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The Project 8 radiofrequency tritium neutrino experiment

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Abstract

The Project 8 experiment aims to determine the electron neutrino mass by measuring the spectrum of tritium beta decay electrons near the 18.6 keV endpoint. Unlike past tritium experiments, which used electrostatic and magnetostatic spectrometers, Project 8 will detect decay electrons nondestructively via their cyclotron radiation emission in a magnetic field. An individual electron is expected to emit a detectable pulse of microwaves at a frequency which depends on the electron energy. Precise measurement of these pulse frequencies is a novel spectroscopy technique particularly well-suited for the high rate, high precision, low background needs of a tritium experiment. The collaboration is currently operating a prototype designed to detect single 83mKr conversion electron decays in an 0.9T magnetic field. We report on recent activities on the prototype, and on progress towards the design of a large tritium experiment with new neutrino-mass sensitivity.

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1. Introduction

The β decay of tritium produces electrons in the energy range E_e = 0–18.575 keV, with a shape known to high precision from elementary weak-interaction theory [1]. Near the endpoint the spectral shape is:

$$\frac{d\Gamma}{dE_e} = \frac{G_F cos^2(\theta_c)}{2\pi^3}|M_{nuc}|^2 F(E_e) \times \left((E_0 + m_e - \epsilon) \cdot \sqrt{(E_0 + m_e^2 - \epsilon)^2 - m_e^2}\right) \times \left(\epsilon * \sqrt{\epsilon^2 - m_\nu^2}\right)$$

where E_0 is the effective endpoint energy including recoil effects, $\epsilon \equiv E_0 - E_e$ is the neutrino energy, and F is a (nearly-constant) Fermi function. An energy-conserving step function has been omitted. In the presence of multiple neutrino species, the spectrum is a sum of three spectra with different mass eigenstates m_ν weighted by their coupling to electrons. Near the endpoint, i.e. at small ϵ, the shape variations are dominated by the last term, representing the neutrino phase-space density, i.e., the number of available neutrino momentum states per unit energy ϵ. This approximates the relativistic shape $\frac{d\Gamma}{dE_e} \propto \epsilon^2$ if $\epsilon >> m_\nu$, or the nonrelativistic shape $\frac{d\Gamma}{dE_e} \propto \sqrt{\epsilon - m_\nu}$ if $\epsilon - m_\nu << m_\nu$. An observation of the tritium electron endpoint might therefore reveal at what E_e the recoiling neutrinos look non-relativistic, and this serves as a measurement of the neutrino mass. This measurement has been attempted repeatedly, and the most recent results are consistent with $0 < m_\nu < 2.0$ eV[2]. The KATRIN experiment, now in its construction and calibration phase, has a design sensitivity of 0.2 eV (for exclusion at 95% CL)[3]. Tritium endpoint spectroscopy aims for a fundamentally different observable than double beta decay, which yields a non-null result only if the

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neutrino is Majorana, and is complementary to cosmology, where neutrino mass bounds are obtained only in the context of a complex multi-parameter model, including assumed knowledge of the cosmic relic neutrino number density.

2. The Project 8 concept

The Project 8 collaboration is developing a new method for beta-electron spectroscopy, with the goal of performing high-statistics, low-systematics measurements of the tritium endpoint[4]. The technique begins with tritium decays at low pressure in a nearly-uniform magnetic field. The electron undergoes orbital motion in the magnetic field, and emits cyclotron radiation while doing so. The cyclotron radiation is coherent, but at a frequency $\omega_c(E_e) = qB/(m+E_e)$ which depends on the mildly-relativistic electron kinetic energy E_e. By detecting single-particle cyclotron radiation and measuring its frequency, we can infer the electron energy. This technique is compatible with a very high-rate source, and thus high statistical power, because the cyclotron radiations of different E_e electrons are separated cleanly in frequency space. Analog filters in the frequency-domain can remove all low-energy events (i.e., high-frequency electromagnetic radiation) without causing pileup, livetime, or other effects in the narrow high-energy (low frequency) region of interest.

Several parameters need to be controlled to make such an experiment work. First, the radiation must be coupled into low-noise amplifiers in such a way as to yield high signal-to-noise detection of the cyclotron signal. The primary noise source is expected to be blackbody radiation rather than, e.g., the sum of tails of low-energy electron radiations, and commercially-available amplifiers seem to be adequate. Second, the electron must be kept in the apparatus long enough (without hitting the apparatus walls or undergoing inelastic scattering) to perform a frequency measurement; the Nyquist limit enforces a relationship between frequency-precision and measurement-duration. To keep electrons away from the apparatus walls, we use a magnetic bottle to confine the electrons temporarily. To delay inelastic scattering, we operate the experiment at low total gas pressure.

