PROCEEDINGS OF SCIENCE

Direct Neutrino Mass Measurement in the Project 8 Experiment

Brent A. VanDevender[*†]
Pacific Northwest National Laboratory
E-mail: brent.vandevender@pnnl.gov

Project 8 proposes to be the next generation direct neutrino mass measurement after KATRIN. Like KATRIN, Project 8 is a tritium endpoint experiment that looks for the effect of neutrino mass on a precisely measured tritium beta decay electron spectrum. Electron spectroscopy in Project 8 is done by Cyclotron Radiation Emission Spectroscopy (CRES). The concept of CRES is reviewed with recent results from a prototype instrument demonstration. A plan for a phased approach to develop Project 8 into an experiment with sensitivitiy to neutrino masses allowed by the inverted mass hierarchy is also presented.

XIII International Conference on Heavy Quarks and Leptons
22-27 May, 2016
Blacksburg, Virginia, USA

[*]Speaker.
[†]for the Project 8 Collaboration

PoS(HQL 2016)018

1. Introduction

The absolute scale of neutrino masses is one of the most significant unknown quantities in modern nuclear and particle physics [1]. Absolute neutrino mass affects the formation of large scale structure in the universe, and is likely related to the scale of new physics beyond the Standard Model. Neutrino flavor oscillations require the three neutrino mass eigenvalues to be nondegenerate, such that at most one could be zero. Oscillations therefore set a lower bound on the expectation value of the mass for a particular neutrino flavor with the assumption that the lightest eigenvalue is zero. That lower limit for electron flavor neutrinos is either 9 meV, or 50 meV, depending on whether the ambiguous mass hierarchy is normal, or inverted, respectively [2]. Direct measurements of the absolute neutrino mass scale are done by the methods of beta decay and electron capture endpoint spectroscopy. The most sensitive upper limits on the electron neutrino mass come from tritium beta decay endpoint experiments conducted at Mainz and Troitsk: 2.3 eV and 2.05 eV (both 95% C.L.), respectively [3, 4]. The Karlsruhe Tritium Neutrino (KATRIN) experiment will be sensitive to neutrinos as heavy as 0.35 eV (5σ discovery potential), or able to set an upper limit of 0.2 eV (90% C.L.) [5]. KATRIN will exhaust the quasidegenerate mass region where the differences between mass eigenvalues are small compared to their absolute scale. Cosmological limits from Planck Satellite observations of the cosmic microwave background (CMB) combined with WMAP data on the CMB polarization already result in a neutrino mass limit 0.22 eV (95% C.L.) [6][1]. After the quasidegenerate region, the next landmark in neutrino mass phase space is the 50-meV lower limit of the inverted hierarchy. The Project 8 experiment will target that sensitivity with a tritium endpoint experiment based on Cyclotron Radiation Emission Spectroscopy [7] and an atomic tritium source.

A tritium endpoint experiment measures the tritium beta decay electron spectrum near its 18.6 keV endpoint. The measured spectrum is fit allowing the mass-squared expectation value of the electron flavor antineutrino emitted in the decay as a free parameter. Formally, the observable is

$$m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2, \tag{1.1}$$

where the U_{ei} are the first row elements of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix, and m_i are the mass eigenvalues. For brevity, the quantity m_{ν_e} is referred to throughout this writing as "the neutrino mass." Equivalence of neutrino and antineutrino mass is assumed. Because the experimental observable is neutrino mass squared, an order of magnitude improvement in neutrino mass actually corresponds to several orders of magnitude improvement in experimental sensitivity. Improved sensitivity requires a more intense tritium source for statistical sensitivity with a corresponding reduction of systematic uncertainties.

KATRIN uses an electrostatic retardation spectrometer with magnetic adiabatic collimation, referred to as a MAC-E spectrometer. A MAC-E spectrometer [8] has its tritium source in a narrow region of high magnetic field. Beta-decay electrons from the source are adiabatically transported to a wide region of low magnetic field. Electron momenta are collimated during transport and

[1] Technically, the cosmological observable is the sum of the three mass eigenvalues and the Planck limit is $\sum_{i=1}^{3} m_i < 0.66$ eV. As long as the limit is in the quasidegenerate region, dividing the sum by three to get the expectation value is a good approximation.

