A Resonant Cavity-Based CRES Demonstrator on the Path to a More Precise Neutrino Mass Measurement with Project 8

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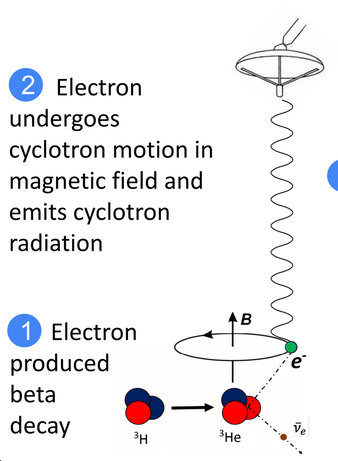
Project 8: measuring neutrino mass by observing tritium β⁻ decay with Cyclotron Radiation Emission Spectroscopy (CRES)

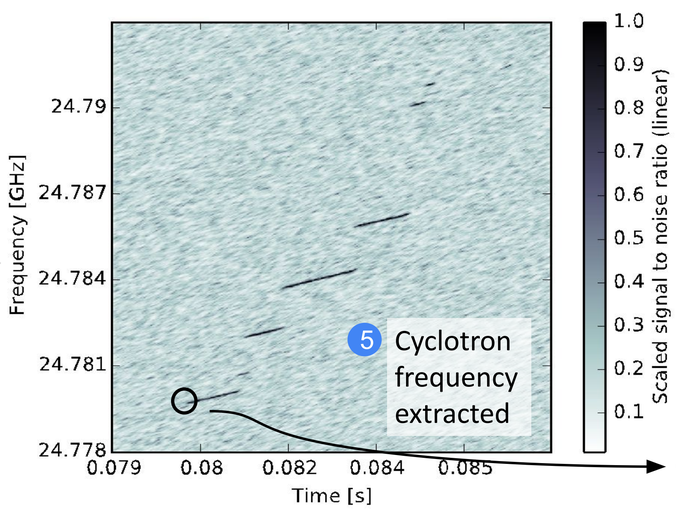
1 Electron produced beta decay

2 Electron undergoes cyclotron motion in magnetic field and emits cyclotron radiation

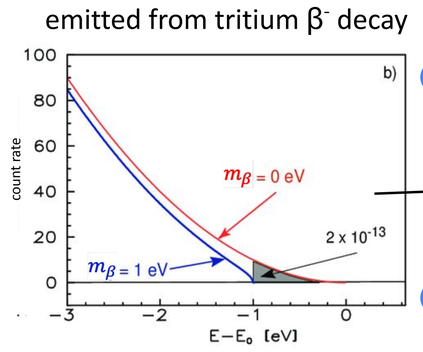
3 Cyclotron radiation (1 fW) collected, digitized

