Project 8: Using Radio-Frequency Techniques to Measure the Neutrino Mass

Noah Oblath
Massachusetts Institute of Technology
for the Project 8 Collaboration

Topics in Astroparticle and Underground Physics
September 9, 2015
Using Tritium $\beta$ Decay

Zoom in on the endpoint...

$m_\nu = 0$ eV

$m_\nu = 2.2$ eV

$3 \times 10^{-10}$ of the full spectrum

$m_\nu = 2.2$ eV (current limit from $^3$H)

\[
\frac{dN}{dE} \approx K F(Z, E) p(E + m_e c^2) \left( (E - E_0)^2 - \frac{1}{2} m_\beta^2 \right)
\]

\[
m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}
\]
Beyond KATRIN

![Image of a town scene]

**Endpoint of the Tritium β-decay Spectrum**

- $m_\nu = 0$ eV
- $9 \times 10^{-15}$ of the full spectrum
- Oscillation scale $m_\nu = 0.01$ eV
- $m_\nu = 0.2$ eV

$E - E_0$ (eV)
Overview

• Goal: use a novel technique to be more sensitive to the neutrino mass

• New technique: Cyclotron Radiation Emission Spectroscopy (CRES)

• First direct measurement of single-electron cyclotron radiation made in June, 2014

• Currently seeking improvements in energy resolution and statistics

• Preparing for first tritium measurement
Novel Technique: CRES

Cyclotron Radiation Emission Spectroscopy

- Enclosed volume
- Fill with tritium gas
- Add a magnetic field

- Decay electrons spiral around field lines
- Add antennas to detect the cyclotron radiation

Cyclotron Radiation

- An electron traveling in a magnetic field emits cyclotron radiation
- The frequency of the emitted radiation depends on the relativistic boost

\[ \omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e} \]
Pitch Angle

The angle between the electron momentum and the magnetic field

- Correction term for the cyclotron frequency
- Power emitted

\[
\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e} \left(1 + \frac{\cot^2 \theta}{2}\right)
\]

\[
P_{\text{tot}} = \frac{1}{4\pi \varepsilon_0} \frac{2q^2 \omega_c^2}{3c} \frac{\beta^2 \sin^2 \theta}{1 - \beta^2}
\]
Novel Technique: CRES

Cyclotron Radiation Emission Spectroscopy

- Enclosed volume
- Fill with $^{83m}$Kr gas
- Add a magnetic field

- Decay electrons spiral around field lines
- Waveguide & cryogenic amplifiers to detect the cyclotron radiation
Project 8 Prototype

Cryocooler

Cryogenic Amplifiers

Signal

Gas Supply

Waveguide

Superconducting Solenoid Magnet

Gas Cell

Cryogenic Amplifiers

Superconducting Solenoid Magnet
Prototype - Gas Cell

- Gas Lines
- Trapping Coil
- Waveguide
Frequency vs Time
First Observation

Features

![Graph showing features related to frequency and time.](image)

- Initial trapping
- Scatter off of residual gas
- Energy loss due to cyclotron radiation
- Scatter out of the trap
- Tracks #1 to #7

**Frequency** - 2.4 GHz (MHz)

**Time (ms)**
First Observation

Frequency - 24 GHz (MHz)
\[ \omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e} \left( 1 + \frac{\cot^2 \theta}{2} \right) \]
Energy Spectrum

Trap current 800 mA

Energy Spectrum

FWHM: 15 eV

Reconstructed energy (keV)

Counts per second per 40 eV

Counts per 4 eV

Trap current 400 mA

Moving Forward

Using CRES to measure electron energies

Done

Improving Energy Resolution

In progress

Measuring the tritium spectrum
Recent Improvements

• New trap geometry

• Lower noise level
  ❖ Sidebands
  ❖ Extended energy spectrum
Recent Improvements

- New trap geometry
- Lower noise level
  - Sidebands
  - Extended energy spectrum

Improving energy resolution
“Bathtub” Trap

• Improved field homogeneity

• Larger trapping volume
Resolution Improvement

32 keV electrons -- \( \frac{1}{2} \) bathtub trap @ 1A

Compare to FWHM \( \approx 140 \) eV for a 1A harmonic trap
Resolution Improvement

32 keV electrons -- ½ bathtub trap @ 1A

Compare to FWHM ≈ 140 eV for a 1A harmonic trap
Resolution Improvement

32 keV electrons -- ½ bathtub trap @ 1A

Compare to FWHM ≈ 140 eV for a 1A harmonic trap
Disentangling Energy and $\theta$

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e} \left( 1 + \frac{\cot^2 \theta}{2} \right)$$
Disentangling Energy and $\theta$

$$\omega = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e} \left( 1 + \frac{\cot^2 \theta}{2} \right)$$

Use the axial frequency: modulation of the cyclotron radiation signal

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

For an approximation of a bathtub trap

28
Disentangling Energy and $\theta$

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e} \left( 1 + \frac{\cot^2 \theta}{2} \right)$$

Use the axial frequency: modulation of the cyclotron radiation signal

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

For an approximation of a bathtub trap

Expected frequencies: 50-200 MHz

![Graph showing fraction of power vs. frequency (GHz)]
Sidebands Found!

Very Preliminary
Sidebands Found!

[Very Preliminary]
Sideband Oscillations

Upper Sideband

Central peak

Lower Sideband

Very Preliminary
Three Degrees of Freedom

Data

\[ \omega_m \]

\[ \omega_a \]

\[ \omega_c \]

Hypothesis

Magnetron (\(\omega_m\))

Axial (\(\omega_a\))

Cyclotron (\(\omega_c\))

B field
Extended Energy Spectrum

Very Preliminary

Energy Histogram (bin width = 50.0 eV)

- Low E peaks
- 17.83 keV
- 30.4 keV
- 32 keV
Preparing for Tritium

- New cell design
- New cell windows
- Dedicated gas source
- ...
Summary

• Goal: use a novel technique to be more sensitive to the neutrino mass:

• New technique: Cyclotron Radiation Emission Spectroscopy (CRES)

• First direct measurement of single-electron cyclotron radiation made in June, 2014

• Currently seeking improvements in energy resolution and statistics

• Preparing for first tritium measurement
Projected Sensitivities

Sensitivities for different gas densities (number per cm$^3$)