Many of the usual systematic errors associated with tritium measurements are absent: we can perform differential measurements, not integral ones, which lowers the requirement of source density/pressure stability. No electrostatic fields are used in the apparatus, so there is no requirement of an ultra-stable voltage reference. (The magnetic field stability requirement is not onerous and is amenable to calibration in-situ using NMR, EPR, or a low-energy electron or ion cyclotron resonance.) There may be the possibility of designing an experiment with an atomic T source rather than a T_2 gas source, which would remove the systematic error (and the energy spread) associated with tritium molecular final states. This is discussed later.

3. Experimental status

The Project 8 collaboration is currently operating a small proof-of-concept prototype attempting to detect single-electron cyclotron radiation for the first time [5]. The experiment is housed in a warm-bore superconducting solenoid originally intended for NMR. The solenoid field is held at 0.945T, as measured with an NMR probe, and a shallow magnetic bottle is created by depressing the field with an additional small copper coil. This puts the nonrelativistic cyclotron resonance around 26.4 GHz, and the 17.8 keV electron signal around 25.5 GHz. Along the axis of the field is an evacuated WR42 waveguide into which we can admit ^{83m}Kr gas by diffusion from a ^{83}Rb source adsorbed to zeolite. Decays of ^{83m}Kr release conversion electrons, primarily in narrow lines at 7.5, 17.8 and 30.2 keV; we will attempt to detect the 17.8 and 30.2 keV lines.

The waveguide is coupled to two ultra-low-noise cryogenic amplifiers (Low Noise Factory LNF-LNC22 series). In one configuration, the upper and lower ends of the waveguide are read out separately; in another, the lower port is shorted (i.e. reflective) and both amplifiers are used in series on the upper port. After amplification, the region-of-interest is mixed down to an intermediate frequency of 1.5GHz. A tunable oscillator and filter further selects a narrow bandwidth, which is mixed down to near baseband before digitization at up to 500MB/s. A final magnetic field calibration is done by injecting a tone signal from a sweeper, which interacts with the electron paramagnetic resonance of a 2,2-diphenyl-1-picrylhydrazyl (DPPH) sample which has been placed permanently inside the waveguide. The DPPH signal has been seen clearly in this system.

When the waveguide is exposed to krypton, we search for signals using a variety of real-time and offline analyses. Real electron signals should appear as “chirps” in the data. A single electron should appear as an sudden excess of power at some frequency; as the electron loses energy, the frequency should drift upwards coherently; and the signal should vanish suddenly when the electron scatters and leaves the magnetic bottle. The "chirp" shape is fit and used to extract the electron's energy at its earliest appearance. Due to the electron's motion back and forth in the magnetic bottle, the signal should also exhibit a variety of sideband structures, which may be detected in future experiments but are below the signal-to-noise ratio of the prototype. The prototype is expected to yield ^{83m}Kr decay electron detections at high signal-to-noise. The precision of these *frequency* measurements of these electrons should be excellent (the equivalent of 0.1–0.2 eV, consistent with our future tritium-spectroscopy needs) but since the magnetic field is made nonuniform by the trapping coil, we expect to see an *energy* spread of $\approx$ 5 eV. Higher-uniformity trap configurations are under investigation for this prototype.

Previous prototype operations, using a cold-bore superconducting magnet and less-reliable preamplifiers, permitted debugging of the digitizer, receiver, and Kr source systems, but not successful end-to-end operations. The warm-bore, LNF-amplified prototype is in the final stages of assembly but has not had its first runs as of this writing.

4. Single-electron maser studies

The default running mode of Project 8 is a "listening" mode; the electron appears, emits cyclotron radiation spontaneously, and this is detected. We have studied an alternative "probe" mode, in which a microwave probe beam is injected at the endpoint cyclotron resonance. An electron in resonance with this beam will undergo *stimulated emission*, resulting in additional power available for high signal-to-noise detection[6]. However, the beam resonance also perturbs the electron's energy—the excess power is detected at the probe frequency, not at the frequency corresponding to the original electron cyclotron. (The electron energy is made to oscillate around the probe frequency, due to the same physics as longitudinal phase stability in a synchrotron.)