selected for a minimum energy with an electrostatic filter in the region of low magnetic field. Electrons clearing the electrostatic barrier are reaccelerated and tagged on a detector in a second narrow region of high magnetic field. The KATRIN experiment uses the maximum possible source column density (*i.e.*, volume density integrated along the direction of the magnetic field) consistent with the removal of electrons that have not scattered in the source. The source intensity cannot be increased by increasing the volume density or the length along the magnetic field, as electrons from the back of the source would not escape without scattering. The source intensity can only be increased by expanding the source radially which requires a proportional expansion of the wide low-magnetic-field region. That region of KATRIN's apparatus is already 10 m in diameter. A MAC-E spectrometer capable of reaching to the floor of the inverted neutrino mass hierarchy would have to be hundreds of meters in diameter. Such a technical feat seems impossible, and KATRIN will likely be the last tritium endpoint experiment of its kind. A new method of electron spectroscopy will be required that can accommodate much more tritium for statistical sensitivity and reduce systematic uncertainties accordingly. In particular, any tritium endpoint experiment much more sensitive than KATRIN will have to use *atomic* tritium (T) in order to avoid a systematic uncertainty associated with the final states of the daughter $^3HeT^+$ ion populated in beta decay of the natural molecular state of tritium gas (T_2) [9].

2. Cyclotron Radiation Emission Spectroscopy

The idea of Cyclotron Radiation Emission Spectroscopy (CRES) for a future tritium endpoint experiment was initially proposed by Monreal and Formaggio [10]. In a CRES experiment, tritium gas beta decays in a region of uniform magnetic field $B \approx 1$ T. The decay electrons spiral around magnetic field lines in a cyclotron motion emitting radiation as a result of the centripetal acceleration. Tritium endpoint electrons in a 1 T field radiate power $P \sim 1$ fW at the cyclotron frequency $f \approx 27$ GHz. Frequency is related to kinetic energy E by relativistic kinematics:

$$f = \frac{1}{2\pi} \frac{eB}{m_e + E/c^2}, \tag{2.1}$$

where e and m_e are the charge and mass of the electron, respectively, and c is the speed of light in vacuum. A measurement of frequency is trivially inverted to get the desired energy. Precision in the frequency domain is virtually unlimited and absolute standards are available for calibration. Furthermore, tritium gas is transparent to the microwave signal permitting a sensitivity scaling involving the *volume* of the tritium source, contrasted with the source *area* dependence of MAC-E sensitivity.

An energy resolution of 1 eV corresponds to a frequency resolution of 50 kHz and requires an electron to be observed for at least a few microseconds. The former condition is easily attained. The latter condition leads to the ultimate limit in CRES sensitivity to neutrino mass. A tritium endpoint electron travels hundreds of meters in a few microseconds. Any realistic apparatus must therefore confine the electron to some instrumented region without disturbing its energy. Magnetic trapping seems the most appropriate method. Equation 2.1 is the instantaneous relation between f and E. An actual measurement requires a finite observation time. The measured frequency, or equivalently, energy, of an individual electron is therefore actually a spectrum broadened by the variations in B sampled during the observation interval.

The neutrino mass sensitivity of a CRES tritium endpoint experiment has been estimated as a function of the instrumented volume of tritium [11]. The estimate includes statistical sensitivity, conservative backgrounds, effects of electron mean free path in the source that corresponds to the mean observation interval, molecular final states for T_2 sources, and variations in magnetic field. The most sensitive possible CRES experiment is found to require sub-part-per-million magnetic field uniformity in a volume $\sim 10-100\,\mathrm{m}^3$ with an atomic tritium source density of $10^{12}\,\mathrm{T/cm}^3$. That hypothetical experiment is capable of setting an upper limit of 40 meV (90% C.L.) on neutrino mass, below the floor of the inverted hierarchy.

