PROCEEDINGS OF SCIENCE

Project 8: First Results & More

N. S. Oblath[*][†]
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA, USA
E-mail: `nsoblath@mit.edu`

Neutrinos are the most common matter particles in the universe, and yet several fundamental questions about them remain unanswered, including the absolute mass scale. The most sensitive direct probes of neutrino mass are made by tritium beta-decay experiments; the neutrino mass can be determined by making a careful measurement of the beta-decay electron energy spectrum. The Project 8 experiment aims to measure the neutrino mass with a novel technique involving tritium beta-decay: measuring the frequency of the cyclotron radiation emitted by the electrons as they travel in a magnetic field. I will present recent results from the Project 8 prototype experiment, as well as our initial plans for making a measurement of the tritium spectrum.

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[*] Speaker.

[†] On behalf of the Project 8 Collaboration

1. Neutrino Mass via Tritium Beta Decay

While neutrino oscillation experiments have successfully shown that neutrinos change flavor, and therefore have non-zero mass, the absolute mass scale remains unknown. The simplest way to directly measure the mass of the neutrino is using beta decays. Neutrino mass has an effect on the kinematics of decay process [1]. While the neutrinos themselves are difficult to measure, the energies of the outgoing electrons can be precisely determined. The neutrino mass can then be inferred from the shape of the electron energy spectrum:

$$\frac{dN}{dK_e} \propto F(Z,K_e) \cdot p_e \cdot (K_e + m_e) \cdot (E_0 - K_e) \cdot \sum_{i=1}^{3} |U_{ei}|^2 \sqrt{(E_0 - K_e)^2 - m_i^2} \cdot \Theta(E_0 - K_e - m_i). \quad (1.1)$$

The Fermi function, $F(Z,K_e)$, takes into account the Coulomb interactions of the electron with the recoiling nucleus; Z is the proton number of the final-state nucleus, K_e is the electron's kinetic energy, p_e is the electron's momentum, E_0 is the Q-value of the decay, and U_{ei} are the elements of the PMNS matrix for neutrino mass states $m_{i,i=1-3}$. The only dependence on the neutrino mass comes from the phase-space factor. The shape of the spectrum is independent of all other properties of the neutrino, including whether neutrinos are Majorana or Dirac particles.

One technique being used to precisely measure the beta-decay spectrum relies on a spectrometer to precisely select high-energy electrons from tritium decays. The most recent experiments to use this technique are the Mainz and Troitsk experiments. They placed similar limits on the neutrino mass: $m_{\beta\nu} < 2.3$ eV [2, 3]. KATRIN, the next-generation of spectrometer-type experiments, aims to lower that limit by an order of magnitude, to 200 meV (90% CL) [4]. KATRIN is currently under construction and commissioning in Karlsruhe, Germany.

The lower limits for the neutrino mass from oscillation experiments provide a strong motivation for probing to lower neutrino masses. However, with KATRIN, the technologies used in spectrometer-type tritium experiments have been pushed to their current practical limits. A new technique is needed to push the mass sensitivity lower.

2. A New Technique

The Project 8 collaboration proposes an alternate method of measuring the electron energies: measure the cyclotron radiation emitted by the electrons spiraling around magnetic field lines. An enclosed volume of tritium is placed in a uniform magnetic field, and as the tritium nuclei decay, the electrons will spiral around the magnetic field lines. The spiraling electrons are being accelerated, and therefore emit cyclotron radiation. The frequency of that radiation is proportional to the magnetic field strength, and inversely proportional to the electron's kinetic energy:

$$\omega_\gamma = \frac{eB}{\gamma m_e} = \frac{\omega_c}{\gamma} \approx \frac{\omega_c}{1 + K_e/(m_e c^2)} \left(1 + \frac{\cot^2\theta}{2}\right). \quad (2.1)$$

By measuring the frequency of the cyclotron radiation, one can measure the electron's kinetic energy without interfering with the electron itself. The pitch angle, θ, is the angle between the electron momentum vector and the magnetic field. Eq. 2.1 is valid for angles near 90°; the effect of the pitch angle on the frequency of the cyclotron radiation is small, but potentially observable. Using a 1-T magnetic field, the endpoint of the tritium spectrum (18.6 keV) falls around 26 GHz. The power emitted as cyclotron radiation depends both on the relativistic velocity of the electron, β, and θ:

$$P(\beta,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta^2\sin^2\theta}{1-\beta^2}. \tag{2.2}$$

The electrons that radiate the most power will be the easiest to detect. Equation 2.2 shows that the power will be greatest for electrons with $\theta \approx 90^\circ$. Conveniently, these electrons also travel the slowest in the direction of the magnetic field, increasing the amount of time they can be observed.

The primary concern for making a precise electron energy measurement is the ability to measure frequency precisely. The desired energy precision is therefore the place to start in considering the requirements for this type of experiment. To achieve the necessary energy precision, ΔE, we need to achieve a relative frequency precision of $\Delta f/f = \Delta E/m_e$. KATRIN is designed to achieve $\Delta E \approx 1$ eV; for Project 8 to achieve a similar accuracy means that $\Delta f/f \approx 2\times 10^{-6}$. This accuracy is reasonable with current technologies. With a 1-T magnetic field, $\Delta f \approx 52$ kHz at 26 GHz.

The desired frequency accuracy determines for how long we must be able to observe single electrons. To have a frequency resolution of Δf, we must measure each electron for $t_{\min} = 1/\Delta f$. With the design parameters discussed above, the electrons must be coherently measured for at least 20 μs. The minimum measurement time places constraints on a number of physical parameters of the experiment. The gas density must be low enough that, on average, 18.6 keV electrons can travel for $t_{\min}$ without scattering. Furthermore, the experiment must be large enough so that the electron can be tracked continuously.

The signal detected for a single electron may be more complicated than the single frequency at which the cyclotron radiation is emitted. In particular, the detected signal can include a Doppler shift due to the velocity of the electron parallel to the magnetic field, a dependence on the electron-antenna distance, and effects from the angular dependence of the power distribution of the radiation.

3. Prototype Experiment

The Project 8 Collaboration has constructed a prototype experiment to demonstrate the Cyclotron Radiation Emission Spectroscopy (CRES) technique. The initial goals of the prototype are to verify that we can, in fact, detect the cyclotron radiation from a single electron, and then to use such detections to perform a spectroscopic measurement. We will use a ^{83m}Kr radioactive source, which emits a conversion electron with energies of 17.8 keV, 30 keV, and 32 keV (there is also a 9 keV electron, which is too low in energy to be detected with our current setup) and has a half-life of 1.83 hours. The source is a good stand-in for tritium: it is gaseous, emitting the electrons isotropically, and the energy of one of the electron lines is close to the tritium-decay endpoint.

Figure 1 shows a diagram of the magnet insert for the prototype experiment, which is located at the University of Washington, in Seattle, WA, USA. A superconducting solenoid provides the 1-T magnetic field. The electrons are trapped in a small ($\approx 10\text{mm}^3$) magnetic bottle in the bore of the magnet. The magnetic field from the solenoid traps the electrons in the horizontal plane; a trapping coil within the bore of the magnet decreases the field slightly in a small volume, trapping

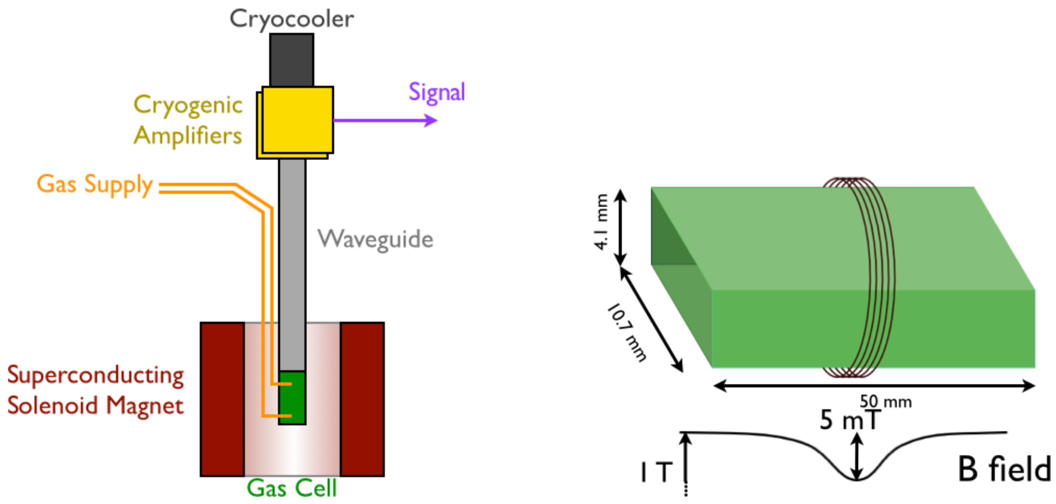

Figure 1: (left) Schematic diagram of the prototype experiment. (right) Diagram of the gas cell, rotated 90° with respect to the diagram at left, that is inserted in the solenoid magnet. The gas cell comprises a 5 cm length of WR-42 aluminum waveguide stock. A magnet coil wound around the gas cell provides a small dip in the magnetic field that traps electrons for observation.

the electrons vertically. Whether or not electrons are trapped depends on the depth of the magnetic bottle potential, and the pitch angle of the electrons. Electrons with large pitch angles ($\theta \geq 85^\circ$) will be trapped. Fortunately, these electrons also emit the most power as cyclotron radiation. Though this angle selection severely limits the number of electrons we will detect, it maximizes the signal-to-noise ratio for each electron.

The cyclotron radiation couples to the TE_{10} mode of the WR-42 waveguide, and is then measured by two low-noise cryogenic amplifiers. The rectangular cavity of the waveguide also serves as the gas cell to contain the ^{83m}Kr gas. Signals from the amplifiers are mixed down to baseband, digitized and written to disk. After the data has been recorded, we analyze it to search for excesses of power as a function of frequency. Fig. 2 is a spectrogram of a simulated electron. The characteristic signal that we expect to see is a “chirp” in time-frequency space. Each column in the spectrogram is a power spectrum created from a ≈ 30-μs time slice. The signal rises in frequency as a function of time because the electron emits energy as cyclotron radiation. The main background in our analysis is the random noise that sometimes fluctuates high enough to mimic a signal. The process of identifying these chirps involves applying a threshold to remove most of the noise, and then using a clustering algorithm (DBSCAN [6]) on the points that remain.

4. First Observation and Spectroscopy

After a round of important hardware upgrades in the first half of 2014, we started taking data on June 6, 2014. Figure 3 shows the first event in our data, collected in the first second of data recorded. We demonstrated that these events were electrons from ^{83m}Kr decays by showing that they only appear in the frequency bands we expect for 18-, 30-, and 32-keV electrons, and that we do not see any if we reverse the polarity of our magnetic trap. This first observation of single-electron cyclotron radiation was published in [7].

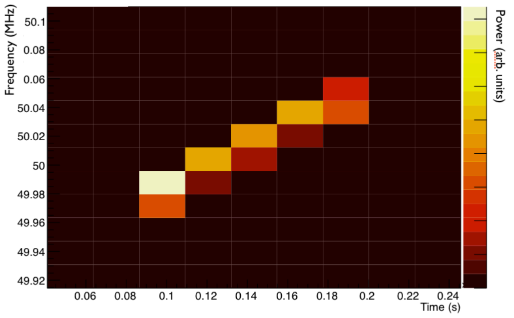

Figure 2: A spectrogram of a simulated chirp. The frequency of the signal increases as a function of time because the electron is emitting energy as cyclotron radiation.