4 Fourier-transform



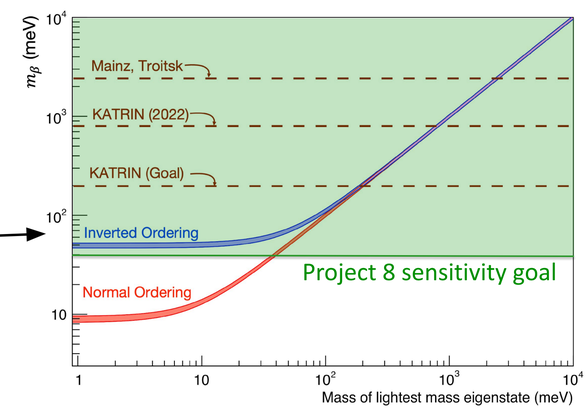


Energy spectrum of electrons emitted from tritium β⁻ decay



7 Repeated for many decays

8 Neutrino mass info extracted from spectrum

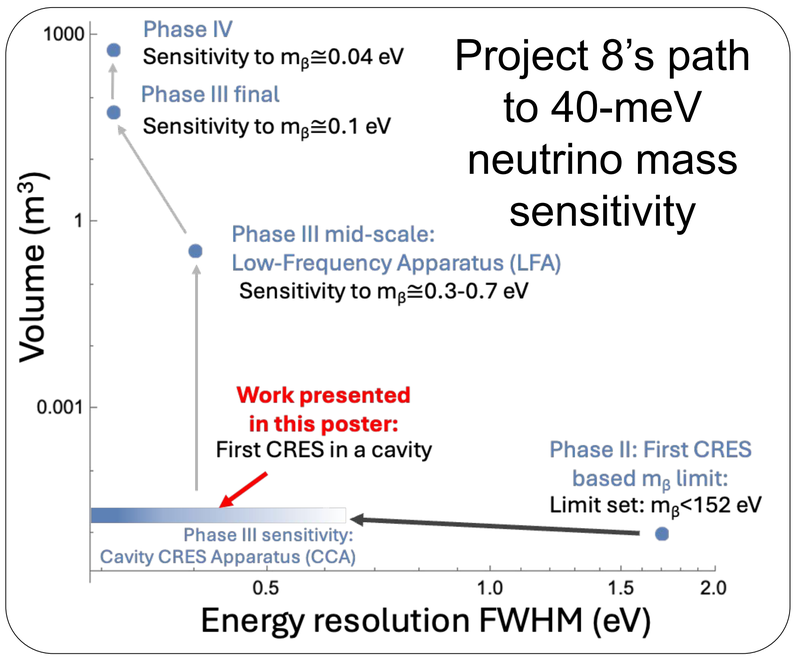


6 Electron kinetic energy assessed

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

Goal: sensitivity to 40 meV, measuring the mass or excluding the inverted ordering. Simultaneous sensitivity to active and sterile neutrinos.

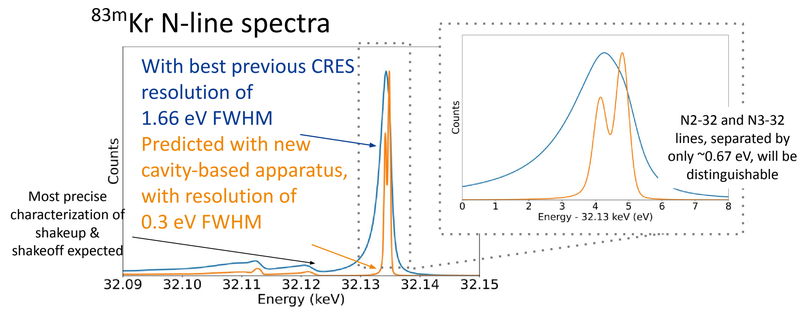
Project 8's path to 40-meV neutrino mass sensitivity



New cavity-based apparatus will demonstrate many technologies needed to reach 40 meV

- Cavity-based geometry is compatible with orders-of-magnitude **increased detector volume**.
- Improved signal-to-noise ratio from cavity-enhanced cyclotron emission will enable **higher detection efficiency**.
- A <0.3-eV-wide electron gun calibration source will enable **improved detector response characterization** and **absolute magnetic field calibration**.
- Well-understood signal morphology **embeds magnetic field calibration information in the CRES data**.

Science with this detector

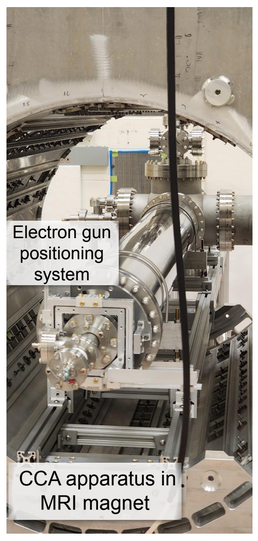


- K-, L-, M-, N- conversion electrons from ^{83m}Kr will be probed with highest resolution yet.
- Combined with absolute magnetic field measurements from electron gun and other magnetometry, this will enable an important systematic check for KATRIN's neutrino mass measurement

Two calibration techniques to reach the sensitivity goal: electron gun and precision magnetometry

Electron gun: a controlled source of **monoenergetic electrons** for calibration.

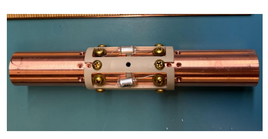
- Capable of **creating electrons with continuously variable energy** → move electrons into cyclotron resonance. **This is not possible with any other calibration method.**
- Capable of **injecting electrons in different radii to get a full magnetic field map**.
- Additionally enables tests of: **(1) magnetic field uniformity; (2) frequency response and reconstruction pipeline; (3) energy-frequency conversion accuracy.**
- An **electron source in which the beam is guided primarily by magnetic fields rather than electrostatic optics** is a distinctive feature of the Project 8 electron gun effort.



Magnetometry: ultra-precise Nuclear Magnetic Resonance (NMR)

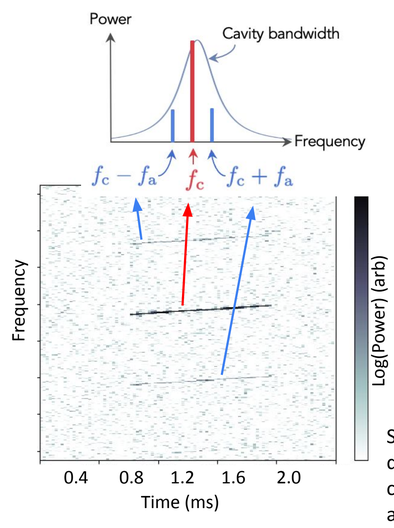
- 0.1 ppm **NMR magnetometry in-situ in the cryogenic CRES volume**
- "Birdcage" cavity design: we **place windows/cuts in a way the cavity becomes a resonator for both the RF NMR mode and the microwave CRES TE_{011} mode.**
- We will use **Metastability Exchange Optical Pumping (MEOP)** to polarize spins to get a strong enough NMR signal.

