Mass Through Frequency:

The Project 8 Neutrino Experiment

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We have made a very important advance over the past century. Neutrinos have mass.

That means that the mechanism by which neutrinos gain mass is different from the other fermions.

This discovery leads to specific predictions...
In both cases, differential spectrum depends on the neutrino momentum.

\[ \dot{N} \propto p_\nu E_\nu \]

Kinematic spectra from beta decay or electron capture embed the neutrino mass near the endpoint.

Kinematic determination of neutrino mass (dispersion relation).
First, pick a source…

- $^3$H
  - $18.5$ keV
  - $\tau_{1/2} = 12.3$ yrs

- $^{163}$Ho
  - $2.83$ keV
  - $\tau_{1/2} = 4570$ yrs

- $^{187}$Re
  - $2.5$ keV
  - $\tau_{1/2} = 4.5$ Gyrs

- $^{115}$In
  - $155$ eV
  - $\tau_{1/2} = 4.1 \times 10^{20}$ yrs
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<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Number</th>
<th>Energy (keV)</th>
<th>Half-Life</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td>3</td>
<td>18.5</td>
<td>12.3 yrs</td>
<td>Electromagnetic/ Frequency</td>
</tr>
<tr>
<td>$^{163}$Ho</td>
<td>163</td>
<td>2.83</td>
<td>4570 yrs</td>
<td>Calorimetric</td>
</tr>
<tr>
<td>$^{187}$Re</td>
<td>187</td>
<td>2.5</td>
<td>4.5 Gyr</td>
<td>MARE (ended)</td>
</tr>
<tr>
<td>$^{115}$In</td>
<td>115</td>
<td>155</td>
<td>$4.1 \times 10^{20}$ yrs</td>
<td>No experiment yet</td>
</tr>
</tbody>
</table>
Electron transfers all of its energy to the absorbing medium.

**Calorimetric**  
(Cryogenic Bolometers)

Electromagnetic filtering of electrons of selected energy.

**Electromagnetic Collimation**  
(MAC-E Filter)

Use photon emission from magnetic field interaction to infer beta energy.

**Frequency-Based**  
(Cyclotron Resonance Emission Spectroscopy)
Electromagnetic filtering of electrons of selected energy.

**Electromagnetic Collimation**
(MAC-E Filter)
KATRIN’s 1st Measurement!

Integrated Spectrum

- KATRIN data with 1 σ error bars × 50
- Fit result

- Residuals (σ)
- Time (h)

- Count rate (cps)
- Retarding energy - 18574 (eV)
Squashed neutrino mass values obtained from tritium $\beta$-decay in the period 1990-2019

\[ m^2(\nu_e)c^4 < 1.1 \text{ eV}^2 (90\% \text{ C.L.}) \]

Factor of 2 improvement in 30 days!
Use photon spontaneous emission from electron in magnetic field.

Frequency-Based
(Cyclotron Resonance Emission Spectroscopy)
Cyclotron Resonance Emission Spectroscopy (CRES)

Frequency Approach

\[ ^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \bar{\nu}_e \]

Use frequency measurement of cyclotron radiation from single electrons:

- Source transparent to microwave radiation
- No e- transport from source to detector
- Leverages precision inherent in frequency techniques

B. Monreal and JAF, Phys. Rev D80:051301
Cyclotron Resonance Emission Spectroscopy (CRES)

\[ f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\text{kin}}} \]

\[ f_{c,0} = 27.992 \, 491 \, 10(6) \, \text{GHz} \, \text{T}^{-1} \]

- Narrow band region of interest (@26 GHz).
- Small, but detectable power emitted.

\[ P (17.8 \, \text{keV}, 90^\circ, 1 \, \text{T}) = 1 \, \text{fW} \]
\[ P (30.2 \, \text{keV}, 90^\circ, 1 \, \text{T}) = 1.7 \, \text{fW} \]

B. Monreal and JAF, Phys. Rev D80:051301
A “typical” event

(actually, this was our first event)
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Phase I:

Demonstrate CRES technique on $^{83m}$Kr mono-energetic electrons.

Status: Complete! Technique demonstrated.
Phase II:

First $T_2$ spectrum. Extract endpoint. Study systematics and backgrounds.

