for upcoming technologies based on quantum science and electronics. The present project envisioned to tailor various topological properties of quantum materials using light. Recently, we have successfully demonstrated that light can be used to realise valleytronics in graphene at room temperature – an essential step for working quantum computer at room temperature. Due to such crucial advancement, our work has been highlighted at various international levels such as Forbes magazine etc. Please see the detail in Forbes USA "TOP 10 OMNI WISHES FOR 2022 WITH EXPONENTIAL IMPACT". The expected outcomes of present proposal is going to be ground breaking and expected to get publish in high impact journals. More details about our work, please visit our research website: Ultrafast Lab.

May 2022

Faculty: Himadri Shekhar Dhar, Assistant Professor

Field of research: Condensed Matter Physics – Theory (Quantum Information Theory)

Research Interests: Our main research interest lies at the interface of quantum information theory, quantum optics and many-body physics. In particular, we explore complex quantum systems using both analytical and computational tools, to not only obtain novel insight into our physical world, but also to design and control devices that can be harnessed in modern quantum information and computation technology.

Openings: 1-2 doctoral scholar(s).

Potential project(s):

1. Manipulation of spin ensembles for quantum computation and error-correction

We are interested in harnessing the dynamics of realistic spin ensemble systems interacting with quantum cavities to develop new approaches to understand effects such as spin squeezing [1] and also to design macroscopic fault tolerant computation models [3] or quantum error correction codes [4].

[1] Reservoir-engineered spin squeezing: macroscopic even-odd effects and hybrid-systems implementations, arXiv:2104.10363.
[2] Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer, Quantum 5, 392 (2021).
[3] Robust Encoding of a Qubit in a Molecule, Phys. Rev. X 10, 031050 (2020).

2. Spatio-temporal correlations and macroscopic coherence in photonic systems

Our main objective in this proposal is to formulate new theoretical approaches to study spatio-temporal correlations and macroscopic coherence in light [5], such as vortex like structures in photon condensates [6]. The aim is to identify states that exhibit novel photon statistics and quantum fluidity, which may prove useful in the study of nonequilibrium physics and design of coherent states [7] for quantum computing.

[4] Quantum fluids of light, arXiv:1205.6500 (2012).
[5] Quest for Vortices in Photon Condensates. arXiv:2104.11002 (2021).
[6] Thermally Condensing Photons into a Coherently Split State of Light, arXiv:1911.06593 (2019).

3. Other potential projects involves lattice-based cryptography and adiabatic quantum computation and dynamics of entanglement in many-body quantum systems.

P.S. Please note that all the references above are freely accessible online.

Prof. Siddhartha Santra

Topic of research: Optimal entanglement distribution for the quantum internet

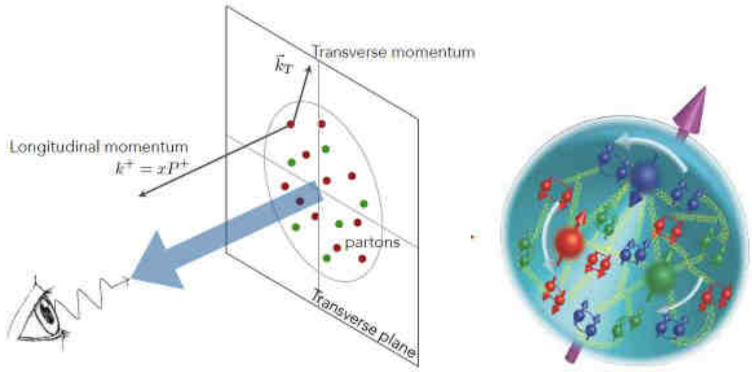
This research proposal will use a combination of analytical and computational methods to obtain optimal entanglement distribution protocols and designs of large scale quantum networks. We will develop theoretical tools at the intersection of quantum information theory, specifically quantum communication, entanglement theory, and theory of quantum operations as well as graph theoretical methods. The computational part will involve writing programs in Mathematica and Python to design and study large scale QNs. A software package to simulate QNs at different scales, connectivities and quality of quantum components will be developed.

Entanglement is a critical resource for the emerging quantum internet. Such a quantum network (QN) will utilize entanglement between its nodes to achieve information-processing tasks beyond the reach of the existing classical internet. Applications include unconditionally secure communication, distributed sensor networks with very high signal-to-noise ratio, scalable quantum processor design and even fundamental tests of the theory of quantum mechanics itself. As such, the design and construction of QNs are the focus of intense current theoretical and experimental research activity nationally and globally. Crucially, the quantum advantage of any network task increases with the rate and quality of the distributed entanglement. The present research proposal tackles important outstanding theoretical and computational questions in optimal entanglement distribution for QNs with the goal of obtaining high entanglement-throughput QN designs and protocols.

