Project 8: Measuring the tritium beta-decay spectrum using Cyclotron Radiation Emission Spectroscopy

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Abstract. The goal of the Project 8 experiment is to measure the absolute neutrino mass using tritium beta decays and a new spectroscopic technique, Cyclotron Radiation Emission Spectroscopy (CRES). CRES has the potential for extremely low backgrounds and high precision. Phase I of Project 8 demonstrated that CRES could be used to detect single-electron cyclotron radiation and perform precision electron spectroscopy. We are in Phase II of the experiment, performing a 2-3-month measurement of the endpoint of the tritium spectrum. We will measure the last ∼2 keV of the beta-decay spectrum, demonstrate our understanding of the systematic uncertainties, and explore the background rate at energies just above the endpoint. In Phase III we will demonstrate the ability to scale up the volume of the experiment, and to create a stable atomic tritium source, which will eventually avoid systematic uncertainties from the final states of the molecule. Phase IV will combine the critical factors of precision, size, and well-controlled systematic uncertainties to reach the final sensitivity of 40 meV. I will present the status of Project 8 Phase II and the plans for Phases III and IV.

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. The neutrino mass can be determined by observing the shape of the endpoint of the beta-decay spectrum with sufficient precision [1].

One method used to precisely measure the beta-decay spectrum relies on a spectrometer to precisely select high-energy electrons from tritium decays. The most recent experiment to use this technique is KATRIN, which placed a limit of $m_\nu < 1.1$ eV (90% CL) [2], where m_ν is the effective electron antineutrino mass [1]. The final goal of KATRIN is to reach a sensitivity of 200 meV (90% CL) [2].

The lower limit for the neutrino mass from oscillation experiments (≈10 meV) provides a strong motivation for probing to lower neutrino masses. However, with KATRIN, the spectrometer technologies used have been pushed to their current practical limits. A new technique is needed to achieve a lower mass sensitivity.

2. Cyclotron Radiation Emission Spectroscopy

The Project 8 collaboration will use an alternate method of measuring the electron energies that was originally proposed in [3]: measure the cyclotron radiation emitted by the electrons in a nominally-uniform magnetic field. This technique is called Cyclotron Radiation Emission

Spectroscopy, or CRES. An enclosed volume of tritium is placed in a uniform magnetic field, and as the tritium nuclei decay, the electrons will travel in circular orbits and emit cyclotron radiation. The frequency of that radiation is proportional to the magnetic field strength, and inversely proportional to the electron's kinetic energy:

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

By measuring the frequency of the cyclotron radiation, one can measure the electron's kinetic energy without interfering with the electron itself. For a detailed look at the phenomenology of this technique, see [4]. Using a 1-T magnetic field, the endpoint of the tritium spectrum (18.6 keV) falls around 26 GHz.

The Project 8 Collaboration is taking a phased approach to developing the technology necessary to turn the CRES technique into a leading-edge neutrino-mass experiment [5]. Phase I demonstrated that single-electron cyclotron radiation could be measured with CRES, and that those measurements could be used to produce an electron energy spectrum of a source with mono-energetic lines. Phase II, the current phase of operations, is aimed at making the first CRES measurement of a continuous beta-decay spectrum using molecular tritium. Phase III will demonstrate two critical techniques: scaling up the size of a CRES experiment by making a free-space CRES measurement, and creating an atomic tritium source compatible with a CRES experiment. Phase IV is the final planned phase of the experiment, in which we will combine the critical factors of precision, size, and well-controlled systematic uncertainties to be sensitive to the neutrino mass down to 40 meV.

3. Phase I: CRES Demonstrator

The goals of the Phase I experiment were to verify that we could detect the cyclotron radiation from a single electron, and to use such detections to perform a spectroscopic measurement. We used a $^{83\mathrm{m}}$Kr radioactive source, which emits conversion electrons with energies of 7, 9, 18, 30, and 32 keV 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 of 18.6 keV.

