Project 8
Using Radio Frequencies to Measure the Neutrino Mass

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MIT

DPF Meeting
Providence, RI
August 12, 2011
Neutrino Mass

Normal Hierarchy

Inverted Hierarchy

Mass (eV)

\[ \sqrt{\Delta m^2_{32}} \]

\[ \sqrt{\Delta m^2_{21}} \]

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Neutrino Mass

**Normal Hierarchy**

<table>
<thead>
<tr>
<th>Mass (eV)</th>
<th>Atmospheric</th>
<th>Solar</th>
</tr>
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<tbody>
<tr>
<td>ν&lt;sub&gt;3&lt;/sub&gt;</td>
<td>0.058 &lt; 0.1 eV</td>
<td>?</td>
</tr>
<tr>
<td>ν&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.009 ?</td>
<td>0.049 &lt; 0.1 eV</td>
</tr>
<tr>
<td>ν&lt;sub&gt;1&lt;/sub&gt;</td>
<td>? ?</td>
<td>0.040 &lt; 0.1 eV</td>
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\[ \sqrt{\Delta m_{32}^2} \]

\[ \sqrt{\Delta m_{21}^2} \]

**Inverted Hierarchy**

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\[ \Delta m_{12}^2 \]

**Degenerate**

< 2.3 eV

\[ \Delta m_{12}^2 \]

> 0.1 eV

e  mu  tau
Tritium Beta Decay

Beta decay allows a precise measurement of the absolute neutrino mass scale

...from which we detect the electron
The shape is modified by the neutrino mass

Zoom in on the endpoint . . .

\[ m_\nu = 0 \text{ eV} \]

\[ 3 \times 10^{-10} \text{ of the full spectrum} \]

\[ m_\nu = 2.2 \text{ eV} \]

(current limit from \(^3\text{H}\))
Energy Spectrum

The shape is modified by the neutrino mass

Zoom in on the endpoint . . .

Goal of KATRIN

\[ m_\nu = 0 \text{ eV} \]

\[ 4 \times 10^{-12} \text{ of the full spectrum} \]

\[ m_\nu = 0.2 \text{ eV} \]

\[ m_\nu = 2.2 \text{ eV} \]
Energy Spectrum

The shape is modified by the neutrino mass

Zoom in on the endpoint …

9×10⁻¹⁵ of the full spectrum

Oscillation scale

m_ν = 0.05 eV
(600 events per Ci·y)

m_ν = 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 achieve the desired target and resolution
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
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

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

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

- Decay electrons spiral around field lines

$\vec{B} \cdot ^3H\cdot ^3H$

$e^-$
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
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 ($\theta$)

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

\[ P_{\text{tot}} = \frac{1}{4\pi\epsilon_0} \frac{2q^2\omega_c^2}{3c} \frac{\beta_{\perp}^2}{1 - \beta^2} \]

• The radiation emitted can be collected to measure the electron energy in a non-destructive manner
Initial Simulation

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

This effect is highly dependent on the antenna configuration.
Observed Frequencies

Central frequency
Dependent on the electron energy

Sidebands
Dependent on the momentum parallel to the magnetic field

This effect is highly dependent on the antenna configuration
Magnetic Field

- Frequency ~ magnetic field strength
- At 1 T, the tritium endpoint falls around 27 GHz

- Power radiated: $10^{-15}$ W
  - $18.6 \text{ keV} = 3 \times 10^{-15} \text{ J}$
  - Measurement time: $\sim 10^{-5}$ s
Is this even Possible?

- With $B = 1$ T
- Energy resolution $\Delta E = 1$ eV
  - $\Delta E/E \sim \Delta f/f \sim 10^{-6}$
  - $\Delta f \approx 50$ kHz
- Power radiated $P_{\text{signal}} = 10^{-15}$ W
- Thermal noise power @ 60 K $P_{kT} = 5 \times 10^{-17}$ W
Complexities

- Electron energy is not constant
Complexities

- Electron energy is not constant
- B field may not be uniform
Prototype Experiment

- A prototype is being built at UW
- There are several questions to answer
  1. Can we detect the signal?
  2. What is the resolution of the technique?
  3. Can we measure the $^8{\text{Kr}}$ spectrum?
Antenna Options

Parallel-strip waveguide

Rectangular waveguide
Prototype Status

• Almost ready to test parallel-strip antenna

• $^{83}\text{Kr}$ source plumbing is being put together

• Magnet, antenna, receiver chain, etc., are ready

• Rectangular waveguide is partially complete
Summary

• Project 8 is the first realistic prospect for a post-KATRIN neutrino mass experiment

• We will soon make the first attempts at single-electron detection with a $^{83m}\text{Kr}$ source

• We will also investigate antenna design and potential energy resolution

• We are currently working on scalable designs for making neutrino mass measurements