Towards a Neutrino Mass Measurement: the Project 8 Experiment

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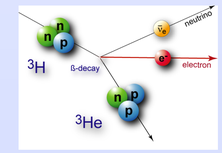
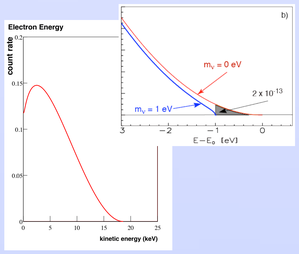
I. Introduction

Beta Decay Experiments

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_e$$

- Tritium beta decay experiments provide a direct measurement of the neutrino mass.
  - Independent of the Dirac / Majorana nature of neutrinos and of cosmological models
- Method: Measure the shape for the beta spectrum near the endpoint.





$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\nu_j}^2} \qquad m_\nu = \sqrt{\Sigma_i |U_{ei}|^2 m_i^2}$$

Can we push further?

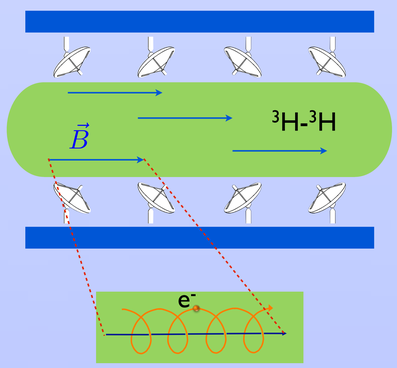
- KATRIN can see or place a limit on the mass at 200 meV (90% CL).
- Any future experiment needs to be able to (a) have a better scaling law for increasing the source mass and (b) improve its energy resolution.
- We propose a new approach: use a measurement of the electron cyclotron radiation as a means to measure the electron energy in a non-destructive way.

II. Radio Frequency (RF) Measurement

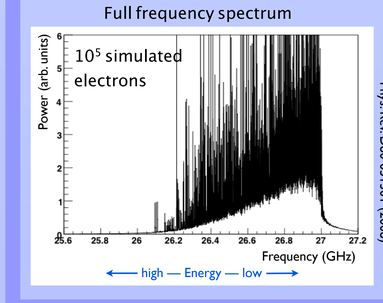
The Concept

- Enclosed volume of ^{3}H . . .
- In a uniform magnetic field . . .
- Decay electrons spiral around the magnetic field lines
- Cyclotron radiation is detected by sensitive microwave antennas

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

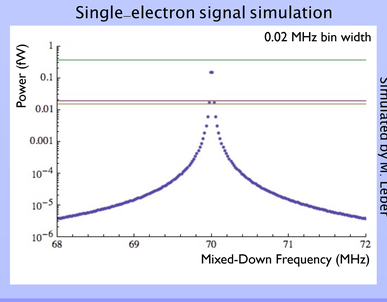


Full frequency spectrum



From B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2008)

Single-electron signal simulation



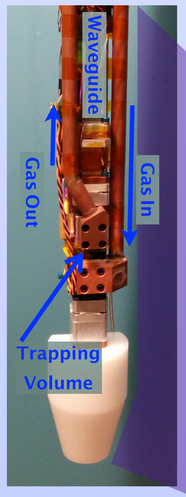
Simulated by M. Leber

III. Prototype

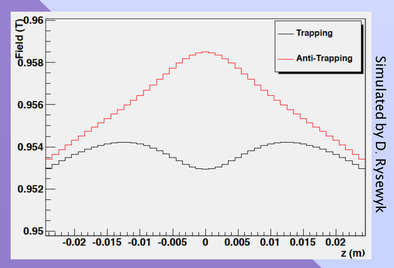
Superconducting Solenoid Magnet

- Previously used as an NMR magnet at UC Santa Barbara
- Single main coil, with multiple trim coils to make the field more uniform
- Magnet bore:
  - Diameter = 5.2 cm
  - Length = 75 cm
    The uniform field region is ≈6 cm long
- Field measured with a hall probe, NMR probe, and electron-spin resonance