Prof. Asmita Mukherjee

Tomography of the Nucleon

I work on QCD and hadron structure. I am mainly interested in the tomographic study of the nucleon in terms of quarks and gluons. These can be done in terms of transverse momentum dependent parton distributions (TMDs). The project involves theoretical calculations of spin asymmetries that can probe the TMDs at the present and future colliders. In another part of the project we want to look at the nonperturbative light cone wave functions of the proton and mesons.Our theoretical predictions are to be used by experiments at the future Electron-Ion Colllider to be built at Brookhaven National Lab, USA.



References : Cos(2\phi) asymmetry in J/\psi production in unpolarized ep Collision;
Raj Kishore, Asmita Mukherjee, Mariyah Siddiqah,
Published in Phys. Rev. D 104, 9, 094015 (2021).
e-Print: 2103.09070 [hep-ph].

Sivers asymmetry in the photoproduction of a J/\psiand a jet at the EIC
Raj Kishore, Asmita Mukherjee, Sangem Rajesh
Published in: Phys.Rev.D 101 (2020) 5, 054003 • e-Print: 1908.03698 [hep-ph]

The Hierarchy Problem and the Higgs boson - with Prof Vikram Rentala

Monday, November 22, 2021 10:56 PM

The Higgs boson discovered at the Large Hadron Collider (LHC) in 2012 was the final missing piece of the Standard Model of particle physics. However, the discovery raises a lot more questions than it answers. Why is the Higgs boson mass of 125 GeV so much smaller than the Planck scale of 10^19 GeV, where quantum gravity effects are expected to be strong? In general, within the framework of effective quantum field theory, it is expected that the Higgs boson receives large corrections to its mass from new physics which is inaccessible to us at current collider experiments. The difference between the observed (tiny) Higgs mass and the large value expected from quantum corrections is called the hierarchy problem. This problem has driven much of the frontier of particle physics phenomenology for the last 40 years.

Exotic theories such as supersymmetry, extra dimensions, technicolor etc., attempt to solve the hierarchy problem, but they also predict that signatures of new physics must be around the corner, waiting to be discovered either at the LHC or near future experiments.

Students who take up this project will be able to explore ideas to solve the hierarchy problem, increase our understanding of the nature of the Higgs boson, build models of SUSY and extra dimensions, and explore alternatives to the framework of local effective quantum field theory.

Prof. Basanta Kumar Nandi
High Energy Nuclear Physics – Experiment

The experimental high energy nuclear physics group is involved in the ALICE experiment at CERN, Geneva. ALICE experiment is dedicated to the search for Quark Gluon Plasma which was formed at the early stage of the Universe. This experiment is currently taking data for different collision systems and at different energies. The group is actively involved in the data analysis of the ALICE data. Currently, physics interest of the group is in the areas of correlations and fluctuations, HBT and heavy flavor measurements.

ALICE is going to have the Forward Electromagnetic Calorimeter (FOCAL) to address the physics at low-x region. India is also planning to join this international effort by contributing to the detector hardware and software development. The FOCAL is a sampling calorimeter consisting of Tungsten(W) and Si. India is planning to contribute part of the Si detector. This is now the R&D phase of the Si sensor. In India BEL will be our partner to design and deliver the Si sensors. It will be fully tested in the laboratory across India and finally shipped to CERN, Geneva for final installation in the ALICE experiment.

The selected candidate will be working on the testing of the Si detectors and physics capability of FOCAL using the Monte Carlo generated data. At the same time the candidate will be involved in the correlation and fluctuation analysis of the pp collisions data at $\sqrt{s}$ = 14 TeV for identified particles using the number correlator (R_2) and momentum correlator (P_2). All these analyses are being carried out in the ROOT environment using C++ language. The candidate is expected to learn C++ and ROOT, if (s)he is not familiar with it.

Experimental High Energy Physics

Proton-proton (p-p) and Heavy Ion collisions at LHC using ALICE Detector

Prof. Sadhana Dash

The physics of heavy ion collisions and quark gluon plasma has been at the frontier of the physics topics at the LHC energies. The availability of heavy -ion and p-p data from ALICE experiment at LHC has generated a lot of theoretical and phenomenological activities all over.

ALICE (A large Ion Collider Experiment) at LHC, CERN is a specific multipurpose experiment to study heavy ion as well as the p-p collisions at LHC energies. The recent observation of experimental signatures in p-p collisions which are reminiscent of QGP has created a lot of interest in medium effects in elementary collisions as well.
The selected student will be involved in data analysis pertaining to heavy ion and pp collisions. She/He will also be involved in some software and hardware development activities involved in such experiments. Currently, we have three interesting problems in our group which require immediate attention and investigation.

Our group is taking part in data analysis related to resonance particles, heavy flavor analysis and particle correlations. Apart from real data analysis, the student will also be involved in some phenomenological studies related to heavy-ion and p-p physics .

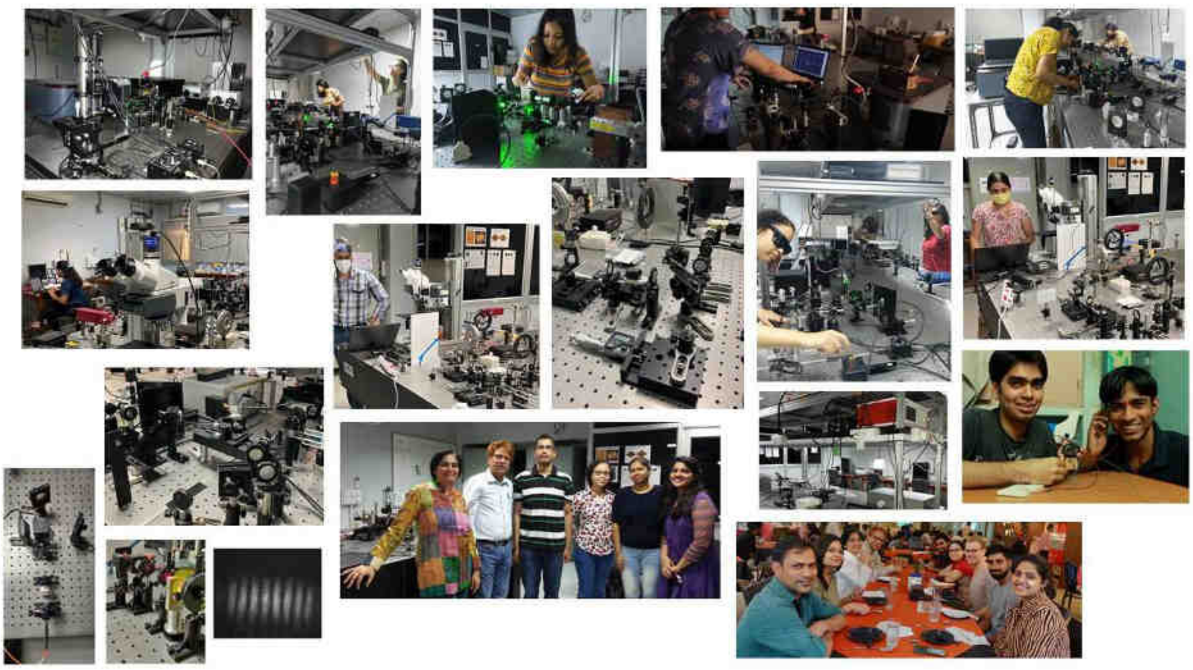
Prof. Parinda Vasa

Active plasmonics: A topic in experimental photonics and semiconductor physics

Photonics is the science and technology of light, with emphasis on applications. One of the distinguishing features of the science of photonics lies in the natural and apparently seamless linkages that this subject provides between fundamental scientific studies and technological applications in diverse areas of contemporary and futuristic importance.

Within the field of photonics, metal nanostructures supporting surface plasmon polaritons (SPPs) carry significant potential for guiding and manipulating light on the nanoscale. They have given rise to the upcoming research field of *plasmonics*. SPPs are spatially confined electromagnetic field modes at a metal-dielectric interface capable of generating intense optical forces on extremely short length- (nanometers) and time- (femtosecond) scales. These intense optical fields can potentially be used to enhance and control the optical properties of quantum emitters (atoms/molecules/excitons), the key components of the modern photonics applications like lasers, sensors and LEDs. The interaction between the localized SPP fields and nearby quantum emitters has led to the emerging and exciting field of *active plasmonics*, dealing with emission and all-optical control of SPPs. Recent advances in nanotechnology have enabled us to fabricate high quality semiconductor and metal nanostructures, in which we have extensively studied several aspects of light-matter interactions, including those in quantum regime.

The offered research topic is about exploring the key phenomenon in light-matter interaction in such emitter/metal hybrid nanostructures, namely the dipole interaction between SPPs and emitters, particularly between SPPs and excitons (Xs) in 2D semiconductors like graphene, MoS_2 and quantum wells. The aim of this project shall be to examine to what extent the X-SPP properties can be controlled via optical as well as fabrication techniques. Our existing studies have demonstrated that these remarkable hybrid metal-semiconductor nanostructures open up exciting possibilities in diverse photonic applications. We will also develop in-depth knowledge about the energy transfer pathways and mechanisms involving long-range interactions in unique electromagnetic environment of the hybrid nanostructures.



Nano-photonics and ultrafast-photonics activity in my laboratory at IIT Bombay. A young and vibrant group of undergraduate and graduate (PhD) students, post-doctoral fellows, project staff and international visitors actively involved in experimentally exploring various aspects of light-matter interactions.

<u>Dr. Parinda Vasa:</u> Professor, Department of Physics, Indian Institute of Technology Bombay, Mumbai, India 400 076, parinda@iitb.ac.in

Selected tutorial/perspective publications:

1. *Exciton-surface plasmon polariton interactions*, **P. Vasa**, Advances in Physics X (invited review article), 5, 1749884, 2020. https://www.tandfonline.com/doi/pdf/10.1080/23746149.2020.1749884?needAccess=true

2. *Strong light-matter interaction*, **P. Vasa**, Encyclopaedia of Applied Physics, Wiley online library, **2019** (tutorial article). https://doi.org/10.1002/3527600434.eap828

Prof. Anshuman Kumar

Optics and photonics (experiment and theory)

Laboratory of Optics of Quantum Materials (LOQM)

Website: http://loqm.tech

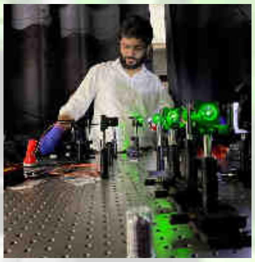
General introduction to our group:

Principal Investigator: Prof. Anshuman Kumar
Physics Department (1st floor), IIT Bombay
Laboratory of Optics of Quantum Materials (LOQM) -- http://loqm.tech

In simple words, the main focus of our current research is exploring fundamental physics and building unique technological solutions using natural and artificial two dimensional materials such as graphene, MoS_2 and metasurfaces. Such materials display many unconventional optical properties which are not found in usual three dimensional materials. We are interested in applications of our work in energy harvesting, sensing, sub-wavelength imaging and optical circuitry.

Here are some candid photos of us working in the lab:



In recent years, we have made a number of important contributions to the field, which were widely covered in the popular press:

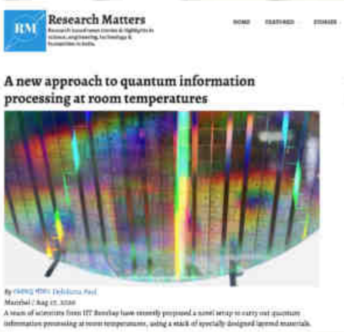

BusinessLine

Science

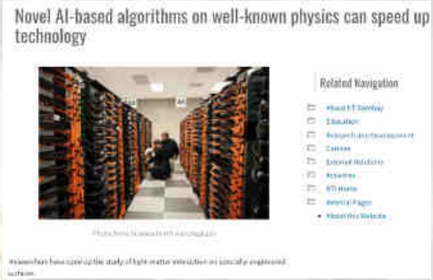
Warming up for speed computing

Indian scientists are steadily making a path towards achieving quantum computing at room temperature

Quantum computers have held the popular imagination since the


Research Matters

A new approach to quantum information processing at room temperatures


Novel AI-based algorithms on well-known physics can speed up technology

Related Navigation

PhD topic for **Optics and Photonics group** at LOQM

Principal investigator:

- Prof. Anshuman Kumar, Physics

Project:

Title: Valleytronics in two dimensional semiconductors via metamaterials
Subgroup to apply: Photonics Experiment or Theory
Positions available: 2

Project abstract:
Recently, atomically thin transition metal dichalcogenides (TMDCs) of the form MX2 (M = Mo,W; X = S, Se, Te) have emerged as a new class of semiconductor materials for both fundamental physics exploration in two-dimensional systems and device applications These monolayer semiconductors are manifested by a direct band gap between the extrema of valence and conduction bands residing at the energy-degenerate K and K' points of the Brillouin zone (called valleys). Harnessing this valley degree of freedom (analogous to spin up/down degree of freedom in spintronics) in TMDC monolayers for quantum information processing requires coherent manipulation of excitons in the K and K' valleys.