Half of the birdcage cavity with visible cuts

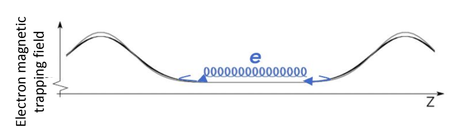


Two halves connected to make a full cavity

Precise electron-by-electron energy reconstruction

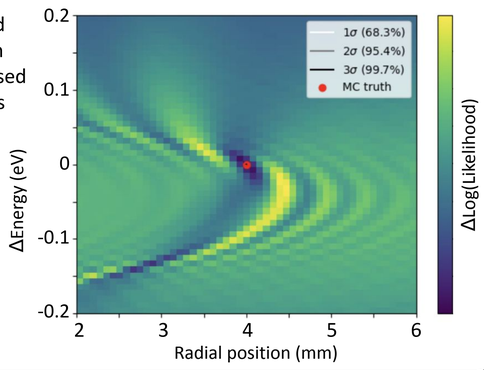


- Matched filtering and deep learning algorithms under development can extract this information to reconstruct electron energy



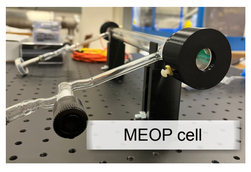
- Electrons that explore different regions of the magnetic trap experience slightly different average magnetic fields
- Electron trajectory information is encoded in spacing and power in RF sidebands of CRES signal

Simulated data from cavity-based apparatus

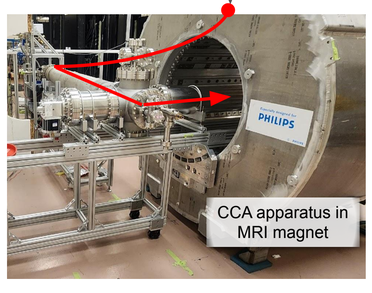


Future CCA Magnetometry Flow Chart

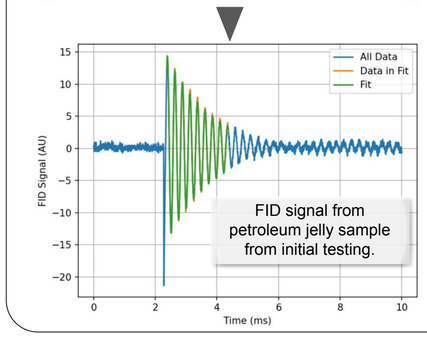
He3 is transferred from storage to MEOP cell where it gets polarized with a laser



Nuclear spin polarized He-3 is transferred to the birdcage cavity.

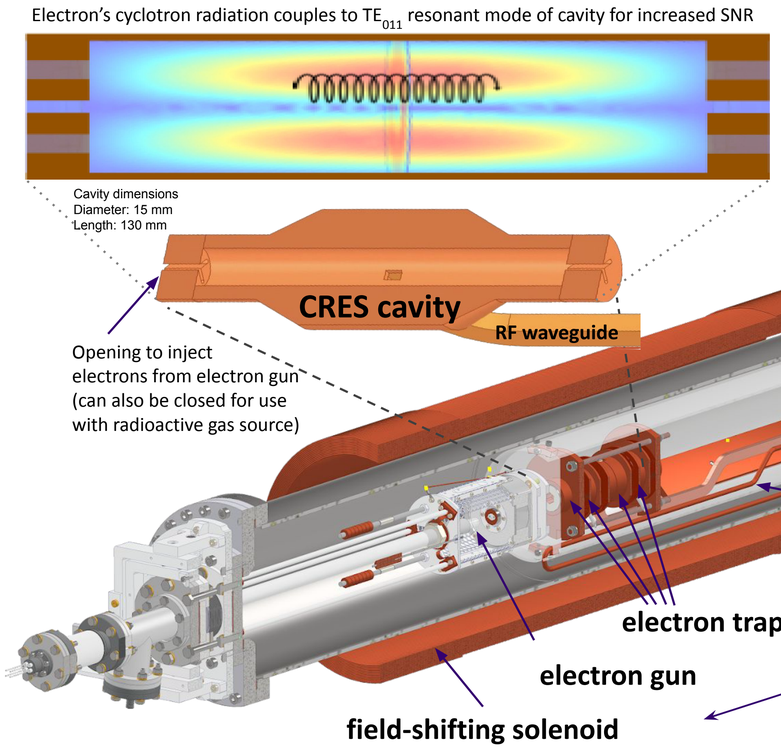


An RF pulse is sent to the birdcage cavity. The RF pulse tips the spins, which precess to produce the NMR signal.



We infer the background magnetic field strength and homogeneity.

Electron's cyclotron radiation couples to TE_{011} resonant mode of cavity for increased SNR



New apparatus is located at the University of Washington, Seattle, within a repurposed medical MRI magnet. Construction is ongoing, with running planned for late 2026.

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