Electron-Trap Insert



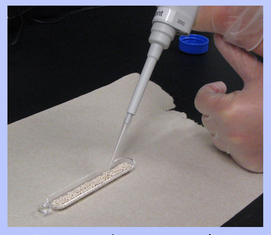
- Cavity made from WR-42 aluminum waveguide stock
- Trapping volume centered in the solenoid
- Small trapping magnet creates a ≈0.01 T dip in the field



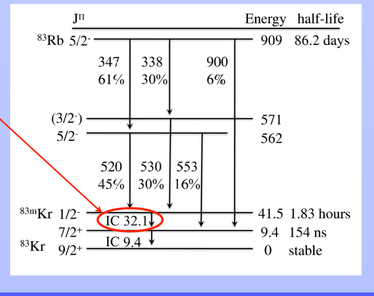
- Cryogenic low-noise amplifiers
- 3 / 8" gas lines deliver ^{83m}Kr to the gas cell
- Source gas contained with Kapton windows

^{83m}Kr Source

- ^{83}Rb made by proton irradiation of RbCl
- Rb isotopes transferred to zeolite beads according to method used by Venos, et al., Appl. Radiat. Isot. 63 (2005)
- Source strength is (2.00 ± 0.02) mCi as of May 2, 2014
- Internal conversions yield 30.4 and 17.8 keV electron lines

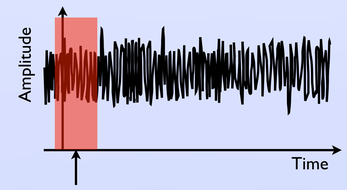


Pipetting the source solution onto zeolite beads

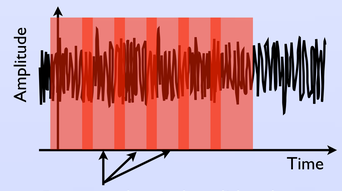


V. Analysis

Short-Time Fourier Transform



Fourier transform the windowed area

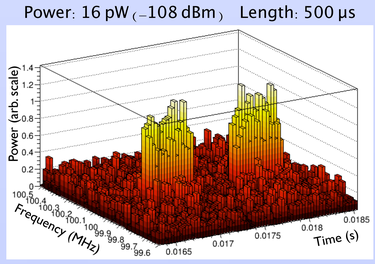


Repeat as the window slides along

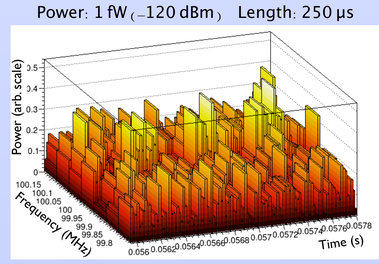
Finding Electron Candidates

- Search for candidates in frequency-vs-time space
- Identify clusters of high-power bins
- Expected signal power is 1 fW (-120 dBm)

Injected Signals
Power: 16 pW (-108 dBm) Length: 500 µs

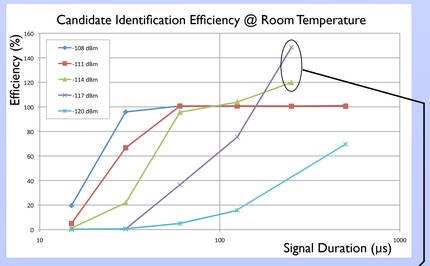


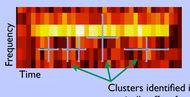
Injected Signals
Power: 1 fW (-120 dBm) Length: 250 µs



Continuous Data

- Continuously digitize at ~200 MHz
- Record all data
- Analyze offline
- Can vary analysis parameters
- Analysis shown here:
  - Time window: 32.8 us
  - Overlap: 50%
  - Threshold: SNR > 6.5
- Background rate: 3.8 / s / MHz