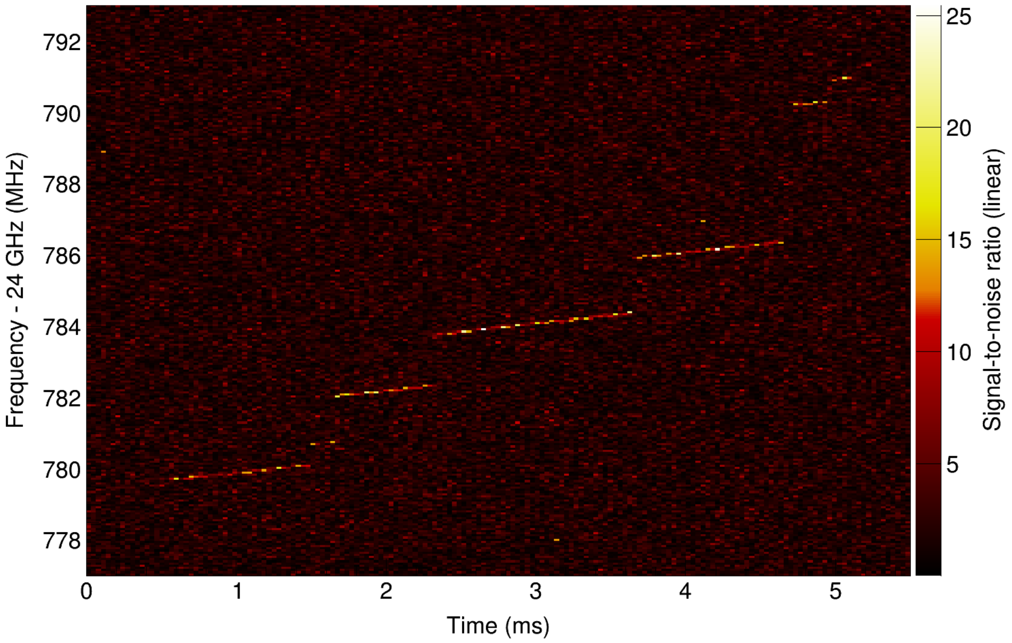

Figure 3: A spectrogram of a the first electron detected with the Project 8 prototype. All of the tracks seen were created by a single electron as it scattered off of gas molecules in the cell. The slope of each track is due to energy loss to cyclotron radiation. Eventually the electron scatters in a way that it is no longer trapped by the magnetic fields.

The spectrogram in Fig. 3 shows several important features that can be observed for most events. Perhaps the most obvious feature is that there are multiple "tracks" that follow each other immediately in time, but have significant jumps in frequency. Each set of tracks that follow each other in time are from a single electron that scatters off of gas molecules (hydrogen is the dominant residual gas) and ends up at a new frequency because the energy and pitch-angle change. The onset of trapping is clearly visible as the start of the first line on the left side of the spectrogram. Eventually the electron scatters into a state that is no longer trapped by the magnetic fields, and the

