Snowmass2021 - Letter of Interest

Project 8 - A Next-Generation Tritium Endpoint Experiment

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 (optional): Project 8

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Abstract: Measurements of the β^- spectrum of tritium give the most precise direct limits on neutrino mass. Project 8 will investigate neutrino mass using Cyclotron Radiation Emission Spectroscopy (CRES) with an atomic tritium source. CRES is a new experimental technique that has the potential to surmount the systematic and statistical limitations of current-generation direct measurement methods. Atomic tritium avoids an irreducible systematic uncertainty associated with the final states populated by the decay of molecular tritium. Project 8 will proceed in a phased approach toward a goal of 40-meV neutrino-mass sensitivity. This LOI motivates Project 8 in the context of a forecast for the next decade, including limits from KATRIN and cosmology.

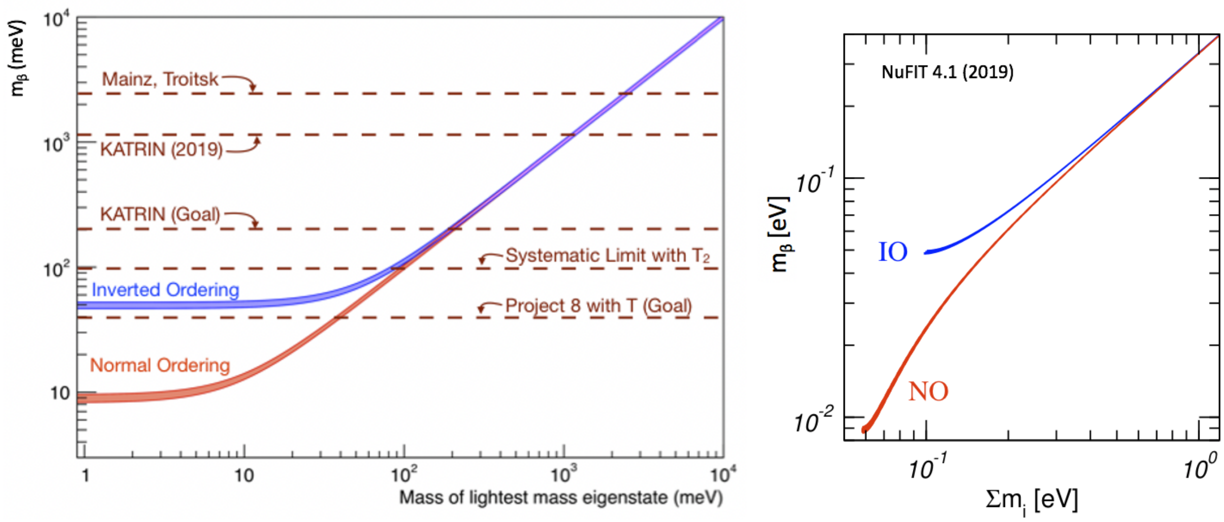

Figure 1: Left: Milestones in neutrino mass phase space. The observable m_β is plotted against the lightest eigenvalue. Right: Relationship between the beta-decay observable and the cosmological parameter Σm_i. Right panel is from nu-fit.org[4].

Though flavor oscillation experiments have proven that neutrinos have mass, the origin of neutrino mass is still not understood, and neither the absolute mass scale nor the ordering of the three mass eigenvalues are known[1]. Neutrino mass is important across domains from particle physics to cosmology where it has potentially left its imprint on the cosmic microwave background (CMB) and matter power spectrum. Fits of Planck satellite observations of the CMB together with observation of the baryon acoustic oscillation (BAO) scale gathered from various data sets determines the parameter $\Sigma m_i \leq 0.13\,\mathrm{eV}$[2] when the data are analyzed in a minimal extension of the ΛCDM model with Σm_i as an additional parameter. Compelling extensions include up to six additional parameters beyond the usual six of ΛCDM[3]. Analysis of Planck plus BAO data in that context relaxes the limit to 0.52 eV[1]. See Figure 1 for the relation between cosmological and direct-method observables. Ideally, a laboratory measurement could provide cosmology with more restrictive neutrino mass limits or values in order to improve its sensitivity to purely cosmological parameters.