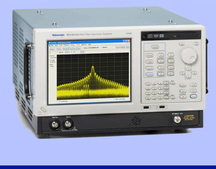


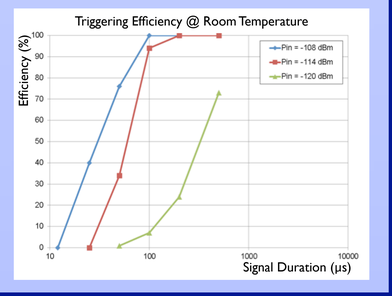
If multiple clusters are identified for a single signal pulse, efficiencies can end up greater than 100%. This does not happen for most of the calibration runs.

Clusters identified in the analysis, vertically offset for clarity

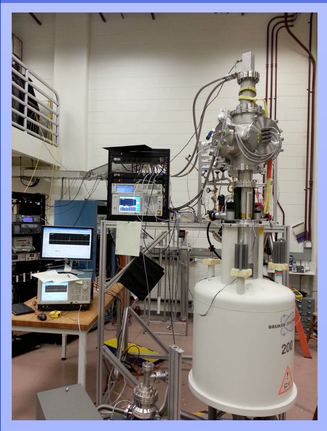
Triggered Data

- Tektronix Realtime Spectrum Analyzer performs FFT calculations in real time
- Frequency mask trigger acquires time-domain data records for signals that exceed the threshold
- Background rate: 0 / s / MHz

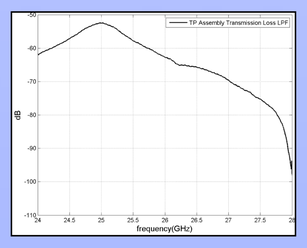




IV. Receiver Characterization

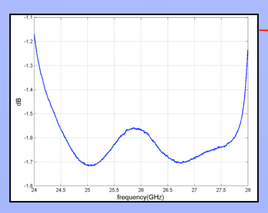


Tickler Port Transmission Loss

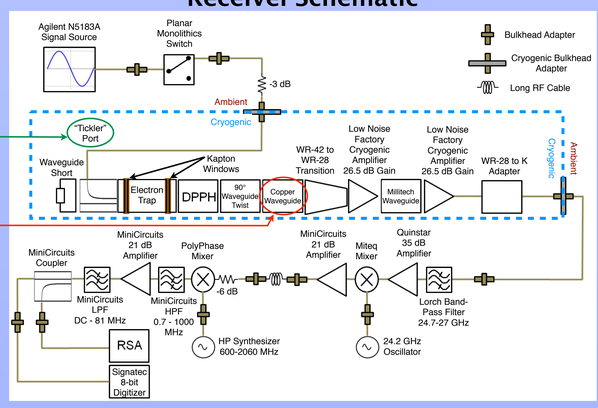


- Calibrate input power such that 1 fW (-120 dBm) reaches the trapping volume
- Performed with a Vector Network Analyzer

Passive Loss: Copper Waveguide



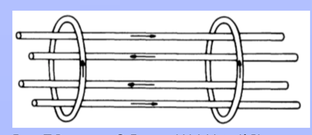
Receiver Schematic



VI. Future Directions

Atomic Tritium Source

- Solenoidal uniform field for electron cyclotron motion
- Pinch coils to reflect electrons
- Ioffe conductors to reflect radially moving atoms



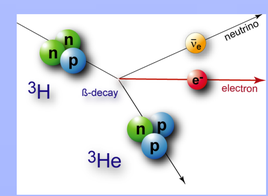
From T. Bergeman, G. Erez, and H. J. Metcalf, Phys. Rev. A **35** 1535 (1987)

Larger Volumes

- Better statistics in the tail of the tritium spectrum
- Must ensure magnetic field uniformity @ 10^{-5} over the active volume

Tritium Measurement

- First attempt will aim for a few-eV mass limit



Project 8 is supported by: