Graduate Research Plan

Title: Upgrade for Project 8 Neutrino Mass Experiment Using Novel Resonant Cavity Readout System

Background

Neutrinos are tiny, abundant, weakly interacting fundamental particles that play a vital role in understanding cosmic phenomena, the origin of particle mass, and in multi-messenger astronomy. The existence of neutrino mass has now been established experimentally, but its absolute scale remains unknown–**an outstanding question with profound consequences for particle physics, nuclear physics, and cosmology**. Project 8, a collaboration of 15 institutions, will measure the absolute mass scale of the neutrino through a phased program utilizing Cyclotron Radiation Emission Spectroscopy (CRES). CRES is a novel technique to measure the energies of electrons using the cyclotron radiation they emit while moving in a magnetic trap, enabling high-precision electron spectroscopy [1]. The collaboration plans to measure the endpoint of the tritium beta decay energy spectrum, which is directly sensitive to the absolute mass of neutrinos. This measurement constrains the effective electron-neutrino mass, a combination of the three neutrino mass eigenstates weighted by their electron-flavor content. With sub-eV resolution, **this measurement will enable a laboratory measurement of the absolute neutrino mass independent of cosmological assumptions.**

Within the next decade, Project 8 will advance the pre-existing experimental upper limit of 0.450 eV on the neutrino mass to a final deployed array of detectors designed to achieve a sensitivity down to 0.04 eV [2]. Achieving this ambitious goal requires a sequence of intermediate prototype systems to incrementally improve the precision of CRES measurements. The current stage of this program is the Cavity CRES Apparatus (CCA) at the University of Washington (UW), the first implementation of CRES in a resonant cavity. In this setup, the cavity captures radio-frequency “chirps” from electrons read out through a waveguide system to reconstruct their energy and motion. The current operational CCA serves as a versatile testbed where key challenges for the experiment can be addressed, including cavity design and scalable readout schemes. My proposed work is the next step: **designing, building, and running CCA+, an upgrade to the cavity system that will extend the apparatus’s capabilities.**

Intellectual Merit

I will demonstrate that cavity-based CRES can achieve the resolution needed to reconstruct the tritium beta-decay endpoint, providing a proof of principle for absolute neutrino mass measurement. By improving cavity geometries and testing advanced readout strategies for CCA+, I will demonstrate a scalable approach to absolute neutrino mass measurement. I will complete this project with [Professor] at the Pennsylvania State University, who is leading readout system design development. To create a next-generation CCA+ design, I will utilize the skills I acquired during the Penn State University REU program. There, I characterized a prototype Project 8 cavity by applying the bead-pull technique, a perturbation technique used to map the electromagnetic field modes. I eliminated systematic fluctuations with machine learning corrections and designed and analyzed upgraded readout strategies. I will leverage these skills in my project plan that proceeds as follows:

Cavity design and prototyping (Year 1): Simulations of CCA-specific candidate cavity designs will guide my prototyping of CCA+ readout systems. This will include a novel patch antenna system to replace the current CCA waveguide to ensure scalability for future detectors [3]. I will explore a multi-mode readout system that captures both electric and magnetic signals, allowing more complete reconstruction of electron events. I will validate these designs using the bead-pull technique to ensure installation readiness.

Installation, data collection, and analysis (Year 2-3): I will install the new cavity into the current CCA detector infrastructure at UW. The existing electron gun will allow me to inject electrons for precision calibration and collect data with the upgraded readout system. I will use machine learning algorithms optimized for precise track reconstruction to analyze the collected data and validate CCA+

performance. Additionally, I will incorporate bead-pull field maps into Project 8's simulation framework to generate realistic electron signals.

Applications to subsequent Project 8 phases (Year 4+): In my graduate research beyond CCA+, I will extend the work on upgraded cavity design and readout development to larger cavities to be used in subsequent phases of the experiment. My emphasis will be on event reconstruction, detector modeling, and statistical analysis of the beta decay spectrum to set an upper limit on the neutrino mass.

The plan outlined here is ambitious but feasible: the existing and operational CCA infrastructure at UW allows me to focus on upgrading its central cavity component while leveraging the collaboration's resources and expertise. Additionally, **Penn State's laboratories provide a current prototype cavity, bead-pull apparatus, and the resources of the Applied Research Laboratory for prototype fabrication**, giving me direct access to the expertise and equipment needed to support this project. The skills I acquired at the Penn State REU have prepared me to contribute effectively and independently. This proposed timeline aligns naturally with Project 8's schedule, ensuring that my results from CCA+ will directly inform the design of the subsequent stages. This project positions me to take a leading role within the Project 8 Collaboration and contribute to transformative advances in experimental particle physics.

A direct measurement of the absolute neutrino mass would have profound impacts across many fields. By measuring neutrino mass independently in the laboratory, Project 8 would **inform theoretical models of early-universe structure and evolution**. Determining the absolute neutrino mass would illuminate the currently unknown mechanism that gives rise to neutrino mass, including **whether neutrinos acquire mass through interactions beyond the Standard Model**. Project 8 may additionally be sensitive to neutrino mass ordering, sterile neutrinos, and the relic neutrino density [1].

Broader Impacts

Beyond neutrino science, the cavity-based detection and precision single-electron spectroscopy technologies developed in this project will have cross-disciplinary applications, including quantum computing and microwave instrumentation. The techniques developed for precise electron reconstruction are directly applicable to the development of superconducting qubits and microwave quantum circuits [4]. The same expertise in precision microwave engineering enables progress in quantum information processing. Within nuclear science, CRES also shows promise for applications in nuclear non-proliferation and security [5]. **This project will develop the technical and interdisciplinary skills needed to advance research in these fields, increasing collaboration among academia and industry.**

I will mentor 1-2 undergraduate students in my lab each year with detector prototyping and simulations to provide hands-on experience in experimental physics. Drawing on skills I gained from co-founding a physics mentorship club at The Ohio State University, I will guide students through experimental design and data analysis. I will assist them in preparing posters for university and conference presentations to develop their scientific communication skills, **furthering a globally competitive STEM workforce**. To engage the broader community, I will organize a graduate-student-led physics outreach table at Happy Valley's Central Pennsylvania Festival of the Arts. The team will run interactive demonstrations across a range of physics topics inspired by current experiments. To demonstrate principles used in Project 8, I will include a ball rolling in a spiral track to illustrate how electrons move in magnetic fields. Using accessible explanations and hands-on activities, **I will introduce festival visitors of all ages to fundamental physics concepts, fostering public scientific literacy and excitement about STEM.**

References

[1] A. A. Esfahani et al. (Project 8 Collaboration), Prog. Part. Nucl. Phys., arXiv:2203.07349 (2022).
[2] E. Novitsk (Project 8 Collaboration), Project 8 Collaboration Meeting, Pittsburgh, PA (2025).
[3] J. Stachurska et al. (Project 8 Collaboration), Project 8 Collaboration Meeting, Pittsburgh, PA (2025).
[4] J. B. Kline et al., arXiv preprint arXiv:2506.05315 (2025).
[5] K. Kazkaz et al., LLNL Tech. Rep. LLNL-TR-866300 (2024).