Metamaterials are artificial assemblies of nanoscale elements which act as an effective media allowing us to mold the light field in any desired way. Metamaterials derive their properties not from the properties of the base materials, but from their newly designed structures. Such systems have immense applications in the areas of invisibility cloaking and diffraction limit breaking superlenses and lead to counterintuitive phenomena such as negative refraction.

In order to manipulate the valley degree of freedom in TMDCs, in this project we will explore ways to engineer the excitonic emission in the two valleys of TMDCs by tuning the local optical density of states via metamaterials. Being at the intersection of these fields, this project would enable you to learn cutting edge techniques in lasers, nanophotonics, nanofabrication and condensed matter physics.

The project has two parts, one theoretical/computational and another experimental. The theoretical part would involve two kinds of calculations: 1) optical susceptibility of 2D semiconductor heterostructures and 2) optical density of states in metamaterials using fully numerical and semi-analytical techniques being developed by our group. Experimental side would involve nanofabrication of metamaterials via electron beam lithography and photolithography, deposition of 2D materials and optical characterization of these coupled modes. **Depending on the interest of the student one can switch to a completely theoretical or completely experimental project. There is scope for pursuing new directions as per student interest within the general field of nano-optics of 2D materials.**

(You may contact the PI for further details about this project)

PI: Prof. Mithun Kumar Mitra

Research Group: Theoretical Biophysics Group
Research Field: Soft Matter Physics - Theory

Website: http://home.phy.iitb.ac.in/~mithun/ **Email:** mkmitra@iitb.ac.in

Research: My group uses theoretical and numerical techniques from equilibrium and non-equilibrium statistical mechanics, soft matter physics and dynamical systems to study the *physics of living systems*. Some of the main themes of our research include -

(i) The physics of development in early embryos - What are the physical principles that control the development process in early embryos? How does the complex organization of living systems arise from simple physical laws?

(ii) Spatial organization of the genome - What physical forces control the organization of DNA inside a nucleus, and how does this structural organization impact the functioning of chromosomes?

(iii) Intracellular transport by molecular motors - How does stuff (proteins/vesicles/...) get transported inside cells? How do non-equilibrium processes controlled by the consumption of ATP ensure reliable deterministic transport?

Please see my group website for further details.

Vacancies: ONE (1)

Interested candidates may contact me by email prior to the admissions process.

Requirements: We are looking for a strongly motivated PhD student who wishes to work on the exciting new frontier of the physics of living systems. The interested student should have

- A strong background/interest in theoretical physics, specifically statistical physics (equilibrium statistical physics and preferably non-nonequilibrium physics and stochastic processes).
- Strong coding skills - Our research involves simulations as well as theory. You should be able to demonstrate strong coding skills (in any language of your choice). Previous demonstrable coding experience is desirable.
- Broadly, you should have an interest in biology and living systems. Previous exposure is NOT required, however you should be excited about learning about such systems. Some of our research involves working in close collaboration with experimental biology colleagues, both in IIT Bombay and elsewhere in India.

Further reading: https://physics.aps.org/articles/v12/2

Selected recent publications from group:

1. The Accidental Ally: Nucleosome Barriers Can Accelerate Cohesin-Mediated Loop Formation in Chromatin
2. Dynein catch bond as a mediator of codependent bidirectional cellular transport
3. Cyto-architecture constrains the spread of photoactivated tubulin in the syncytial Drosophila embryo

Complexity and emergent behaviour in non-equilibrium systems.
Prof. Raghunath Chelakkot (Soft matter and Nonlinear dynamics)

"*Ideas thus made up of several simple ones put together, I call Complex; such as are Beauty, Gratitude, a Man, an Army, the Universe*."
—John Locke, An Essay Concerning Human Understanding

Understanding the complex emergent behaviour of large systems consisting of many interacting entities has been both challenging and exciting for physicists over the past decades. Although conventional theoretical tools were highly successful in studying
the inanimate physical world, the progress in understanding 'complex' systems has been slow and staggered. In particular, the hierarchical organisation and the continuous development of *living matter*, from cellular to organismic scale, remain one of the most difficult problems to crack. However, recent technological enhancements have enabled us to gather more information about these systems, thus providing a new opportunity to understand their properties. (You may watch *2017 Buhl Lecture: The Physics of Life:* by W. Bialek for further information).