3. Atomic Tritium

A semi-quantitative conceptual design of an atomic tritium source appropriate for Project 8 has been made [12]. The most obvious constraint it addresses is the maintenance of tritium in an atomic state (T), rather than its preferred molecular state (T_2). The beta endpoint energy for T_2 is higher by 8 eV than that of T, because of the higher mass of the daughter [9]. The number of events in an interval ε below the endpoint is proportional to ε^3. Therefore even small contamination by an isotopologue with a higher endpoint introduces a significant background, affecting both statistical sensitivity, and systematic sensitivity following from its energy-dependence. It is found that a relative purity of $T_2/T \lesssim 10^{-6}$ is required. At vacuum pressures required for a precise CRES measurement, virtually all recombination to molecules occurs on the walls of the vessel. Project 8's solution is therefore not to have a physical vessel for tritium, but rather to use the magnetic moment of T to confine it in a magnetic trap, while T_2 with much smaller magnetic moment will rapidly evaporate away. A magnetic field that confines the T will also trap the electrons under observation. An appropriate magnetic field geometry is a Ioffe trap like the one used to trap anti-hydrogen in the ALPHA experiment [13]. A Ioffe trap has large gradients near the cylindrical walls that carry counter propagating axial currents, and negligible field far from the walls. We find that a Ioffe trap 5 T deep will confine atomic tritium at 130–170 mK. If the Ioffe trap has a 20-fold symmetry of current pairs then the ratio of uniform field for CRES fiducial volume to total vessel volume is 48%. The ratio increases to 75% for 50-fold symmetry. There is then the problem of source self-heating due to the high beta activity and scattering of electrons in the source. A gas of ^{4}He (no magnetic moment) could be used to maintain thermal contact between the atomic tritium source and the cryogenic walls of a physical vessel. The mean free path for He-T^+ scattering at the assumed vacuum pressure of $10^{12}\,\mathrm{T/cm}^3$ is 50 cm. This sets a lower limit on the smallest physical dimension of the T source; tritium would evaporate from a smaller source due to insufficient cooling. Table 1 reviews the conceptual design parameters of the atomic tritium source.

4. The Four Phases of Project 8

Project 8 is proceeding with the four-phase approach presented in Table 2 to develop the next-generation tritium endpoint experiment based on CRES. Each phase has distinct scientific goals and critical engineering milestones that are necessary to reach the estimated 40 meV sensitivity. The phases are broadly defined and will be conducted in parallel.

Parameter	Value	Comments
T density	$10^{12}\,\mathrm{cm}^{-3}$	required for statistical sensitivity
T temperature	130–170 mK	prevents evaporation from Ioffe trap
T_2/T concentration	$\lesssim 10^{-6}$	limits background from T_2 spectrum
$\delta B/B$	$\sim 10^{-7}$	uniform field for CRES energy resolution
Ioffe trap depth	5 T	confines atomic tritium
Ioffe trap symmetry	20-fold (50-fold)	48% (75%) usable fiducial volume
smallest dimension	50–100 cm	1–2 mean free paths for thermalization

Table 1: Parameters of the conceptual atomic tritium source design for Phase IV.

Phase	Timeline	Source	R&D Milestones	Science Goals
I	2010–2016	^{83m}Kr	single electron detection proof of concept	conversion electron spectrum of ^{83m}Kr
II	2015–2017	T_2	Kurie plot systematic studies	Final-state spectrum test, ^{3}H$-^3$He mass difference, $m_\nu \lesssim$ 10–100 eV
III	2016–2020	T_2	high-rate sensitivity B field mapping	$m_\nu \lesssim 2$ eV
IV	2017...	T	atomic tritium source	$m_\nu \lesssim 40$ meV measure m_ν *or* determine normal hierarchy

Table 2: The four phases of the Project 8 experiment.

Phase I has demonstrated the CRES technique [7] originally proposed by Monreal and Formaggio [10]. The demonstration was made with ^{83m}Kr conversion electrons trapped in a harmonic magnetic bottle ($B \sim \text{constant} + z^2$) inside of a rectangular microwave waveguide. The demonstration will soon be complete with analysis of new data from a run replacing the harmonic trap with a more uniform "bathtub" trap allowing electron energy resolution $\Delta E \approx 1$ eV and magnetic trapping efficiency of up to 10%. Figure 1 shows an early result of that analysis demonstrating the ability to resolve the L-shell ^{83m}Kr conversion electrons and their shake-off satellites with 3.6 eV resolution, including the 1.4 eV $L3$ linewidth.

The distinguishing feature of Phase II is the first CRES measurements of tritium decay. Phase II will similarly occur inside of a waveguide, albeit a larger gauge circular waveguide for slightly increased source volume and to reclaim half of the cyclotron power lost in the rectangular waveguide of Phase I. The result of Phase II will be a test of modern calculations of the molecular final-state spectrum [9], a measurement of the molecular tritium endpoint with $\lesssim 10$ eV precision, and a neutrino mass limit $m_\nu \lesssim$10–100 eV. Figure 2 shows the Phase II instrument with five individual

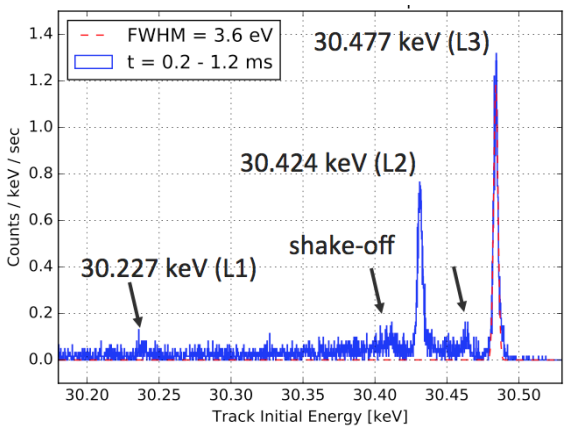

Figure 1: Preliminary result from the Phase I bathtub trap run.

