Measuring the electron neutrino mass using the electron capture decay of ^{163}Ho

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While the mass differences between neutrino mass states are known, their absolute masses and mass hierarchy have not yet been determined. Determining the mass of the neutrino provides access to physics beyond the Standard Model (SM) and the resulting value has implications for the growth of large-scale structure in the universe over cosmic history. Because of the importance of the topic, a number of efforts are already underway to determine the mass of the neutrino including direct kinematic measurements and indirect measurements of astrophysical phenomena that constrain the sum of the mass eigenstates through models of cosmic evolution. Here, we advocate for a collaborative international effort to perform a kinematic determination of the neutrino mass using calorimetric measurements of the decay of ^{163}Ho. This effort is justified by the success of current experiments using the technique, its high benefit-to-cost ratio, the value of approaches with different systematic errors, and the value of measuring the electron neutrino mass ($m_{\nu e}$) rather than the electron anti-neutrino mass.

The electron capture decay of ^{163}Ho provides an attractive system for kinematic measurements of the electron neutrino mass. When ^{163}Ho is embedded in a calorimetric sensor, each decay deposits energy in the sensor equal to the Q-value of the reaction minus the energy of the departing neutrino. The rest mass of the neutrino is manifested as a deficit of events in the region of the decay spectrum near the Q-value. ^{163}Ho is particularly attractive because of its low Q-value of 2.833 keV and its reasonable half-life of 4570 years [Eliseev, 2015]. A low Q-value increases the fraction of events in the interesting endpoint region of the spectrum and a short half-life reduces the amount of Ho that must be embedded in a sensor to achieve a target count rate. Measuring keV-scale energy depositions with eV-scale accuracy is a task that is well within the capabilities of modern cryogenic microcalorimeters [Kempf, 2018; Smith, 2012]. A large array of microcalorimeters each with embedded ^{163}Ho can produce a high statistics decay spectrum whose analysis provides sub-eV sensitivity to $m_{\nu e}$. This approach is the subject of our LOI [Gastaldo, 2017; Nucciotti, 2014].

The state-of-the field for neutrino mass measurements is complex but also fertile for new approaches. After a promising start, KATRIN has set a 1.1 eV upper bound on the electron anti-neutrino mass and is targeting a kinematic measurement based on tritium β-decay with 0.2 eV sensitivity within five years [Aker, 2019]. There is considerable interest in using Cyclotron Resonance Emission Spectroscopy (CRES) to determine the electron anti-neutrino mass but more steps have still to be done to demonstrate scalability to the necessary experimental sensitivity [Esfahani, 2017]. Measurements of astrophysical phenomena constrain the sum of the masses of the three neutrino flavors to < 0.12 eV [Planck, 2018] in the context of the ΛCDM model and the summed mass sensitivities of future experiments such as Simons Observatory are predicted to be as good as 0.02 eV [Ade, 2019]. Astrophysical measurements, however, are less attractive from a fundamental discovery standpoint as they are heavily model dependent.

Surveying this experimental landscape, there is a need for an alternative kinematic technique with mass sensitivity comparable to or better than KATRIN's projected limits and with very different systematic error terms from KATRIN or CRES. In a corroboratory role, a new technique could resolve disagreement between KATRIN and astrophysical results. If its sensitivity surpassed KATRIN's, then a new technique could provide the most stringent kinematic measurement of the neutrino mass to date. Additionally, sensitivity to normal-matter mass states, rather than the anti-neutrino mass states in ^{3}H, could potentially provide additional constraints on possible CPT violating theories.

The main risks associated with the ^{163}Ho approach have already been retired. The ECHo collaboration has demonstrated decay spectra with 275,000 counts using a small array of magnetic microcalorimeters [Velte, 2019] and is presently analyzing data corresponding to a spectrum with ~10^{8} counts. The HOLMES collaboration is developing multiplexed transition-edge sensors (TESs) for this purpose [Faverzani, 2020]. An exploratory project at Los Alamos demonstrated ^{163}Ho spectra with TESs [Croce, 2016]. Together, these three efforts have demonstrated the ability to synthesize, purify, and embed ^{163}Ho, to fabricate microcalorimeters, to measure ^{163}Ho decay spectra at application-relevant resolution levels, and to use modern multiplexing techniques to read out large arrays of microcalorimeters. In addition, recent theoretical work has retired risk about the shape of the ^{163}Ho spectral endpoint [Brass, 2020 and references therein].

The largest challenge remaining to the ^{163}Ho approach is scaling to large arrays in a cost-effective manner. Achieving ~0.2 eV sensitivity will require a spectrum with $\gtrsim 10^{16}$ counts and the relationship sensitivity ~$1/\text{counts}^{1/4}$ can be used to estimate the statistics required for even better mass measurements. To achieve 10^{16} counts in 10 years will require about 32 MBq of embedded ^{163}Ho. Choosing an activity per sensor of 30 Bq, then 10^{6} sensors are required. While 10^{6} sensors will be a challenge, a comparable number (5×10^{5}) of cryogenic detectors are planned for CMB-S4. Further, the physical scale of the experiment will be modest compared to some other approaches. Each sensor and its readout circuitry will likely occupy < 5 mm^{2} of area on a 350 μm thick silicon substrate so the whole experiment will fit on < 5 m^{2} of planar Si weighing about 4.3 kg, which could be contained in one conventional dilution refrigerator.

An international collaboration between groups in the US and Europe is an attractive path to execute a large-scale ^{163}Ho experiment. The detectors for such an experiment might be located at US and European sites but technologies would be common across the collaboration. In order to maximize efficiency, different institutes would provide different subsystems that reflect their particular strengths. While work on ^{163}Ho in Europe is presently more mature than in the U.S., the U.S. community is poised to make important contributions. Work in the U.S. on multiplexed readout is world-leading [Mates, 2017] and the U.S. has excellent facilities for fabricating cryogenic detectors and SQUID multiplexers.

In summary, studies of ^{163}Ho can provide a direct measurement of the neutrino mass with competitive sensitivity and very different systematic errors compared to other approaches. Such a result will be extremely valuable given the current landscape of neutrino mass efforts. An international effort that leverages the strengths of institutes around the world can accomplish this goal in a cost-effective manner. This effort will both benefit from and accelerate other cryogenic detector projects such as CMB-S4, successors to CUORE, and the development of x-ray spectrometers for DOE light sources.

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