There are several cases where this is anticipated to be useful. First, if Project 8's signal-to-noise ratio is initially poor, we may see many false-positive electron detections due to fluctuations of the thermal background. A maser pulse could be used as a follow-up probe of each electron candidate in the region of interest. Second, the maser effect might make it possible to run Project 8 at very high magnetic fields, 3 Tesla and above. At these fields, a spontaneously-radiating electron has a radiation-broadened cyclotron spectrum, which limits energy resolution to $\approx$ 1 eV. Very gentle maser beams could remove the radiation broadening and make high-resolution measurements possible. Several pre-tuned maser beams would shine into the tritium at all times. When an electron appears whose cyclotron motion is already in resonance with one of the maser frequencies, that energy will maintain its energy for a long time (until it scatters) with no radiation broadening; these electrons can be counted and clearly identified as being in one or another narrow maser-selected bin. Electrons which appear at out-of-resonance energies will undergo spontaneous emission but ignore the maser probes. (They might be detected and counted separately with their lower broadened energy resolution.) Therefore, a maser-based Project 8 does not quite perform complete differential measurement—only a handful of narrow bins are available for the high-resolution spectrum. However, the statistical penalty for this appears to be small.

Although there are numerous benefits to working at high fields/high frequencies, millimeter-wave receivers and electronics present practical challenges, hence the primary focus of Project 8 on K-band frequencies and 1 T magnetic fields.

5. Sensitivity projections and scaling laws

To build a large Project 8 spectrometer with new neutrino-mass sensitivity, we must scale up the experiment such that (a) a large-enough total tritium inventory is monitored, while (b) the tritium density is kept low enough that electron-atom scattering does not shorten the observation times; both factors suggest a push for large-volume experiments in large magnetic fields. In the absence of systematic errors and backgrounds, the neutrino mass sensitivity scales as $\sigma_{m^2} \propto \sqrt{\Delta E/(\rho V t)}$ where ρV is the source strength (source density and volume), t is the run time, and ΔE is the optimum analysis window, which in the absence of backgrounds can be thought of like an energy resolution.

Sensitivity obviously increases with the choice of ρV, motivating the push towards large-volume, high-tritium-density experiments. At too-high densities, collisional broadening will drive increases in $\Delta E \propto \rho$, eventually saturating the statistically-obtainable σ_{m^2}. For large-volume experiments, we must ask when the systematic errors dominate over the statistical errors, beyond which point a further increase in the experiment volume is futile. Endpoint experiments virtually never have energy measurements that actually resolve the neutrino mass; the mass is obtained, effectively, by deconvolving the measured spectrum with the known instrument resolution functions of width ΔE. Therefore, a fractional systematic uncertainty is likely to scale up with ΔE. Therefore, a high-density experiment (with large ΔE due to collisional broadening) will reach its systematic-error limits at fairly small volumes. A low-density experiment may be able to expand V until reaching a more fundamental systematic error limits, like tritium molecular final state uncertainties.

The most important error source is our knowledge of the width of the molecular excited-state distribution in the $(^3\text{HeT})^+$ ion which is the final state of the decay $T_2 \rightarrow (^3\text{HeT})^+ + e^- \bar{\nu}$. This distribution is in principle known accurately from atomic theory, but uncertainty in that knowledge is difficult to quantify. Assigning 1% uncertainty to the width (as KATRIN does) suggests an ultimate neutrino-mass sensitivity of 0.1 eV for any future Project 8 experiment involving T_2. With some additional assumptions, this could be obtained with an experiment running $3\times10^{12}/\text{cm}^3$ tritium density with an active volume of order 1 m^3. A much smaller volume, of order 0.01m^3—a tabletop-scale experiment—could in principle reach 0.2 eV sensitivity.

To reach below 0.1 eV, we are exploring the possibility of an atomic tritium source. The requirements for source purity (T/T_2 ratio) are very strict, but Ioffe traps may be able to reach them. Project 8-style spectroscopy appears to be flexible enough to accomodate the complicated gas-injection and Ioffe-conductor arrangements required. This is a topic of active research. An atomic-tritium experiment might see its sensitivity saturate due to thermal, not collisional, broadening; the required scale of the experiment is of order 10 m^3.

6. Conclusions

The Project 8 collaboration is working towards near-future tritium endpoint experiments sensitive to the neutrino mass. Current research is attempting to detect single electron cyclotron radiation from ^{83m}Kr decay, in order to characterize its utility for high-precision electron spectroscopy. We have defined a clear upgrade path towards a larger experiment with new neutrino-mass sensitivity, and early consideration of atomic-tritium studies seem feasible.

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