Oscillation experiments are sensitive to mass squared differences $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$, and the sign of only one of these is known, leading to ambiguity in the ordering of the masses of these states[5]. Precision tritium beta spectroscopy is sensitive to the neutrino mass m_β (Eq. 1) through the distortion of the endpoint region of the spectrum by a nonzero mass. The electron-weighted mass m_β, defined by

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

is approximately equal to m_1^2 for either ordering. The difference between m_β^2 and m_1^2 is due to small contributions that are independently measured in oscillation experiments. The KATRIN tritium endpoint experiment sets the most stringent upper limit[6] on the neutrino mass, of m_β <1.1 eV. KATRIN is designed to reach an ultimate sensitivity of 200 meV; to go beyond this would require addressing statistical challenges posed by the integral nature of the MAC-E integral spectrometer technology and irreducible systematic uncertainties in the final states populated by the decay of molecular tritium. Lower limits from oscillation experiments are either 48 or 8.5 meV (both at 95% confidence) depending on whether the mass ordering is inverted or normal, respectively[1].

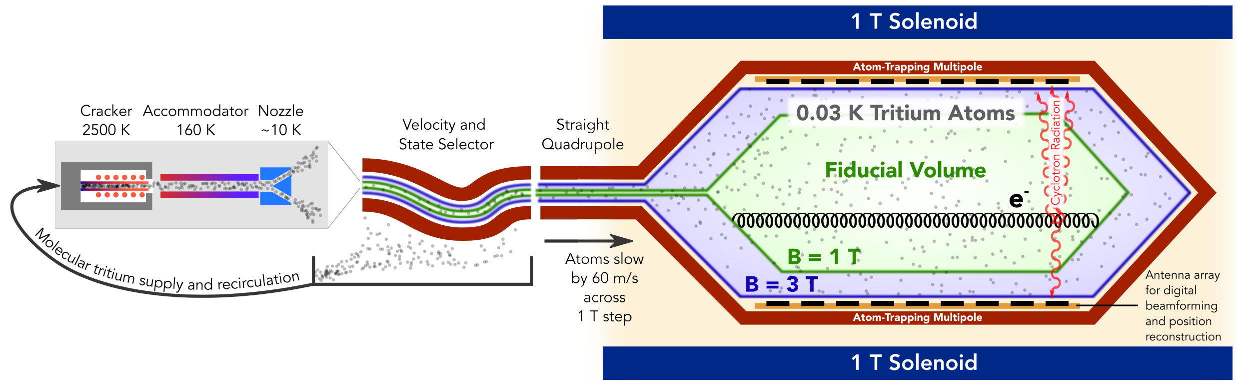

Figure 2: A possible conceptual layout of the Project 8 experiment.

Project 8 will combine an atomic tritium source with the Cyclotron Radiation Emission Spectroscopy (CRES) method's intrinsically high energy resolution, low background, and differential nature to reach sensitivity to m_β as low as approximately 40 meV. The goal of Project 8 is to cover all possible masses consistent with inverted ordering. Figure 1 shows several milestones in neutrino mass phase space relevant for the time covered by this SNOWMASS plan, along with a reference to relate our observable with the comparable cosmological fit parameter discussed below.

In the CRES method[7], the energy of electrons emitted from a gaseous source is inferred from their cyclotron radiation as they spiral in a uniform magnetic field. CRES therefore can improve statistical sensitivity because it directly measures the differential spectrum at once in a selected energy range. That makes efficient use of the available intensity while reducing systematic effects associated with source stability that arise in point-by-point spectrometers. Systematic sensitivity is challenging due to four effects that are indistinguishable from neutrino mass if they are not accounted for: backgrounds, electron energy loss in the source, instrumental resolution, and molecular final states[8]. CRES is expected to have extremely low backgrounds; no background events have ever been observed by Project 8. The source region is transparent to the cyclotron radiation, allowing relatively large sources, and the frequency domain technique has very good resolution. The systematic from molecular final states is avoided altogether if an atomic tritium source is used.

Figure 2 shows a conceptual design that applies the CRES technique to an atomic tritium source for Project 8. Tritium molecules are dissociated in a cracker. Initial cooling of the resulting atoms occurs through the accommodation stage with additional cooling in a magnetic quadrupole velocity and state selector (VSS). Atoms are then injected into a region where they are, briefly, magnetically trapped. Possible atom-trapping configurations are Ioffe traps or Halbach arrays. A CRES antenna array lines the interior of the magnetic trap. The entire assembly (magnetic trap plus antenna array) is inside a 1-tesla solenoid to provide the background field required for CRES.

Project 8's 40-meV neutrino-mass sensitivity requires 5 m^3·y of source exposure at a density of 3.7×10^{18} atoms/m^3. That assumes several demanding conditions: sub-part-per-million magnetic field uniformity and energy resolution of 115 meV (standard deviation) known to a precision of 3%. Project 8 has completed prototype demonstrations of CRES in small volumes[9;10]. Further R&D to meet these stringent demands is ongoing with the goal to develop a quantitative conceptual design for the ultimate experiment sensitive to neutrino masses of the inverted ordering.

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