Status: Ongoing until beginning of 2020.
The Phase II Tritium Insert

Goal: Provide a first demonstration of CRES technique using tritium.
Insert Cryostat

Kr/T Gas Handling

NMR Magnet
New $T_2$ Gas Handling System

- $T_2$ stored in a SAES St172 getter sample
- Continuous pumping of background gasses
- Simple pressure regulation
- Recaptures tritium at room temperature

After $^3$He cleanup and initial getter loading

- AMU 6: $T_2$
- AMU 4: HT
- AMU 2: $H_2$
We usually operate in one of two possible configurations:
(a) **deep trap** for high statistics; (b) **shallow trap** for high precision.

Best demonstrated instrumental width: **$2.0 \pm 0.5$ eV**

($2.8$ eV natural line width)
Reconstruction of events extends as short as 120 μs.

Predicted background from mis-reconstructed noise:
less than 1 event in planned Phase II 100-day $T_2$ data campaign
Reconstruction of events extends as short as 120 \( \mu \)s.

Predicted background from mis-reconstructed noise: less than 1 event in planned Phase II 100-day \( T_2 \) data campaign.
Use a field-shifting solenoid to sweep the 17.8 keV $^{83m}$Kr conversion line across the frequency region of interest for tritium data to determine SNR vs. frequency.

Use detailed Monte Carlo to simulate and study CRES event topologies.

Result is an understanding of the frequency/energy dependence of the efficiency.

First tritium CRES spectrum
First tritium CRES spectrum

First tritium from Phase 2:

• Data from 2018 preliminary 7-day T₂ campaign shown, with endpoint fit using preliminary detection efficiency data and analysis framework.

• Since then, improved systematics data has been taken and better analysis developed for efficiency corrections.

• Higher-statistics T₂ run started.
Phase III:
(a) RF Demonstrator (200 cm$^3$ volume, eV mass sensitivity)
(b) Atomic T Demonstrator (trap atomic tritium at high densities)

Phase IV:
Atomic tritium source. Inverted ordering reach (40 meV)
Phase III:
(a) RF Demonstrator (200 cm$^3$ volume, eV mass sensitivity)
(b) Atomic T Demonstrator (trap atomic tritium at high densities)
Phase III

Wish to transition from small circular waveguide cell to large volume system.

Major new obstacles:
- Maintaining signal to noise across larger volume
- Field homogeneity for energy reconstruction

Remedies:
- Switch from single waveguide to patch array system
- Radial reconstruction

Goal: Expand technique to large volumes
Full design campaign underway to characterize signal-to-noise and localization expected from new phased antenna array.
New Antenna Arrays

Conceptual design of RF array design options

Waveguide Slot Array

Patch Antenna Array

Full design campaign underway to characterize signal-to-noise and localization expected from new phased antenna array.
Need 1 T magnetic field. 10-20 cm long (200 cm$^3$) magnetic “bathtub” trap.

Large bore MRI magnet installed and running
Phase III:

(a) RF Demonstrator (200 cm³ volume, eV mass sensitivity)
(b) Atomic T Demonstrator (trap atomic tritium at high densities)
Need to overcome molecular final states to reach "inverted" scale.
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Atomic tritium provides a narrower profile, allowing one to access inverted scale.
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Atomic tritium provides a narrower profile, allowing one to access inverted scale.

Challenges?
- How to create?
- How to trap?
- How to keep purity?
Use H, D and T have unpaired electrons (non-zero $\mu$)

Atom tend to (anti-)align with B-field if change is adiabatic

Potential energy...

$$\Delta E = -\vec{\mu} \cdot \vec{B}$$

(ATOMS FLOW follow field mimimim)

**Solution:** A large volume magnetic trap for T atoms
Simultaneous efforts to create large flow of tritium atoms, typically at about 100 times higher than commercial crackers (at high temperatures)

Using combination of custom and commercial crackers under development.
Need to reach sub-kelvin temperatures to trap atomic tritium (from very high cracking temperatures).

R&D for velocity/state selector.
Phase IV: 
Atomic tritium source. Inverted ordering reach (40 meV)
Ultimate atomic tritium experiment combines R&D from Phase III into large RF array tritium trap.

Atomic source, transport, and trap combined for large \((m^3)\) instrumented volume.

Target Mass Sensitivity

\[ m_\beta < 40 \text{ meV} \]
CRES can now be added as a *demonstrated* technique for studying beta decay.

*Phase II* continuing to take data this year (and some on the next).

*CRES* continues to expand, with the eventual target of using an *atomic* tritium source.
...and thanks for your attention!