Harvard-MIT Undergraduate Research Conference

A Collaboration Between Harvard and MIT SPS

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The Statistical Physics of the Effect of Translation Dynamics on the Membrane Localization of mRNA in Bacteria

Elgin Gulpinar

Recently, there have been experimental observations of non-uniform gradients of specific mRNA involved in antibiotic resistance pathways in bacterial cells. The surging medical and societal cost of the failure of antibacterial drugs against resistant bacteria, or superbugs, makes such systems very important to study. We seek the understanding of the reasons behind such mRNA gradients, the effective ways in which they can be perturbed, and the thermodynamic variables (temperature, concentration etc.) they are related the most to. Our mathematical machinery involves simulations to reproduce what happens in real cells and theoretical analysis in order to understand them, to see how we can obtain a big picture of the network and perhaps interfere with it. Currently, we are working on explaining the localization of an mRNA onto the cell membrane of E. Coli. Though mRNAs themselves cannot attach to the cell membrane, the domains of the proteins they help synthesize can. During protein production, the synthesis machinery moves along the mRNA and holds the mRNA and the nascent protein together. Thus, the existence of membrane binding domains on the already made part of the protein makes it possible for the mRNA to anchor to the membrane, until protein production is done and the machinery lets go of the mRNA. This mechanism suggests that membrane localization depends on factors such as the collision rate with the membrane, the stickiness of the proteins membrane binding domains, the size of the remaining part of the protein to be produced, and the availability of more free anchors on nascent proteins being simultaneously made by other synthesis machinery progressing along the same mRNA.
Spin-Orbit Coupling in Bose Einstein Condensation with Novel Quantum Phases

Sean Burchesky

Spin orbit coupling adds richness to the conventional two-component Bose-Einstein condensate by providing a means to mix spins and an external degree of freedom. The phase diagram of a psuedo-spin-\(\frac{1}{2}\) spin orbit coupled Bose Einstein Condensate consists of three distinct phases. Two of the possible phases have been observed and characterized. The third phase, the “stripe phase”, is interesting in the sense that the BEC spontaneously develops a periodicity, thereby breaking the continuous translational symmetry of the Hamiltonian. The stripe phase spontaneously develops a condensate phase and breaks translational symmetry while remaining a superfluid, therefor meeting the requirements of a non-trivial supersolid. Finally, I will present some preliminary results on the observation of the stripe phase in the BEC 2 Lab at MIT.

Higher operads and formalizing higher-dimensional topological quantum field theories

Sanath Devalapurkar

In 1988, Michael Atiyah proposed axioms to formalize Edward Witten’s theory of “topological quantum field theories” (TQFTs), which are quantum field theories (QFTs) where the Hamiltonian is zero, i.e., where there is no nontrivial dynamics through time. Such things are important because studying QFTs on such a spacetime yields topological invariants, and hence gives interesting information about the spacetime itself. They are also one step to making precise the notion of a path integral as introduced by Feynman. In order to simplify computations, Atiyah’s formalism was extended to higher dimensions. This motivated the cobordism hypothesis, which says that you can generate a bunch of TQFTs simply by looking at different Hilbert spaces (complex vector spaces). A sketch of a proof of this conjecture using higher category theory was given by Jacob Lurie in 2010, but there are many aspects of his proof that still need to be made formal. I’ll talk about “higher operads”, and discuss how my work on these objects is one step to formalizing his proof and the theory of higher-dimensional TQFTs.
In the 1970s, astronomers noticed a discrepancy between the measured total kinetic energy of galaxies and the energy that theoretical models predicted given the total mass of all the stars and other visible matter in the galaxies. In order to account for this discrepancy, cosmologists proposed the existence of dark matter, an undiscovered form of matter which does not emit or interact with light except gravitationally, and is made up of particles outside the Standard Model of particle physics. Dark matter particles could possibly scatter with baryons, such as protons and electrons. If elastic scattering between dark matter and baryons really occurs, it would affect the development of the universe in detectable, quantifiable ways. In particular, it would create observable changes in linear density fluctuations in the early universe. By analyzing data from the Cosmic Microwave Background and the Lyman-alpha forest, we can place constraints on the strength of dark matter-baryon scattering. This will allow us to narrow down the range of masses that dark matter can have in scattering models. I am studying the elastic scattering between dark matter and electrons in the early universe, from right after the Big Bang up until recombination, when electrons combined with protons to form hydrogen atoms. Using theoretical models, I compare the momentum exchange between dark matter and electrons to that between dark matter and protons to see if there are any regimes of dark matter mass and redshift in which the electron momentum transfer dominates over the proton momentum transfer.