Figure 1 shows a diagram of the experiment, which was located at the University of Washington, in Seattle, WA, USA. A superconducting solenoid provided the 1-T magnetic field. The electrons were trapped in a small ($\approx 20\,\mathrm{mm}^3$) magnetic bottle in the bore of the magnet created with a magnet coil wrapped around the waveguide. The cyclotron radiation coupled to the TE_{10} mode of the waveguide, and was then amplified by two low-noise cryogenic amplifiers. The rectangular cavity of the waveguide also served as the gas cell to contain the $^{83\mathrm{m}}$Kr gas. Signals from the amplifiers were mixed down to baseband, digitized and written to disk. After the data were recorded, we analyzed it to search for excesses of power as a function of frequency. After identifying individual electron events, the cyclotron frequency of each was converted to an energy using Eq. 1, and we could produce a spectrum of the $^{83\mathrm{m}}$Kr conversion electrons. In Phase I we achieved a resolution of ≈10 eV FWHM.

4. Phase II: Measuring the Tritium Spectrum

The current phase of the Project 8 experiment is aimed at making the first CRES measurement of the tritium beta-decay spectrum. We switched from a rectangular waveguide to a circular waveguide with a 1-cm inner diameter to increase the volume of the gas cell and match the polarization of the cyclotron radiation. The length of the cell was also increased to 13 cm, and five trapping coils were wrapped around the waveguide. The increased number of trapping coils allows us to explore a variety of trapping configurations. Most of the other major components of the experiment remained the same. Using 17.8-keV electrons we determined that the resolution of the CRES technique with this apparatus is 2 ± 0.5 eV (FWHM).

In 2018 we made the first tritium spectrum measurement, collecting roughly 400 tritium events in the last 2 keV of the tritium spectrum. We assessed the detection efficiency using

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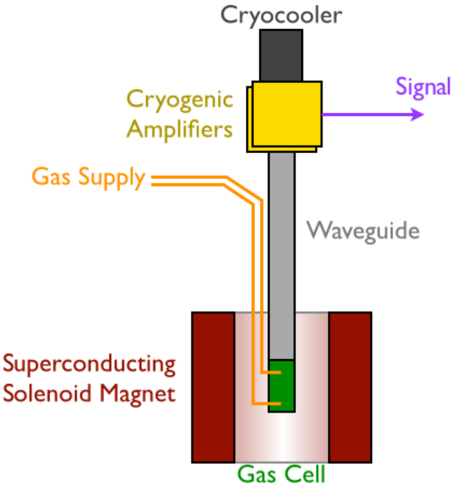

Figure 1. Schematic diagram of the Phase I and II experiments.

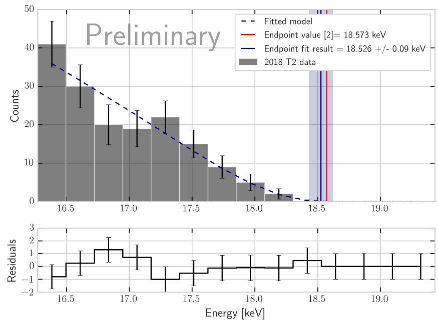

Figure 2. The spectrum of tritium data recorded in 2018, fit with a nominal tritium spectrum distorted by the measured detection efficiency.

^{83m}Kr data, one of the critical systematic uncertainties in performing quantitative spectroscopy. Fig. 2 shows the 2018 tritium events fit with a nominal tritium spectrum distorted by the measured detection efficiency. As of this writing we have started the final tritium dataset of Phase II. We will use that information to demonstrate the power of CRES to make a quantitative measurement of a continuous beta-decay spectrum.

5. Phase III: Technique Demonstrators

After completing Phases I and II, there are two major objectives that must be demonstrated so we can be confident that the full-scale Phase-IV experiment will be successful: detection of CRES events in free space, and the construction and operation of an atomic tritium source. Each of these objectives involves its own campaign of technical demonstrations.