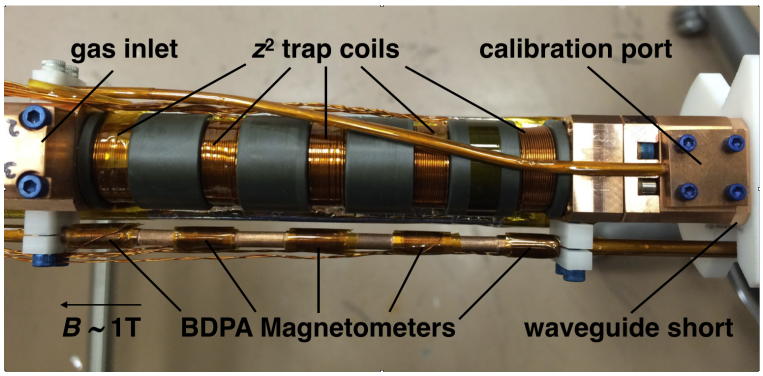

Figure 2: The circular waveguide cell for Phase II.

harmonic ($B \sim z^2$) traps that can be operated in concert to form a larger bathtub than in Phase I. The traps are wound around the circular waveguide section. The assembly in Figure 2 is inserted into the warm bore of an NMR magnet during operation.

Phase III will leave the confined volume of waveguide, instrumenting a tritium source in free space with a phased array of antennas. This is a critical step to move towards the large volumes and high event rates that will be required to accommodate enough tritium for sufficient statistical sensitivity in Phase IV. The result of Phase III will be a limit $m_\nu \lesssim 2\,\text{eV}$, competitive with current limits from the Mainz and Troitsk experiments [3, 4]. Figure 3 shows an example of an inward-looking phased array antenna consisting of open-ended waveguide elements and its beam pattern when phased to focus on the center. The focus can be anywhere inside the ring through the application of digital beam forming, where the relative phase delay of each channel is tuned after sampling but before summation. A map of the signal to noise ratio (SNR) versus the radius of the ring and the number of channels that populate it is also shown.

All of the tritium sources through Phase III will consist of molecular tritium gas. Phase IV will include all development and operation with *atomic* tritium sources. Atomic tritium is required to avoid the irreducible systematic uncertainty associated with the final states of the $^3HeT^+$ ion

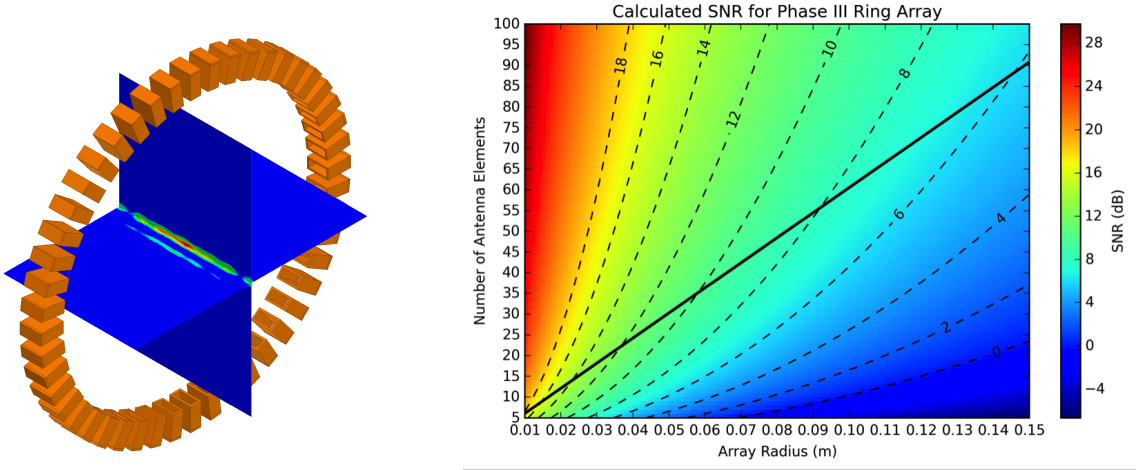

Figure 3: Left: A possible phased array antenna for Phase III. The color of the beam pattern on the vertical and horizontal planes represents gain from its maximum (red) down to -6 dB of the maximum or less (blue). Right: Maximum SNR versus the size and number of channels for a general ring-shaped array. Points above the black line cannot be realized because the number of elements will not fit on a single circular ring.

populated by beta decay of T_2 [9]. The result of Phase IV will be sensitive to inverted hierarchy neutrinos of about 40 meV.