Using explicit constructions of the Weierstrass mock modular form, we offer a closed formula for generating the values of shifted convolution L-values for certain elliptic curves that can be computed to arbitrary precision. These identities provide a surprising relation between weight 2 newforms and shifted convolution L-values.
11:40 AM

32-141

KEYNOTE SPEAKER

Professor Alan Guth

12:40 PM

Lunch

1:20 PM

32-141

KEYNOTE SPEAKER

Professor Isaac Silvera
Target Surface Characterization for Laser Driven Acceleration

Ziyuan Chen

Recent years, ultra-intense lasers have opened up a new, broad field of research and applications. However, during the interaction with such an intense laser and e.g. a solid material, many experimental conditions are challenging to measure. As a result many of these parameters are not accessible in today's state-of-the-art experimental setups. In order to improve the understanding of the physical phenomena it is necessary to develop novel diagnostics which can measure more of the significant parameters. In the case of laser driven particle acceleration, where the laser interacts with a target surface and accelerates ion beams, one of the unknown parameters is flatness of the target surface. Off-line measurements of different materials have been done, however when mounting the target into the vacuum apparatus the target can deform. Moreover, a local variation of the flatness at the laser target interaction point is difficult to determine due to a limited accuracy of the target to laser alignment. We aim to measure the surface roughness of the target surface for laser driven particle acceleration. The used target is a tape drive based target system, which provides a fresh surface after each laser shot. Due to the nature of the tape drive variations in the surface roughness are inevitable. We are characterizing the surface by reflecting a regularly patterned laser probe beam from the surface onto a screen and then comparing the measured pattern from the original pattern. Based on this data, the function of the surface can be reconstructed, and its shape can be obtained.

Experimental Fixed Point Quantum Search

John Peurifoy

Experimental demonstration on a NMR spectrometer of fixed point quantum search, as well as Grover's algorithm, Deutsch-Jozsa, and a general description of working with Bruker Spectrometers. Talk is designed for those who have familiarity in quantum mechanics and Hamiltonians.
Deuterium Neutral Beam Orbits in NSTX-U Nonaxisymmetric Vacuum Magnetic Fields
Jonah Philion

Axisymmetry of the tokamak magnetic field provides good fast ion radial confinement. Perturbations from this symmetry could induce fast ion radial diffusion and loss. A nonaxisymmetric perturbation was chosen to model the effect of this symmetry loss on NSTX-U deuterium neutral beam ions. Passing and banana orbits in the perturbed field were simulated by integrating the Lorentz force over a duration shorter than the collision time of ions. Upon comparison with analogous orbits in the unperturbed field, the perturbation is shown to have a dispersive effect on the magnetic moment of particle orbit guiding centers. In particular, banana orbits acquire oscillating magnetic moments when subject to the nonaxisymmetric field. The behavior is modeled as a diffusion coefficient which varies with the magnetic moment and canonical angular momentum of the orbit.

Probing High-Temperature Superconductivity with Extreme Pressures
Grace H. Zhang

Superconductors carry electrical currents with zero resistance, capable of transferring power without energy loss, expelling magnetic fields to levitate trains, and producing interference effects in quantum circuits. Unlike low-temperature superconductivity, which occurs in conducting parent metals, high-temperature superconductivity is born out of ceramic insulators cuprates, typically sheets of copper oxide sandwiched between charge reservoirs. These materials exhibit a plethora of intriguing quantum orders; in particular, the copper oxide layers behave like an electronic traffic jam under normal conditions but paradoxically superconduct upon donations of extra charge carriers from the charge reservoirs. In this work, we study the effects of pressure on these charge carriers, in context of these cuprates phase diagrams, which map out the boundaries at which these different quantum orders appear and vanish under varying conditions of the material itself and its environment. We demonstrate high pressure as a tool for accessing and controllably exploring previously uncharted territories of the cuprate phase diagram and introduce techniques for investigating their electronic structure under these extreme conditions.
Cape Cod: New Orleans of the North

Matthew Cappucci

Buzzards Bay has infamously been dubbed “New Orleans of the North” by some, given that it has the highest theoretical storm surge output for a Category-4 hurricane as simulated by NOAA’s SLOSH model for any point in the contiguous United States. Past hurricanes have shown how vulnerable New England is to strong tropical cyclones, such as was the case during the Hurricane of ’38, but to what extent could something of this nature befell the Cape again? And, to a greater extent, how prepared are we for such an occurrence? This brief presentation will give a closer look at many of these questions that have thus far remained concealed “under the radar.”