One way to approach the problem is to develop minimal theoretical models that reproduce the large-sale behaviour of such complex systems. In the past decades, the area called 'active matter' emerged as a highly promising candidate. In such systems, the individual entities execute autonomous motion, which, combined with simplified interactions, leads to large-scale properties. A major difference with a more familiar, inanimate physical matter is that these 'active' entities burn energy at the microscopic level and produce useful work. This continuous consumption of energy at the microscopic scale makes such systems inherently non-equilibrium. Because of these properties, the active matter models are now widely used to study the emergent behaviour observed in the biological living matter.

The major theoretical challenges in this field are the following.

1. Characterise the new and complex structures which emerge in active matter models and study them using the theoretical and computational tools of non-equilibrium statistical physics and nonlinear dynamics.
2. Extend the conventional computational and analytical tools used in theoretical physics to understand the collective behaviour in active systems.
3. Using the underlying symmetry of the systems, develop mean-field 'active' models to study the non-equilibrium dynamics.

Being a new research area, there is a large number of research problems waiting to be explored. Solving them demand a creative application of analytical and computational tools, hence an exciting experience for researchers. Each of these topics takes us a tiny step closer to understanding the complex spatiotemporal organisation in living matter.

A few relevant publications

M. Sanoria, R. Chelakkot, A. Nandi, *Percolation transition in phase separating active fluid* (2022)
S. Das, R Chelakkot *Morphological transitions of active Brownian particle aggregates on porous walls*, Soft Matter (2020).
R. Chelakkot, L Mahadevan *On the growth and form of shoots,* J. Roy. Soc. Interface (2017)

Physics of Living Systems (Theory)

Principal Investigator: Amitabha Nandi
Department of Physics,
Indian Institute of Technology Bombay, Mumbai
Email: amitabha@phy.iitb.ac.in

Our research involves the study of physical processes that govern biological systems at various spatial scales. There has been a growing interest during the last two decades in studying biology using quantitative approaches. Significant advancements in experimental techniques have led to a better understanding of mechanical and dynamical processes inside cells and tissues, thus opening up a box full of exciting and challenging questions for theoretical physicists, mathematicians, and engineers.

If you are new to this field of research, here is an article and a lecture video which you may go through to get an overview:

(1) The Physics of Life, article by Gabriel Popkin,
(2) The Physics of Life: How much can we calculate , talk by William Bialek

An important recurring feature of biological systems is the emergence of new properties at larger spatial and temporal scales caused by the interaction among the microscopic constituents. The seminal article by P. W. Anderson, titled More is Different may shed further light on this idea.

We use theoretical and computational techniques to study various dynamic processes inside living cells and their implications to key functions of a cell and to *morphogenesis*, namely, the process of development of an organism. To do this, we use methods from non-equilibrium statistical mechanics, nonlinear dynamics, and soft-matter physics.

Research projects

1. *Study of transport inside cells*

Intracellular transport is a complex non-equilibrium process that allows reliable delivery of material, thus enabling the proper functioning of a living cell. Cargoes inside cells are transported both passively by diffusional mechanisms, as well as actively, due to non-equilibrium forces generated locally within the cells. While diffusional transport helps the cargo probe, the local environment, active transport, on the other hand, is helpful to traverse large distances in a directed way. Our goal is to study the mechanisms of active transport in various scenarios by developing theoretical models that take the non-equilibrium forces into account. Examples include the study of active transport along axons in neuronal cells and the active transport of vesicles during endocytosis.

2. *Study of cytoskeletal and tissue dynamics in the hydrodynamic limit*

The active gel formalism to describe the cytoskeleton as an out-of-equilibrium continuum fluid has been very successful in describing and understanding several biological functions of a living cell. We are interested to use and improvise this theory to study complex dynamic behaviors at cellular and tissue-scale. Examples include the study of cell division and the emergence of spatio-temporal instabilities in cells and tissues.

3. *Physics of morphogenesis*

During the course of development of an organism, tissues are dynamically remodeled due to mechanical forces generated within the cells, causing biological functions like cellular rearrangements, cell division, and apoptosis (cell death). This further drives spatial organization at larger length-scales, causing the formation of complex biological structures, like the different organs with highly specialized functions. We are interested in how forces of non-equilibrium origin are generated and how they redistribute various chemical agents or morphogens spatially, leading to the formation of spatial structures. This involves theoretical study of collective cellular flows and the formation of morphogen (chemical) gradients using theoretical and computational techniques.

