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

Noah Oblath
MIT

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Tritium Beta Decay

...from which we detect the electron

Beta decay allows a precise measurement of the absolute neutrino mass scale
The shape is modified by the neutrino mass

Zoom in on the endpoint ...

$m_\nu = 2.2 \text{ eV} \quad 3 \times 10^{-10} \text{ of the full spectrum}

$m_\nu = 0 \text{ eV} \quad 3 \times 10^{-10} \text{ of the full spectrum}

m_\nu = 2.2 \text{ eV} \quad (\text{current limit from } ^3\text{H})
Endpoint of the Tritium $\beta$-decay Spectrum

- $m_\nu = 0$ eV
- $m_\nu = 0.2$ eV
- $m_\nu = 2.2$ eV

Goal of KATRIN: $4 \times 10^{-12}$ of the full spectrum
Endpoint of the Tritium $\beta$-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
Beyond KATRIN

Limiting Factors

- **Flux:** Cannot increase source column density; can only scale up the area

- **Resolution:** Cannot reasonably scale up the size of the spectrometer

\[ \Delta E = \frac{B_{\text{min}}E}{B_{\text{max}}} \]

A new technique is necessary to improve on the neutrino mass sensitivity
A New Technique

- Enclosed volume
A New Technique

- Enclosed volume
- Fill with tritium gas

\[ ^3\text{H} - ^3\text{H} \]
A New Technique

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

\[ \vec{B} \quad ^3\text{H} - ^3\text{H} \]
A New Technique

- Enclosed volume
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- Decay electrons spiral around field lines
A New Technique

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

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

\[
\vec{B} \quad ^3\text{H} - ^3\text{H}
\]
Cyclotron Radiation

- The frequency of the emitted radiation ($\omega$) depends on the relativistic boost ($\gamma$ and $\beta$ dependence), and is independent of the pitch angle of the electron ($\theta$)

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

$$P_{\text{tot}} = \frac{1}{4\pi\varepsilon_0} \frac{2q^2\omega_c^2}{3c} \frac{\beta_{\perp}^2}{1 - \beta^2}$$

- The radiation emitted can be collected to measure the electron energy in a non-destructive manner
Frequency Spectrum

- Low energy electrons dominate at higher frequencies
- Rare, high energy electrons give a clean signature at the endpoint

Demonstrating the Technique

- A prototype is being built at UW
- Superconducting solenoid
- Waveguide antenna
- Questions to answer
  1. Can we detect signals from electrons?
  2. What is the resolution of the technique?
- Use a $^{83\text{m}}\text{Kr}$ source
  - 18 and 30 keV conversion electrons
Antenna Insert

Aluminum Rectangular Waveguide

Cryogenic Amplifier

Trapping Magnet
Electron Tracking Simulations

Performed with the Kassiopeia simulation package

Simulation by D. Rysewyk
Electron Tracking Simulations

Performed with the Kassiopeia simulation package
Other Details

• Magnetic field strength: 1 T
• Cyclotron frequency: 27 GHz
• Insert cooled to 100K
• Trapping volume: ~1 mm³
• Bandwidth: 100 MHz
Taking Data

- Untriggered
- Digitize and write to disk
  - Current system: 8-bit Signatec @ 200 MHz
  - Upgrade: 8-bit digitizer attached to a ROACH FPGA processing board
- January dataset
  - 7.5 TB on disk
- New run planned for September
Data
Data

Power Spectrum

Amplitude

Time

FT

Frequency (MHz)

Power

10^3

10^1

1

10^{-1}

10^{-3}

0 1 2 3 4 5

Frequency (MHz)
Power Spectrum
Cartoon Signal

![Graph showing power vs. frequency]
Frequency vs. Time

Color = Power Detected

Frequency

Time
Frequency vs. Time

Color = Power Detected

Frequency

Time
Frequency vs. Time

Color = Power Detected
Frequency vs. Time

Color = Power Detected

Frequency

Time
Frequency vs. Time

Color = Power Detected

Frequency

Time
Frequency vs. Time

Color = Power Detected

Frequency

Time
Frequency vs. Time

Color = Power Detected
Candidate (simulated)
Current Status

- Analysis is underway of our existing data

- Next data run: September
  - Magnetic field measurement
  - Lower noise temperature
• Assuming we are able to detect electrons . . .
• Can we improve on the sensitivity to neutrino mass?
  ❖ Larger volume for higher statistics
  ❖ Systematic uncertainties ultimately limited by the $T_2$ final state distribution
  ❖ Atomic tritium would bypass this limit
  ❖ R&D is beginning on a gaseous atomic tritium source
Projected Sensitivities

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

Current effort to detect electrons
• Analyzing existing data
• Further data taking planned for September

Moving to a tritium measurement
• Scaling up volume
• Atomic tritium source
Caltech  
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