PROCEEDINGS OF SCIENCE

Building an atomic source for the Project 8 experiment

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There have been significant gains in characterizing neutrino properties in recent years, however the absolute neutrino mass scale continues to be elusive. The Project 8 collaboration seeks to probe this quantity directly via kinematic analysis of tritium beta decay, using the cyclotron radiation emission spectroscopy (CRES) technique. In order to make neutrino mass measurements with a design sensitivity of 40 meV, the Project 8 experiment must use atomic tritium. To create an atomic tritium source suitable for the Project 8 experiment, molecular tritium is thermally dissociated into atomic tritium, which is then state selected and cooled. I will report on the current status of the atomic source development, covering subsystems for dissociation in coaxial cracker design, followed by accommodation from a surface which is held at 10 K. The requisite low-field-seeking states are then magnetically guided, evaporatively cooled, and injected into the trap where the atoms decay.

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1. Introduction to neutrino mass measurement

There have been significant gains in characterizing neutrino properties in recent years, however the absolute neutrino mass scale continues to be elusive. Of the currently available neutrino mass measurement techniques, the best upper limit has been set by experiments using a kinematic decay method. This method examines the high-energy tail ("endpoint region") of tritium beta decay spectra, whose shape depends on the neutrino rest mass m_β. This extracted neutrino mass m_β is an incoherent sum of the neutrino mass eigenstates, with $m_\beta = \sqrt{\sum_{i=1}^{3} |U_{e,i}|^2 m_i^2}$; where $U_{e,i}$ are the PMNS mixing matrix elements associated with beta decay, and m_i the neutrino mass eigenvalues [1].

Currently, the best upper limits have been set by the KATRIN experiment, which measures the integrated spectrum of an ultra-luminous gaseous molecular tritium source with a MAC-E filter technique [2]. In order to go beyond the design sensitivity of the KATRIN experiment (0.2 eV) and probe the inverted hierarchy region of phase space, we must explore new ideas.

2. The Project 8 experiment

The Project 8 experiment [3] is proposed as one of these next-generation neutrino mass measurement experiments. This experiment also examines the endpoint region of tritium beta decay spectra, but with a novel approach. The Project 8 experiment detects cyclotron radiation emitted from tritium beta decay electrons trapped in a homogeneous magnetic field, called "CRES" (cyclotron radiation emission spectroscopy). The frequency of this detected radiation maps to the beta decay electron's kinetic energy, so can be used to reconstruct the differential beta decay spectrum.

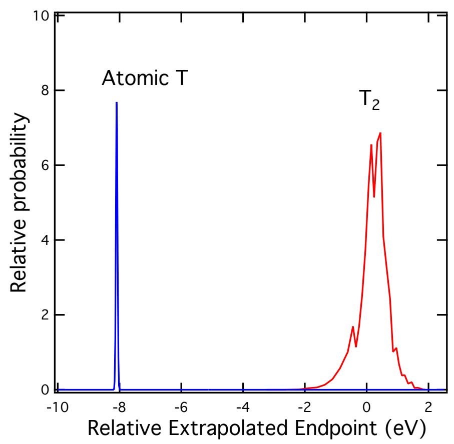


Figure 1: Comparison of final state energies of atomic tritium (T) and molecular tritium (T_2), from [1].

In order to scale up from the successful demonstrator experiment and achieve its final design sensitivity of $m_\beta = 40$ meV, the Project 8 experiment must improve both its statistical reach and systematics mitigation. The statistical sensitivity can be increased by trapping more beta electrons, thus by increasing the CRES detection volume. The volume properties and geometry are covered in more detail here [4].

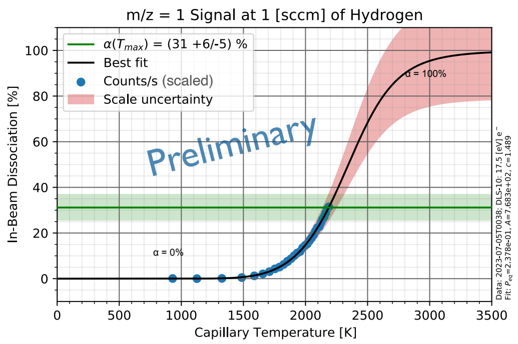
The biggest gains in systematic sensitivity come from getting a handle on one of the current largest irreducible systematics in modern beta decay experiments: the molecular final states of tritium (see Figure 1).

The uncertainty in the calculated distribution of energy going into rotational, vibrational, and electronic excitation within the tritium molecule can smear out the neutrino mass by about 100 meV. In order to circumvent this systematic, the Project 8 experiment will need an atomic tritium source.