To see publications from our group, please visit our website

Join Us

We are looking for motivated Ph.D. candidates interested to work on theoretical problems on the physics of living systems. Our research often involves collaboration with experimentalists. A short term aim would be to develop theoretical models using inputs from experiments, to explain the phenomena seen in experiments, and, to come up with predictions/hypothesis that can be further tested in experiments. A long term goal would be to work in developing a theoretical framework that can be used to understand some of the generic features across biological systems. We seek candidates with:

1. a strong background in theoretical physics and mathematics,
2. good programming skills, and,
3. strong motivation to work at the physics-biology interface. Previous knowledge of biology is not required.

Interested candidates may get in contact with me via email. More details about the IIT-B Ph.D. program can be found here.

Gravitational wave astronomy with binary black-holes Archana Pai

The field of gravitational wave astronomy is where radio astronomy was in 1930s when Karl Jansky detected radio waves from the MilkyWay galaxy at Bell Telephone Laboratories. In last several decades, radio astronomy has unravelled so many mysteries of our universe with the discovery of many stars and galaxies, as well as observation of new class of objects like quasars and pulsars. The LIGO(Laser Interferometric gravitational wave observatory) started taking observational data since September 2015 after achieving an impressive strain sensitivity of the order of few times 10^{-24} per sqrt Hz. The European gravitational wave interferometer Virgo joined the observational run of LIGO last year in the second observational run. During the past three observational data runs, the LIGO-Virgo detectors have observed several tens of binary black hole mergers as well as merger of binary neutron star and neutron star black hole merger. The detections has unraveled many puzzles in astronomy, cosmology and gravity. To name a few, clear evidence of the existence of stellar mass black hole above 25 $M_{\odot}$, alternative formation channel for stellar mass black holes which is the merger of two compact objects forming more massive and possibly black hole, direct conclusive evidence of the existence of the intermediate mass black hole in gravitational wave astronomy, known as GW190521[2]. The detection of this system has opened up questions on the black hole formation scenarios. The electromagnetic follow-up of the binary neutron star culminated in to unraveling the long standing short-Gramma Ray Burst Puzzle [3-4]

My research group is a member of LIGO Scientific collaboration(LSC) and is one of the leading groups in LSC working on detection of intermediate binary black in the LIGO-Virgo data. The group lead the intermediate mass black hole search in the third observational run [5]. The PhD student lead the development of the matched filter based massive black hole binary search which was deployed during the third observational run [6]. The improvements made by another PhD student lead to the detection of GW190521. The group is also involved in developing methodology to detect gravitational waves from the eccentric binary system [7].

The following two research projects will be offered for the selected candidate.

1. **Exploring Machine Learning techniques in searching for generically spinning intermediate mass black hole systems in the gravitational wave astronomy** – In this project, the student will explore Machine Learning ideas for gravitational wave searches from massive black hole binaries. The project is computational in nature and involves aptitude of playing with data. The student is required to have strong background in physics, statistics as well as python/matlab/C as well as Linux.

2. **Exploring time-frequency based morphological approaches in eccentric black hole binaries** – We lack template based approaches in the detection of eccentric compact binary systems. Neverthless, clear indication of the eccentricity will carry information about the formation channel. In this project, we plan to develop exploratory ideas to detect stellar mass eccentric binary systems. The eccentricity leaves definite signatures in the time-frequency representation of the signal which can be exploited to probe the eccentricity [8]. The project is analytical cum computational in nature. The student is expected to have background of python/matlab/C as Linux operating system.

For summary of publication: GoTo department page

References

[1] LIGO Scientific and Virgo Collaborations (Abbott B P,... **A. Pai,**....et al.), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett., **116**, 061102 (2016)

[2] LIGO Scientific and Virgo Collaborations (R. Abbott ,... **A. Pai,**....et al.), *GW190521: A Binary Black Hole Merger with a Total Mass of 150* $M_{\odot}$ Phys. Rev. Lett. **125**, 101102 (2020)

[3] LIGO Scientific and Virgo Collaborations (Abbott B P,... **A. Pai,**....et al.), *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral,* Phys. Rev. Lett. **119**, 161101 (2017)

[4] LIGO Scientific and Virgo Collaborations, EM Partners (Abbott B P,... **A. Pai,**....et al.), *Multi-messenger Observations of a Binary Neutron Star Merger*, Astrophys. J. Lett., **848**, Issue 2, L12, 59 pp. (2017).