5. Conclusion

Project 8 is being executed as four distinct phases. Each phase demonstrates an advance of CRES spectroscopy necessary for later phases and generates its own scientific results. Major parallel efforts are underway on Phases I–III. First Phase I results are published [7], with improved analysis of new Phase I data underway at the time of this writing. That will demonstrate CRES as a spectroscopic technique with sufficient energy resolution, backgrounds, and linearity for a tritium endpoint experiment, using ^{83m}Kr as a proxy for tritium. The Phase II instrument has recently collected its first data. Phase II will generate Project 8's first tritium results, particularly a neutrino mass sensitivity on order 10–100 eV, by early 2017. The Phase III result, $m_\nu \lesssim 2$ eV, competitive with current limits, can be produced by about 2020. Formal planning of Phase IV, the ultimate CRES tritium endpoint experiment with an atomic tritium source, has recently begun.

6. Acknowledgements

The Project 8 Collaboration acknowledges financial support received from the University of Washington Royalty Research Foundation, the Massachusetts Institute of Technology Wade Fellowship, the U.S. Department of Energy Office of Science, Office of Nuclear Physics to the University of Washington under Award No. DE-FG02-97ER41020, to the University of California, Santa Barbara under Award No. DE- SC0004036, and to the Massachusetts Institute of Technology under Award No. DE-SC0011091, the National Science Foundation under Award No. 1205100, and

the Laboratory Directed Research and Development Program at Pacific Northwest National Laboratory, a multiprogram national laboratory operated by Battelle for the U.S. Department of Energy under Contract No. DE-AC05-76RL01830. A portion of the research was performed using PNNL Institutional Computing at Pacific Northwest National Laboratory. The isotope(s) used in this research were supplied by the United States Department of Energy Office of Science by the Isotope Program in the Office of Nuclear Physics.

References

[1] D. Geesaman *et al.*, Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science. Department of Energy and the National Science Foundation, 2015.

[2] X. Qian *et al.*, *Statistical evaluation of experimental determinations of neutrino mass hierarchy*, Phys. Rev. D **86** 113011 (2012).

[3] Ch. Kraus *et al.*, *Final Results from phase II of the Mainz Neutrino Mass Search in Tritium β Decay*, Eur. Phys. J., **C40** 447 (2005).

[4] V. N. Aseev *et al.*, *Upper limit on the electron antineutrino mass from the Troitsk experiment*, Phys. Rev. D **84** 112003 (2011).

[5] J. Angrik *et al.*, KATRIN design report 2004, FZKA-7090 (2005).

[6] P. A. R. Ade *et al.* (Planck Collaboration), *Planck 2013 results: XVI - Cosmological parameters*, Astronomy and Astrophysics **571** A16 (2014).

[7] D. M. Asner *et al.* (Project 8 Collaboration), *Single-electron detection and spectroscopy via relativistic cyclotron radiation*, Phys. Rev. Lett. **114** 162501 (2015).

[8] V. M. Lobashev and P. E. Spivak, *A method for measuring the anti-electron-neutrino rest mass*, Nucl. Instrum. Meth. A **240** 305 (1985).

[9] L. I. Bodine, D. S. Parno, and R. G. H. Robertson, *Assessment of molecular effects on neutrino mass measurements from tritium β decay*, Phys. Rev. C **91** 035505 (2015).

[10] B. Monreal and J. A. Formaggio, *Relativistic Cyclotron Radiation Detection of Tritium Decay Electrons as a New Technique for Measuring the Neutrino Mass*, Phys. Rev., D **80** 051301 (2009).

[11] P. J. Doe *et al*, *Project 8: Determining neutrino mass from tritium beta decay using a frequency-based method*, arXiv 1309.7093 (2013).

[12] B. M. Clark, Magnetic trapping of atomic tritium for neutrino mass measurement, Bachelor's thesis, California Institute of Technology (2014).

[13] C. Amole *et al*, *The ALPHA antihydrogen trapping apparatus*, Nucl. Instrum. Meth. A **735** 319 (2014).