

PROJECT 8

Snowmass2021 - Letter of Interest Secondary Physics Potential of the Project 8 Experiment

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Project 8 is an experiment designed to measure the absolute neutrino mass using cyclotron radiation emission spectroscopy (CRES). In addition to probing the electron-weighted neutrino mass through endpoint investigations, beta-decay spectrum measurements can also be used to study other neutrino properties that affect the spectrum shape. The large statistics, fine energy resolution, and differential nature of the measurement of the tritium beta-decay spectrum provide Project 8 the opportunity to pursue additional secondary physics measurements including the observation of neutrino mass ordering and searches for sterile neutrinos. This LOI discusses the secondary physics opportunities of the Project 8 experiment, beyond the neutrino mass measurement, that can play a unique and complementary role in understanding the properties of neutrinos.

NF Topical Groups:

- ☒ (NF1) Neutrino oscillations
- ☒ (NF2) Sterile neutrinos
- ☐ (NF3) Beyond the Standard Model
- ☐ (NF4) Neutrinos from natural sources
- ☒ (NF5) Neutrino properties
- ☐ (NF6) Neutrino cross sections
- ☐ (NF7) Applications
- ☐ (NF8) Theory of neutrino physics
- ☐ (NF9) Artificial neutrino sources
- ☐ (NF10) Neutrino detectors
- ☐ (Other) *[Please specify frontier/topical group(s)]*

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Collaboration: Project 8

Introduction

Tritium beta-decay endpoint spectrum measurement is currently the most precise laboratory method for determining the absolute scale of neutrino mass. The shape of spectrum near the endpoint for such an experiment can be written as

$$\frac{dN}{dE} = 3rt(E_0 - E)\sqrt{(E_0 - E)^2 - m_\beta^2}, \quad (1)$$

where r is the event rate in the last eV of the spectrum when $m_\beta = 0$, t is the runtime, and E_0 is the endpoint energy. The observable in such a measurement is the incoherent sum of mass eigenstates given by

$$m_\beta^2 = \sum_{i=1}^3 |U_{ei}|^2 m_i^2, \quad (2)$$

where U_{ei} are the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mass mixing matrix terms and m_i are individual neutrino mass eigenvalues.

The Project 8 experiment [1] plans to improve on the existing tritium beta-decay measurements in two different ways: by measuring beta-decay of atomic tritium and by using the CRES technique for spectrum measurement. The former reduces the systematic effects associated with the decay of molecular tritium [2], while the latter allows for a high-statistics differential spectrum measurement with excellent energy resolution over a range of energies. Leveraging these unique capabilities, Project 8 is projected to achieve m_β sensitivity of ~ 0.040 eV (90% C.L.). The advantages of the CRES method and the use of atomic tritium generally also extend to the rest of the measured spectrum, equipping Project 8 with unique access to other secondary physics capabilities.

Shape of Beta-decay Spectrum

The electron-weighted neutrino mass m_β from Equation 2 is composed of PMNS mixing matrix elements U_{ei} and individual neutrino mass terms m_i . The measured spectrum can be thought of as a combination of the individual spectra corresponding to m_i , with each scaled by $|U_{ei}|^2$. The spectrum will thus have discontinuities in the derivative, referred to as *kinks*, at the transition points between individual spectra. The positions of the kinks are dictated by m_i while their relative magnitudes are governed by $|U_{ei}|^2$, as shown in Figure 1. In principle, a high-statistics experiment with energy resolution better than the characteristic energy/mass differences and low backgrounds would be able to resolve all the kinks and measure the terms $|U_{ei}|^2$ and m_i .

