PHYSICS
ARTS & SCIENCES

SUMMER RESEARCH OPPORTUNITIES FOR UNDERGRADUATE students

FOR APPLICATION YEAR: 2024

PROJECT TITLE: **Spin Fractionalization in Kondo Lattices**

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Project Description

Overview - This is a project in the general area of theoretical condensed matter physics, in which we study how the quantum behavior of many electrons leads to various properties that materials exhibit. This is important from both fundamental understanding of the nature and potential applications point of view. The universe we live-in is governed by the standard model which describes the ground state, a.k.a. the vacuum as well as the low lying excitations, a.k.a. the elementary particles on this vacuum background. This understanding based on quantum field theory [1] is verified by many experiments using large and expensive synchrotrons with extremely high energies.

In condensed matter, however, each class of materials is a mini-universe with its own vacuum and excitations but nevertheless is governed by similar quantum field theories. The advantage is that the energy scales are much smaller and theoretical predictions can be verified using much cheaper table-top experiments around the globe. Furthermore, unlike the universe in these systems the vacuum and excitations are tunable using various knobs that are available to the experimentalist.

One such problem is the confinement of quarks into protons and neutrons. Normally, gluons create an attractive strong force between quarks that becomes stronger with distance. Thus it is impossible to move apart the constituent quarks of a proton. Imagine a universe in which one could tune the coupling so that at some specific threshold, the quarks become deconfined. Since the quarks carry fractional charges, this process is tantamount to charge fractionalization. These research topics belong to the general area of strongly correlated systems, i.e. systems in which many fermions interact strongly with each other. In this limit, many of the standard approaches to study quantum systems breaks down and new and creative approaches are needed.

In this project we deal with the problem of spin fractionalization in a

strongly correlated system called Kondo lattice model [2, 3]. This model is used to theoretically study a class of materials called heavy fermions. The model has a vacuum and its low-lying excitations are spin-1 particles that are called magnons. To simplify matters we use a strong coupling expansion, which assumes the vacuum has relatively low correlations [4]. We would like to see under what conditions these magnons fractionalizes into their, more elementary, constituent spin-1/2 particles which are called doublon and holon. The doublon and holon attract each other and under usual circumstances, they are trapped into a magnon boundstate by a confinement force. Such fractionalization has application in fault-tolerant topological quantum computation, as storing information in non-local qubits made of fractional particles protects them against decoherence and local noise sources.
One way to achieve such fractionalization is by introducing an attractive Coulomb interaction between electrons. Although this is normally not feasible, together with an undergraduate student we have shown that one could engineer heavy fermion materials in proximity to a superconductor [5]. This effectively has the same effect, creating a repulsion between doublon and holon that leads to fractionalization of the magnon. This is a prediction that experimentalists can verify by scattering neutrons from heterostructures made of heavy fermions and superconductors.

Specific Aim - The specific aim of the project is to study whether such fractionalization can take place naturally. In a Kondo lattice, the uncertainty principle allows virtual doublon-holon pairs to be created and shortly-after annihilated, so that the vacuum is not an empty space. Rather it is a plasma of bubbling doublon-holon pairs, very similar to the electron-positron plasma in the vacuum of the universe. The goal of the current project is to see whether this plasma by itself can lead to fractionalization of a given magnon. The importance of the plasma is that such virtual doublon-holon pairs are quantum mechanically indistinguishable from the doublon-holon of a magnon and can exchange a partner, effectively modifying their interaction. Furthermore, they can get polarized and screen the electromagnetic interaction between the doublon and holon of a magnon boundstate. We will assess to what extent these effects are successful in liberating the doublon and holon out of a magnon. We will cast the resulting liberation in terms of deconfining transition of the gauge fields. Furthermore, we will focus on computing experimentally measurable quantities, and potentially collaborate with experimentalists on verifying theoretical predictions.

Strategy - The first goal is to derive an effective Hamiltonian describing the system. This is equivalent to a large matrix whose eigenvalues are the spectrum of the system. The next step is to diagonalize the Hamiltonian. To this end, we use a technique called renormalization group (RG), which allows to gradually take into account the influence every doublon-holon pair have on a given magnon. This is tantamount to iteratively diagonalizing a large matrix. To this end, we draw Feynman diagrams that represent elementary processes involved and derive the so-called RG equations. These are a set of differential equations that govern the evolution of the system in the configuration space. Once integrated out, we can predict the behavior of the Kondo lattice. In particular we are interested in computing the so-called dynamical spin susceptibility which can be measured experimentally via neutron-scattering spectroscopy. Consequently, the project may involve collaboration with the Oak Ridge National Laboratory, but this is yet to be determined.

Mentoring plan - The projects I assign to students are usually so challenging that we have to work on it together and typically they require work beyond the duration of two month to come to a full fruition. Nonetheless, there are concrete milestones that can be passed along the way. We meet twice a week and find how to proceed. Throughout my career and now as a PI, I have had a successful experience with undergraduate internship, the most recent case is Ethan Huecker, who did his capstone project with me on fractionalization in Kondo lattice heterostructures. Our work led to the paper [5] which Ethan presented in person at the APS March meeting 2023. I also organized a series of journal clubs on topology following lecture notes by John McGreevy, in which Ethan played a major role. It was a pleasure seeing his scientific maturity over the course of the project, and also helped me to learn how to dissect an ambitious idea into smaller projects with clear milestones. We also have outdoor group activities to help team building and collaboration within the group. After leaving my group, Ethan started his graduate studies in University of Florida since Sept 2023.

Required Background - This is an advanced project at either graduate or senior undergraduate level. It assumes that the student has a solid background in mathematics and has had two semesters of quantum mechanics and is proficient with linear algebra and the ket/bra language. Familiarity with 2nd quantization and a coding language like Python or MATLAB is very helpful but not necessary.

References -

[1] E. Fradkin. Quantum Field Theory: An Integrated Approach (Princeton Univ. Press) (2021).
[2] P. Coleman. Introduction to Many-Body Physics (Cambridge Univ. Press) (2015).
[3] H. Tsunetsugu, M. Sigrist & K. Ueda. “The ground-state phase diagram of the one-dimensional kondo lattice model.” Rev. Mod. Phys., 69, 809-864 (1997).
[4] J. Chen, M. Stoudenmire, Y. Komijani & P. Coleman. “Matrix product study of spin fraction- alization in the 1d kondo insulator.” Preprint: Arxiv:2302.09701 (2023).
[5] E. Huecker & Y. Komijani. “Spin fractionalization in a kondo-lattice superconductor het- erostructure.” Phys. Rev. B, 108, 195120 (2023).