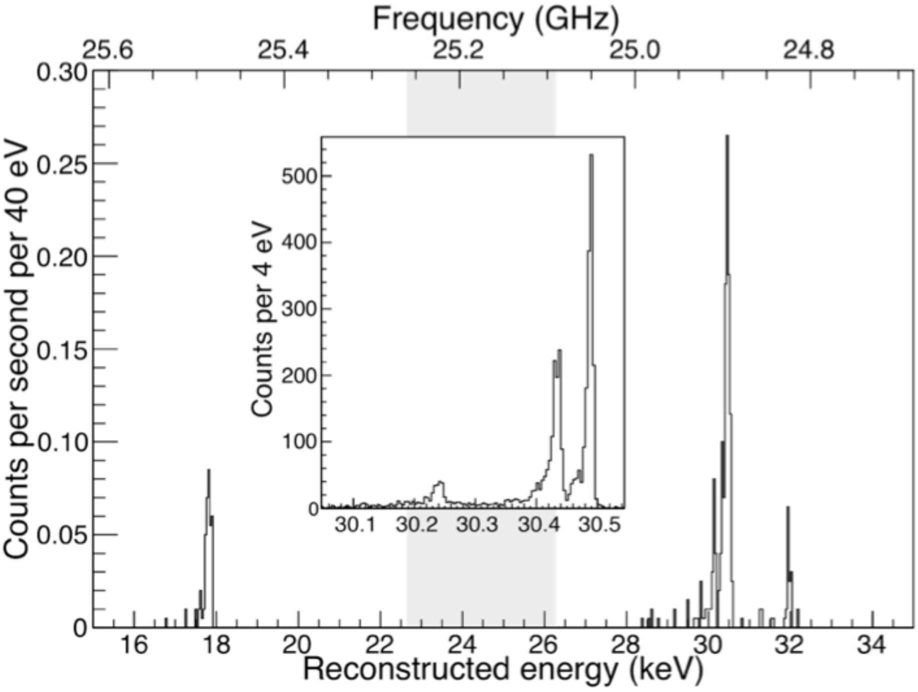

Figure 4: (background) The full ^{83m}Kr spectrum, including the 17.8 keV, 30 keV, and 32 keV electron peaks. The trap depth for this dataset was 3.3 mT, and the energy resolution was ≈100 eV. (inset) The spectrum of the peaks around 30 keV, measured with a trap depth of 1.6 mT, and an energy resolution of ≈10 eV.

tracks in the spectrogram stop.

Another striking feature is that the tracks all slope upwards in frequency as a function of time. The rise in frequency of a single track is due to the electron losing energy to cyclotron radiation as it travels in the magnetic field.

Though each track slopes upwards, and in this spectrogram all of the jumps between tracks go upwards in frequency, there are many examples in our dataset where the jumps between tracks go down in frequency as well. The change in frequency between tracks depends both on the change in energy of the electron when it scatters, and the change in pitch angle. Though the former always results in an electron with lower energy (and therefore higher frequency), the latter can cause the frequency to go up or down.

After identifying individual electron events, the cyclotron frequency of each is converted to an energy using Eq. 2.1 (under the approximation that $\theta = 90°$), and we can produce a spectrum of the ^{83m}Kr conversion electrons. Figure 4 shows the energy spectrum of ^{83m}Kr, as reported in [7]. The background spectrum shows the wide view of the 17.8-, 30-, and 32-keV electrons, while the inset zooms in on the set of peaks around 30 keV. The two spectra have different resolutions because the depth of the magnetic trap was different when collecting the two datasets. For the background plot the trap was approximately 3.3 mT deep, and the energy resolution was approximately 100 eV. For the inset spectrum, the trap was approximately 1.6 mT deep, and the energy resolution improved to 10 eV. In a shallower trap the magnetic field is more uniform over the volume of the trap, resulting in an improved energy resolution.

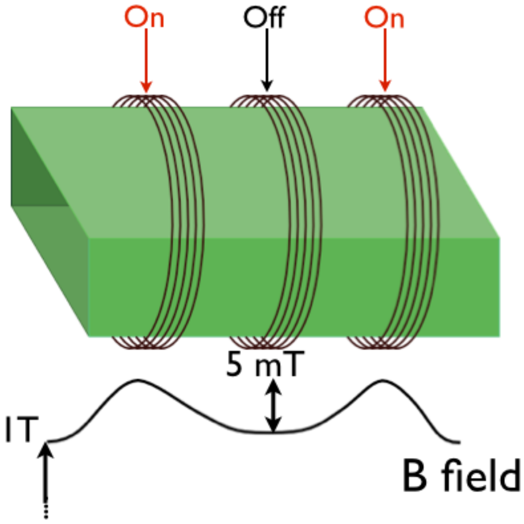

Figure 5: Diagram of the gas cell using the "bathtub" trap setup. The two side coils are energized, and the center coil is turned off. Other modes of operation can include the half-bathtub trap, using the center coil and one side coil, or the full bathtub with the center coil used to flatten the bottom of the trap.

