Academic Goals

High-energy Astrophysics A fundamental process in plasma physics is magnetic reconnection – the breaking and reconnection of magnetic field lines across a magnetic shear, during which released magnetic energy is converted into plasma kinetic energy. In strongly magnetized astrophysical plasmas, relativistic magnetic reconnection is theorized to be fundamental in governing high-energy particle acceleration and radiation [1]. Recent theoretical progress has been motivated by two questions: (i) what determines the timescale of magnetic energy release, and (ii) how particles are accelerated to high energies [2]. A complete theory of reconnection-driven particle acceleration, from subrelativistic to ultrarelativistic momenta, is still in progress.

In the extreme plasma environments surrounding compact objects, such as magnetars and black holes, strong magnetic fields heavily influence plasma dynamics. My work examines the propagation of thermal radiation from highly magnetized NSs through atmospheric plasma and the magnetosphere. As such, the study of emissions in the extreme regime of relativistic reconnection is a natural extension. Advancements of late can be attributed largely to particle-in-cell (PIC) simulations [2]; the PIC field solver uses finite element methods (FEM) to solve Maxwell's equations. When modelling the more complex geometry of the BL1U septum magnet, I used FEM in OPERA-3d[1] to simulate field behaviour. My familiarity with FEM analysis and particle simulations is thus highly relevant for applications of PIC methods in numerical experiments. My first introduction to plasma physics was in my electromagnetic theory (PHYS 401) course, which strongly motivated me to delve deeper into plasma astrophysics and wave phenomena.

A long-standing problem in nuclear physics is determining the unknown equation of state (EoS) for cold, dense matter. The theory governing the strong interaction – quantum chromodynamics (QCD) – predicts that hadronic matter undergoes a phase transition to quark matter at sufficiently high energy densities. Although this has been observed in the appearance of quark-gluon plasma (QGP) from ultrarelativistic heavy-ion collisions [3], the EoS is incomplete for matter above the critical nuclear saturation density [4]. Such matter is thought to exist only in the cores of NSs; thus, astrophysical observations may help parameterize the supranuclear EoS and probe the properties of matter in NS interiors.

While my current efforts have been dedicated to studying NS emissions from a relatively cold, condensed surface, the principal motivation for my research is to test fundamental physics in the high-energy regime. Constraining the NS EoS investigates strongly interacting matter and its underlying theory, QCD, by studying the densest objects in the universe. My research focus is on testing strong-field QED, similarly through examination of objects and processes that cannot be replicated on Earth. The uniqueness of the extreme conditions of the high-energy universe is what drew me to the field.

Neutron pairing in the NS inner crust is described by the microscopic Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity. Sufficiently low-temperature fermions can form bound pairs (called Cooper pairs) with zero total momentum. An ensemble of such weakly-bound fermions – behaving like bosons in a Bose-Einstein Condensate (BEC) – becomes a fermionic superfluid. The spectrum of BCS superfluidity can be explored using ultracold atomic gases as a quantum simulator [5] by tuning the interatomic interaction strength. In the so-called 'unitary limit', the complete thermodynamic properties of a Fermi gas can be described by a single dimensionless number, independent of its constituents [6]. This extraordinary universal character extends across diverse systems, from cold atomic gases to dense quark matter, which aligns well with my interest in the extreme; I consider it one of the most alluring prospects of entering AMO physics.

[1] https://www.3ds.com/products-services/simulia/products/opera/

AMO physics In isolated quantum many-body systems, thermalization is thought to be sufficiently described by the eigenstate thermalization hypothesis (ETH) [7]. In essence, ETH purports to explain how local observables of closed quantum systems appear thermal, despite unitary evolution of system dynamics. Exceptions to this description are found in disordered systems, notably in integrable systems and many-body localized (MBL) phases [8]. Many open questions remain with regards to the localized/delocalized phases themselves, transitions between them [7], and the ETH range of validity. I am especially intrigued by new universality classes of quantum dynamics [9], unveiled by such MBL phases. Remarkably, systems belonging to the same universality class behave in precisely the same way, insensitive to scaling. Thus, MBL transitions are a promising avenue of study for progressing our understanding of non-equilibrium quantum systems.

Quantum entanglement, as characterized by entanglement entropy, can be used to derive statistical properties of a system from a single pure state [10] (assuming the system is in microscopic thermal equilibrium). Thus, the entanglement spectrum (ES) is invaluable for characterizing thermalization and localization in many-body systems. Moreover, the unique entanglement properties of MBL states – specifically, the ability to retain the memory of the initial state [7] – naturally lends itself to storing quantum information.

Cold-atom systems are effective for accessing the ES of many-body states, which can be realized through Ramsey interferometry of ultracold atoms in optical lattices [11]. While working with UCN, I developed a firm theoretical understanding of Ramsey's method as a similar application is used to extract the nEDM. In both cases, the measurement principle involves an acquired phase, though one is a quantum phase estimation via a controlled phase shift based on the Rydberg blockade [11] (ES), while the other relies on detecting the ensemble phase to search for energy differences (nEDM).

Neutral atom systems are a promising candidate for achieving scalable universal quantum computers (QCs), despite the low fidelity of multi-qubit gates due to crosstalk and unwanted interactions [12]. A promising solution is encoding in hyperfine states of optically trapped neutral atoms (e.g. rubidium), with multi-qubit gates mediated by exciting atoms to strongly interacting Rydberg states [13]. As atomic lifetime is directly correlated with the number of interaction cycles available in a quantum simulator, long-lived Rydberg atoms are of considerable interest. Recent experimentation has demonstrated significantly lengthened interrogation times using laser-trapped circular Rydberg atoms (CRAs) [14] in a cryogenic environment. The primary objective of my thesis was to improve nEDM measurement sensitivity, achieved by increasing UCN statistics (via simulation) or by extending neutron lifetimes (via cryogenics/moderation). Naturally, a similar approach could be applied to further improving atom-field interaction times for CRAs.

My interest in AMO also stems from its cross-pollination with numerous other fields, prominently condensed matter and nuclear physics. The highly collaborative nature of modern AMO and its applications to high-energy physics have further fueled my enthusiasm for the field. In particular, I am interested in the use of quantum simulators to study lattice gauge theories (LGTs) – describing fundamental interactions within the SM – as an alternative to numerical simulations and cost-intensive particle colliders. Large-scale simulations of Rydberg-atom arrays can emulate LGTs at the boundary of classical computational limits [15], motivating the application of these methods to probe more complex (non-Abelian) gauge theories – e.g. low-energy QCD or other non-perturbative models.

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