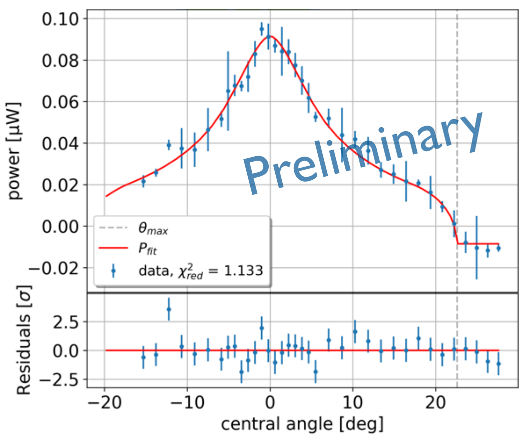
3. Atom source production

There are a few key ingredients for preparation of an atomic tritium source with characteristics suitable for the planned 40 meV final experiment. To achieve this sensitivity, we require a high atom flux (10^{19} atom/s) at 10 mK with the correct spin state to ensure successful trapping.

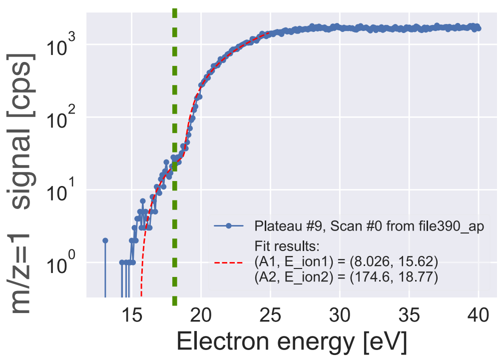
The first step to preparing this atom source is to dissociate molecules into atoms. In order to accelerate the R&D process and avoid unnecessary contamination, tritium is substituted for hydrogen due to its similar properties. We have successfully demonstrated thermal dissociation of molecular hydrogen at JGU Mainz, up to 2500 K, with input flows up to 20 sccm (more than an order of magnitude higher than in previous literature [5]) via mass spectrometry. A sample dissociation measurement is shown in Figure 2a. We can also reconstruct the shape of the resultant atomic beam via measurements of recombinant heating on a thin tungsten wire (Figure 2b). Additionally, quantifying the signal-to-noise ratio (SNR) is key to optimal mass spectrometer configuration selection (Figure 2c).



(a) Estimated dissociation efficiency. Credit: A. Lindman.



(b) Atomic beam shape. Credit: C. Matthé.



(c) Optimization of mass spectrometer SNR. Optimal electron energy setting is denoted by the green dashed line. Credit: L. Thorne.

Figure 2: Atomic hydrogen beam characterization studies at the JGU Mainz setup.

With a well-characterized source of hydrogen atoms in hand, the next step is cooling ("accommodation"). This will be done in two steps: first to 150 K to take advantage of a minimum in recombination probability to reduce atom losses. Heat transfer calculations and material selection is in progress, as well as purchase of the necessary liquid nitrogen cooling system. The second step, development of a 10 K nozzle cooled by liquid helium, is also in progress.

Upon exiting the 10 K nozzle, the atoms will be cooled further via the Magnetic Evaporative Cooling Beamline (MECB). This technique filters out "hot" atoms with high transverse momentum, allowing for cooling via internal collisions. Tests with a ^{6}Li source are currently being conducted at UT Arlington to validate simulations and establish the proof-of-principle.

The final step in the atom source preparation is trapping. To this end, we are designing a vertical magneto-gravitational atom trap. This trap will be formed by a Halbach array, developed at UIUC in Illinois, and contain atoms at 10 mK.

4. Summary

After successfully demonstrating the CRES technique as a candidate for measuring neutrino mass with molecular tritium [3], the Project 8 collaboration is developing an atomic tritium source to achieve its 40 meV design sensitivity. We present updates from the atomic development efforts, including measurements from the first atom beam characterization campaigns, as well as a glimpse into ongoing simulation efforts on the cooling and atom trapping components.

References

[1] J.A. Formaggio, A.L.C. de Gouvêa and R.H. Robertson, *Direct measurements of neutrino mass*, *Physics Reports* **914** (2021) 1.

[2] M. Aker, K. Altenmüller, M. Arenz, M. Babutzka, J. Barrett, S. Bauer et al., *Improved upper limit on the neutrino mass from a direct kinematic method by KATRIN*, *Physical Review Letters* **123** (2019) .

[3] A. Ashtari Esfahani, S. Böser, N. Buzinsky, M.C. Carmona-Benitez, C. Claessens, L. de Viveiros et al., *Tritium beta spectrum measurement and neutrino mass limit from cyclotron radiation emission spectroscopy*, *Phys. Rev. Lett.* **131** (2023) 102502.

[4] J. Stachurska, *Going Big for Phase III of the Project 8 Neutrino Mass Experiment*, in *XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)*, Proceedings of Science, September, 2023.

[5] K. Tschersich, *Intensity of a source of atomic hydrogen based on a hot capillary*, *Journal of Applied Physics* **87** (2000) 2565.

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