Project 8: a radiofrequency approach to the neutrino mass

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Neutrino mass

Oscillation experiments measure $\Delta(m^2)$

- **normal hierarchy**: $m_3$
- **inverted hierarchy**: $m_2$ and $m_1$
- **degenerate hierarchy**: $m_3$

Kinematics say $< 2$ eV
Cosmology says (?) $< 0.3$ eV

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

Current limit 2.0 eV, BR < $10^{-10}$
KATRIN goal 0.2 eV, BR < $10^{-12}$
$\Delta m_{23} \sim 0.05$ eV, BR < $10^{-14}$

$Q = M_T - M_{^3\text{He}} - M_e$

Most $E_e$ at $\sim 3$ keV
Cyclotron radiation

- Accelerating charge = EM radiation
- Coherent, narrowband
- High power per electron

\[ P_{\text{tot}} = \frac{1}{4\pi\varepsilon_0} \frac{2q^2\omega_c}{3c} \frac{\beta_1^2}{1 - \beta^2} \]

- Electron energy contributes to velocity \( v \), power \( P \), frequency \( \omega \)
  - Can we detect this radiation, measure \( v, P, \omega \), and determine \( E \pm 1 \text{ eV} \)?
100,000 tritium decays in 30µs
Frequency precision

- Schawlow: “Never measure anything but frequency”
- $f \cdot \Delta E/E \sim \Delta f = 1/\Delta t$
- 1 eV energy resolution
  - $\Delta f / f = 2 \times 10^{-6}$ (easy!)
  - $\Delta t = 20\mu s$ (hard!)
    - $\beta c \cdot \Delta t = 1400$ meters
- Thermal noise:
  - $P_K(T) = k_B T \Delta f$
- Redshift/blueshift!
Low-energy electrons cannot be both redshifted and narrow-frequency: no “fakes”
UW prototype

S.S. Cr. tubes connected to physics can for support

Magnetic bottle stores electron

1x3cm preamp on top

1cm^2 pin diode on bottom

32.5°

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\( ^{83}\text{Rb} \rightarrow ^{83m}\text{Kr} \)  
(t\( _{1/2} \)=86 d, BR=100%)  
\( ^{83m}\text{Kr} \rightarrow ^{83}\text{Kr} + 17.8 \text{ keV e}^- + 14.3 \text{ keV } \gamma \)  
(t\( _{1/2} \)=1.8 h, BR=25%)  

Simulations: single-electron cyclotron radiation will be above thermal noise

\[ \begin{array}{c}
\text{Energy [fJ]} \\
\text{24} \\
\text{22} \\
\text{20} \\
\text{18} \\
\text{16} \\
\text{14} \\
\text{12} \\
\text{10} \\
\text{8} \\
\text{6} \\
\text{4} \\
\text{2} \\
\end{array} \]

\[ \begin{array}{c}
\text{Freq [Hz]} \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\times 10^9 \\
\end{array} \]

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Ben Monreal PANIC II

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preamp

balun

parallel plates
Complexities

I. Electron energy not constant

Current detector simulation

0.5 ms trapped electron

(Frequency after mixing)
Complexities

1. Electron energy not constant
2. B-field may not be uniform

Current detector simulation
Complexities

1. Electron energy not constant
2. B-field may not be uniform
3. Oscillations, Doppler shifts = frequency sidebands

*Magnet construction, DAQ, bandwidth, and SNR are all entangled*

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- **Bad**: most e⁻ escape in < 1µs (long)
- **Bad**: no power at \( f = f_0 \); just red/blueshift
  - (redshift at waveguide group velocity)
  - need high-bandwidth data analysis
- **Good**: data analysis is JUST fourier trans

Long solenoid/waveguide

- **Bad**: most e⁻ escape in < 1µs (long)
- **Good**: simplest possible spectrum (peak at \( f_0 \))
- **Good**: only need \( \sim \)1 MHz DAQ
- **Bad**: 30GHz is tough cavity size

Long solenoid/cavities

- **Good**: keeps e⁻ in view of simple antenna for a long time
- **Bad**: center frequency depends on pitch angle, radial position
- **Maybe**: all of the unknowns are encoded in the rich sideband structure (?)
Resonant cavity

Longish, uniform field

Is there a long-lived signal to trigger on? YES

Can we determine the cyclotron frequency precisely? YES

Reanalysis can subtract “phase shift” = narrow peak at $f_0$
Conclusions

- Project 8 is the first realistic prospect for a post-KATRIN neutrino mass experiment
- Coming soon: 1st single-electron detection with $^{83m}$Kr source
  - Quick low-res $T_2$ experiment?
- Come up with “scalable design” and build tabletop version (≈few-eV $m_\nu$ sensitivity)
  - We welcome magnet and RF engineering advice
- Proposal for large experiment