Majorana Teleportation—Phase coherent Electron Transport via Majorana Bound States

Jonathan Ward

Everything in the universe can generally be divided into two categories: matter and antimatter. One spin-$\frac{1}{2}$ particle eludes this binary—the Majorana Fermion. The Majorana is both matter and antimatter; it acts as its own antiparticle. The first signatures of the Majorana, discovered in 2012, demonstrated a quasi-particle with zero-energy—a necessary prerequisite for a particle to be its own antiparticle. Subsequently, in March 2016, experimentalists found evidence for the topological nature of the quasiparticle pair—the energy of each constituent particle grew better defined as the distance between the particles was increased. The ongoing objective is now to demonstrate that an electron can occupy the nonlocal state associated with a pair of Majoranas and then return to its original local state. This nonlocal state is expected to facilitate the transport of the electron over a long distance while maintaining the phase of the electron—this is termed “Majorana teleportation”. I will discuss an interferometry-based method for detecting Majorana teleportation.
The ‘Typical’ New England Tornado

Matthew Cappucci

Though Massachusetts may be far from the traditional “Tornado Alley,” statistically there once was a time when, per unit area, Massachusetts averaged the most tornado fatalities in the entire nation out of all fifty states. How can that be? Do statistics lie? In just the past five years, Massachusetts has bore witness to all types of tornadoes, ranging from supercellular to LEWP/convective fineline to outflow-boundary-related to fair-weather to tropical, and everything in between. We’ve had tornadoes at 3 AM, 3 PM, 10 AM, and 10 PM but is there any correlation? A look at the past five years of New England tornado climatology will provide an inside glimpse as to just how well-known Massachusetts should be for its twister history.

Anisotropic Dielectric Tensors in 2D Heterostructures

Zachary Hall

Much of the last two decades of materials research has focused on 2D materials such as graphene; but although they offer incredible electronic properties, actual 2D materials have been challenging to realize beyond the mesoscopic scale. van der Waals heterostructures, 3D metamaterials composed of 2D layers held together by van der Waals interactions, promise to realize these extraordinary electronic properties at greater length scales. Further, because the layers fall well within the interaction regime, it is hoped that these heterostructures will reveal new and exciting properties as they are studied. This interaction between layers, however, means that electronic properties of van der Waals heterostructures are extraordinarily difficult to calculate. Due to new computational tools, rigorous calculation of these properties has only just become possible. We will present calculations for graphene-hBN metamaterials with interesting anisotropic results.
Controllability of Unitary for Quantum Computation

Baian Chen

Corresponding to the “if-then” clause in classical computation framework, Controlled-Unitary also plays a significant role of “if-then” clause in quantum computation and algorithm. It is widely used in quantum algorithms like Grover’s and Shor’s algorithm, but actually arbitrary Controlled-Unitary is not trivially constructable. Due to the possible entanglement of systems, we cannot simply construct and then discard a supporting system after computation, and due to no-cloning theorem, an arbitrary Controlled-Unitary cannot be constructed trivially by controlled-copy as what we’ve done in classical framework. Thus, it is important to figure out the controllability of different group of unitary, and develop protocols to control them.

Selective Excitation of NV Centers in Diamond

Amir Karamlou

The nitrogen-vacancy (NV) centers in diamond hold a great potential in the field of quantum information processing. The ground state is a spin triplet with two levels ($m_s = \pm 1$) degenerate at zero magnetic field. In this work, we came up with a mechanism to make transitions between $m_s = \pm 1$ at zero field splitting.
Spectral Reshaping using Polaritons: Influencing UV Dynamics with IR Polaritons

Jamison Sloan

I will discuss my summer research in which I investigated the ability of light confining materials like graphene to change and reshape the spectrum of an atomic emitter. I found significant ability of graphene to enhance the radiative spectrum of a hydrogenic emitter. The impact of using different models of the conductivity of graphene was also assessed with strong results. The future of the project will involve making even more realistic predictions that can be used to plan future experiments.