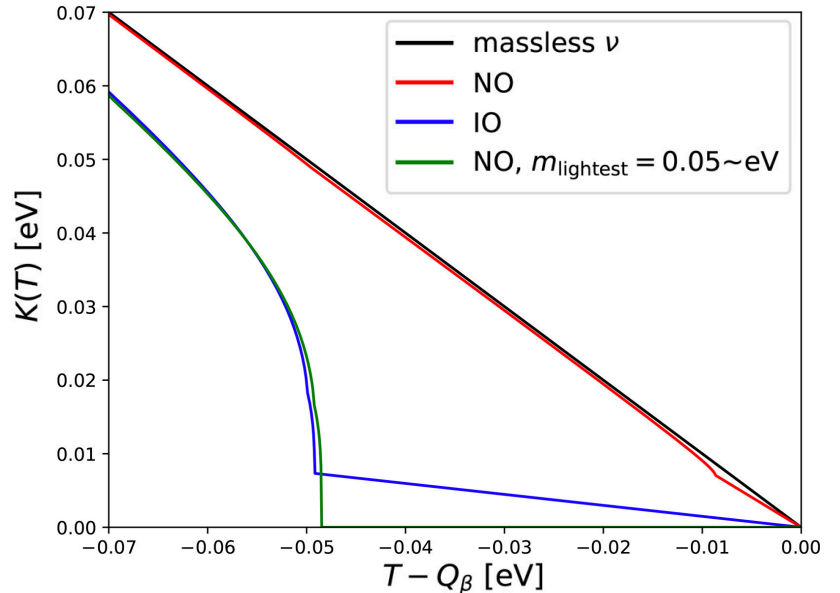


FIG. 1. From [3]. The endpoint spectrum of tritium beta-decay. Shown in red (blue) is the NO (IO) scenario under the assumption that the lightest neutrino is massless. In green is the NO scenario with $m_1 = 0.05$ eV. Kinks are apparent in all the spectra (except black) at the transition points between individual mass spectra.

Three Active Neutrino Mixing Parameters (NF01, NF05)

Sensitivity to m_β in the non-degenerate regime opens up the opportunity for Project 8 to resolve kinks in the spectrum. In addition to potentially placing constraints on some of the individual PMNS matrix elements, at its sensitivity goal, Project 8 would also have the ability to identify the neutrino mass ordering. Under the assumption of $m_1^2 - m_2^2 \simeq 0$ and PMNS matrix unitarity, the three-neutrino spectrum can be reduced to a two-neutrino spectrum as:

$$\frac{dN}{dE} = \eta \frac{dN}{dE}(m_L) + (1 - \eta) \frac{dN}{dE}(m_H), \quad (3)$$

where m_L and m_H are the effective mass terms with $m_H^2 - m_L^2 \simeq |\Delta m_{13}|^2 \simeq |\Delta m_{23}|^2$, $\eta = |U_{e1}|^2 + |U_{e2}|^2 = \cos^2 \theta_{13}$ for normal ordering and $\eta = |U_{e3}|^2 = \sin^2 \theta_{13}$ for inverted ordering. Based on the known values of θ_{13} , it is apparent that the value of η is ≈ 1 under NO and ≈ 0 under IO. This way, with little external knowledge from the reactor neutrino experiments, a direct neutrino mass experiment with sufficiently fine energy resolution and statistics could determine the neutrino mass ordering as shown in a Bayesian analysis [4]. A detailed paper presenting this result is being prepared. While a measurement of m_β can resolve the mass ordering if the true ordering is normal and $m_\beta < \sim 0.048$ eV [5], sufficient sensitivity to kinks in the spectrum can enable the ordering to be determined even if it is inverted.

Sterile Neutrinos (NF02)

Sterile neutrinos that mix with the active neutrinos would create distortions in the beta-decay spectrum and thus could be accessible to the Project 8 experiment. The differential beta-decay spectrum in the presence of one heavy sterile neutrino $m_s \gg m_\beta$ can effectively be written as:

$$\frac{dN}{dE} = \cos^2 \theta \frac{dN}{dE}(m_\beta) + \sin^2 \theta \frac{dN}{dE}(m_s), \quad (4)$$

where θ describes the mixing angle between active and sterile neutrino states. The combination of active and sterile neutrino spectra would introduce kinks in the spectrum similar to those in Figure 1, but at much lower energies given by $\sim E_0 - m_s$.

Additional sterile neutrino states at eV-scale have been suggested as a solution to the anomalies in the reactor [6, 7], accelerator [8, 9], and radioactive source [10, 11] neutrino flavor oscillation experiments. With a kink search at an energy of $\sim E_0 - 2$ eV, beta-decay measurements have sensitivity to high mass splittings not accessible to reactor neutrino experiments. Project 8 may be able to search for the eV-scale sterile neutrinos using the data generated for absolute mass measurement without a need for major hardware changes. The KATRIN experiment has already performed a search for sterile neutrinos [12] on their beta-decay spectrum and is expected to cover the suggested values of $\sin^2(\theta_{ee})$ above the mass splitting of ~ 10 eV² with their full dataset. A similar search may be possible by the Project 8 experiment using its high-statistics beta-decay spectrum of atomic tritium. The use of differential spectrometer in Project 8 may be beneficial in providing a stronger signature in the search for sterile neutrinos [13]. Given the very different systematic effects in these two experiments, Project 8 will provide highly complementary results to the KATRIN experiment.

A keV-scale sterile neutrino is a promising dark matter candidate [14]. Similar to eV-scale sterile neutrinos, keV-scale sterile neutrinos would also introduce kinks in the beta-decay spectrum, but at much lower energies of a few keV. Although Project 8 has not yet made plans to extend the spectrum all the way down to include kinks from possible keV-scale sterile neutrinos, no significant limitations are anticipated in translating the CRES technology to the relevant energy range [14].

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