[5] LIGO Scientific and Virgo Collaborations (B.P. Abbott ,... **A. Pai,**....et al.), *Search for intermediate mass black holes in the third observing run of Advanced LIGO and Advanced Virgo*, A&A, 659 (2022) A84 arXiv:2105.15120

[6] K. Chandra, V. Villa-Ortega, T. Dent, C. Mclsaac, **Archana Pai**, I. W. Harry, G. S. Cabourne Davis, and K. Soni, *Optimized PyCBC search for gravitational waves from intermediate-mass black hole mergers,* Phys. Rev. D **104**, 042004 (2021)

[7] LIGO Scientific and Virgo Collaborations (B.P. Abbott ,... **A. Pai,**....et al.), *Search for Eccentric Binary Black Hole Mergers with Advanced LIGO and Advanced Virgo during their First and Second Observing Runs*, Astrophys. J. 883 (2019), no. 2, 149

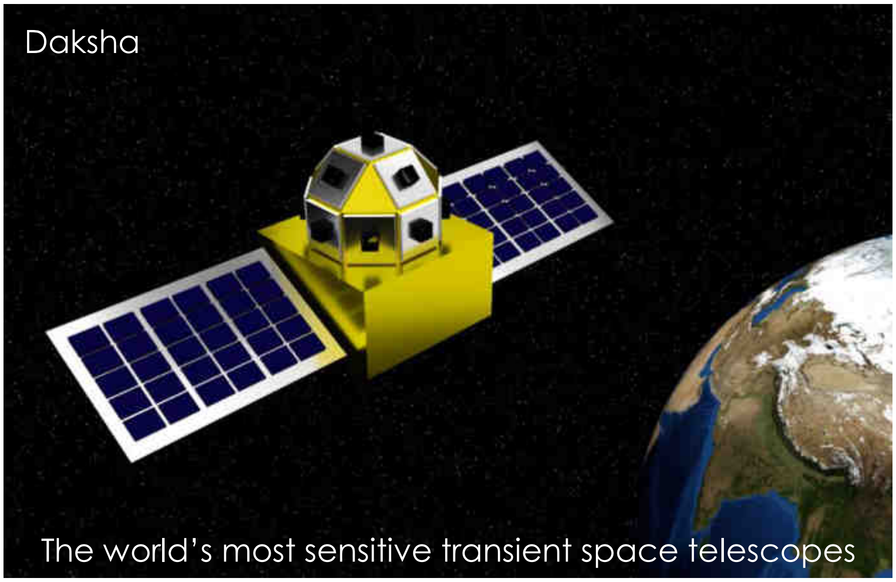
[8] Nirban Bose and **Archana Pai**, *Effective chirp mass in the inspiral frequency evolution of the non-spinning eccentric compact binary,* Phys. Rev. D. **104**, 124021 (2021)

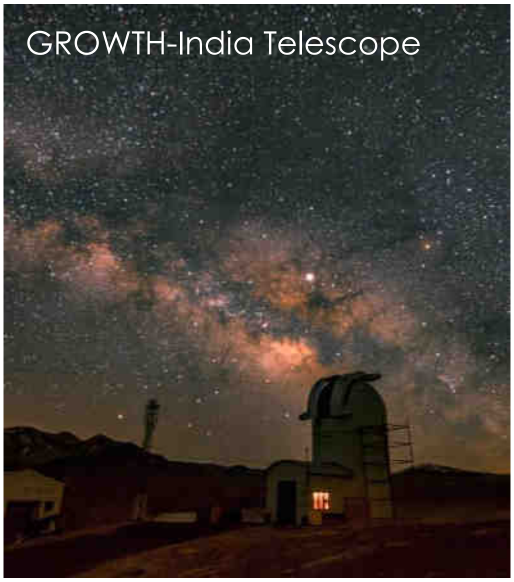
SPACE TECHNOLOGY & ASTROPHYSICS RESEARCH

STAR LAB

•

VARUN BHALERAO





Astrophysics

Transients, X-ray sources, Instrumentation

We study the most energetic objects and explosions in the universe: including Gamma-Ray Bursts, Gravitational Waves, Supernovae, Neutron Star binaries, near-earth Asteroids, Fast Radio Bursts, and many astrophysical transients.

Our group specializes in development of cutting-edge instruments for Astrophysics. We played the central role in the development and automation of the GROWTH-India telescope: India's first and only fully robotic research telescope. As a part of the core instrument team for AstroSat CZTI, we develop new techniques for searching for transients. Our group leads Daksha: an ambitious project to develop the world's most sensitive space telescopes. We are working on the science and engineering aspects: designing, building and testing the electronics and mechanical systems of the space telescope. Our large group consists of students with physics and engineering backgrounds. *We are especially interested in students with a strong electronics background in addition to physics.*

For more details see:
https://www.star-iitb.in/