5. Recent Improvements

We have two main methods of seeking to improve the energy resolution of the spectrometer: change the trap geometry, and remove the dependence of the frequency on pitch angle. For the former, we have an alternate trap geometry called a "bathtub" trap, as is shown in Fig. 5. Two magnet coils are used, with their currents reversed relative to the current direction used in the single-coil trap mode. This produces two bumps in the magnetic field, with a flatter region in the middle where the electrons are trapped. There is therefore a larger volume at the center of the trap with a more uniform field, which leads to an improved energy resolution It has the additional benefit of significantly increasing the volume of the trapping region, which produces a greater number of electron detections. Initial tests with the bathtub trap show that we will be able to achieve a resolution of a few eV.

The second method for improving the resolution of our experiment is to separate the dependency of the cyclotron radiation on the electron energy from the dependency on the pitch angle. If the only frequency observed is ω_γ from Eq. 2.1, the conversion of frequency to energy will always have an extra uncertainty due to the potential variation in pitch angle. However, the axial frequency of the electron, the frequency with which it travels back and forth in the trap in the direction of the magnetic field, depends strongly on the pitch angle. For example, for a certain approximation of the bathtub trap, the axial frequency is:

$$\omega_a \propto v \left(\frac{a}{\sin\theta} + \frac{4\sin\theta}{m\cos^2\theta} \right)^{-1}, \tag{5.1}$$

where a and m are characteristics of the trap shape, and v is the speed of the electron. Due to the Doppler effect on the cyclotron radiation, some of the power emitted leaks from the main frequency peak into sidebands separated by factors of ω_a from ω_γ. However, the amount of power in the

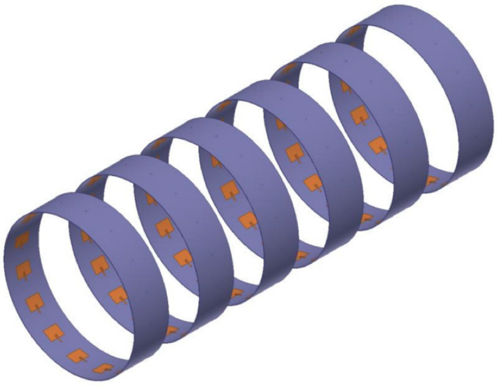

Figure 6: Design under consideration for an array of patch antennas, which might allow us to detect electrons in a much larger volume than in our current apparatus.

sideband peaks, which depends strongly on θ, is estimated to be no larger than -30 dB relative to the central peak. In February 2015, after equipment upgrades that reduced the thermal noise background, we implemented a preliminary analysis that averaged the power spectrum along each track, and, for some electrons we were able to see the first pair sidebands. In the future this type of analysis will be used to significantly improve the uncertainty on the energy measurement for all electron tracks.

6. Future Work: Measuring the Tritium Spectrum

The overall goal for the Project 8 experiment is to measure the mass of the neutrino using tritium beta decays. We are currently working on the design of our first tritium gas cell. It will fit in the current apparatus, replacing the existing Krypton gas cell. We will be able to make our first measurement of the tritium beta spectrum, though it is not expected to have a significant sensitivity to the neutrino mass.

Future iterations of Project 8 will require significantly higher statistics to measure the endpoint of the tritium beta-decay spectrum with sufficient accuracy. To that end we are developing plans for a gas cell with a significantly larger volume. In our current waveguide-based apparatus, we are limited to a small trapping volume. One alternative we are pursuing is an array of small patch antennas arranged in a cylindrical patter, as shown in the diagram in Fig. 6. The signals from the different antennas will be combined coherently, with the appropriate phase delays, to allow us to continuously observe an electron in the volume surrounded by the antennas.

To significantly improve on the sensitivity to the neutrino mass compared to what the KATRIN experiment will achieve, we will need to use an atomic tritium source, rather than the molecular sources that have been used for neutrino mass experiments. Due to vibrational and rotational states of the ^{3}H-^{2}H molecule that results from a single tritium decay, any experiment using a molecular tritium source will be ultimately limited to a neutrino mass of approximately 100 meV. We are currently in the very early stages of designing an atomic tritium source that will allow the Project 8 experiment to make a significant contribution to the measurement of the absolute neutrino mass.

References

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