5.1. Free-Space CRES

In any tritium-endpoint neutrino-mass experiment the source volume is a key factor in determining the statistical sensitivity of the experiment: the fraction of electrons in the last 10 eV of the spectrum is approximately 3×10^{-10}, so a large source is important. The primary goal of the Phase III free-space CRES demonstrator is to create an apparatus that can be easily scaled to larger volumes. In Phases I and II, the gas volume was limited to the inside of a small waveguide. It would difficult to scale such a system to the volume we need for Phase IV. Instead, we will move to a larger magnet, and a configuration with an array of antennas that sit outside the gas volume, as shown in Fig. 3. The free-space radiation from the electrons is detected by a cylindrical array of antennas. This apparatus will observe a gas volume of approximately 200 cm^3, and be placed inside of an MRI magnet. The technical challenges in this campaign include the cryogenics system to suppress background noise, and designing the unique antenna arrays to detect the faint signals. Digital beam-forming will be used to spatially locate electrons within the fiducial volume of the tritium source. Using this apparatus we will improve the precision of the CRES technique by optimizing experimental parameters such as the gas pressure, and by developing improved reconstruction and analysis techniques. We will address systematic uncertainties such as the detection efficiency and the precise understanding of the magnetic field.

5.2. Atomic Tritium Source

Another key factor in determining the ultimate sensitivity for Project 8 is the fundamental resolution with which we can measure the beta-decay spectrum. With molecular tritium the ultimate achievable resolution is limited to 100 meV by the vibrational and rotational final

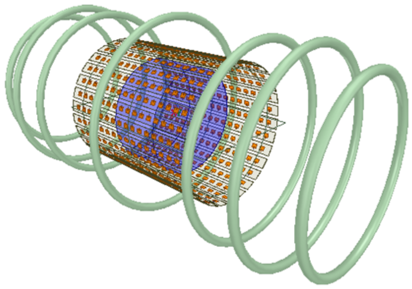

Figure 3. Conceptual design for the Phase III free-space CRES demonstrator, including the fiducial volume surrounded by an array of patch antennas, and magnetic trapping coils.

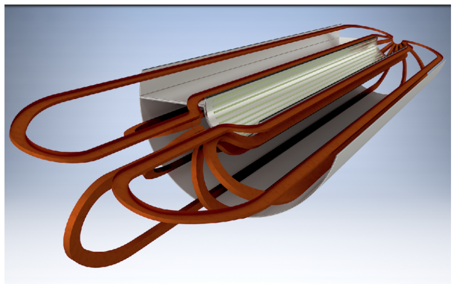

Figure 4. Conceptual design for the Phase III atomic-tritium source demonstrator, showing the tritium trapping region and the Ioffe coils that will form the trapping field.

states of the ^{3}HeT$^+$ molecule [7]. By using atomic tritium we can surpass that limitation, and therefore an atomic tritium source is the second experimental campaign of Phase III. We will need to efficiently create the atomic tritium, cool it to sub-Kelvin temperatures, and then trap it in the detector volume. Ioffe coils will be used to generate the high magnetic-field gradient necessary to keep the tritium from touching surfaces, on which it would otherwise recombine to molecular tritium. Fig. 4 shows a model of the Ioffe trap for the demonstrator apparatus. We will study the systematic uncertainties associated with the atomic source, and the magnetic fields used to trap the tritium, and we will better understand how to scale up the size of the source, providing a sufficient number of tritium decays to reach the desired statistical sensitivity.

6. Summary and Phase IV

Phase IV is the final planned stage of the Project 8 experiment. It will bring together the key components of high precision, large volume, and well-controlled systematic uncertainties to be sensitive to the neutrino mass down to 40 meV. The Project 8 collaboration has already demonstrated the inherent high precision of the CRES technique. Over the course of Phase III we will work to improve that with an optimization of relevant experimental parameters such as the gas pressure, and with the development of new analysis techniques. A large source volume is necessary to get a sufficient number of tritium decays near the beta-decay endpoint. The Phase-IV experiment aims for an effective exposure of $\approx$10 m^3 yr. In Phase III we will have shown that we can detect and reconstruct free-space CRES signals. We will have also shown that we can build an atomic tritium source using scalable techniques. These techniques will be the key to developing the final Project 8 experiment.

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