Cyclotron Radiation Emission Spectroscopy for measuring neutrino mass and searching for chirality-flipping interactions

Elise Novitski
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An extremely brief introduction to neutrino mass

- Neutrinos have mass
- The origins of neutrino mass are not yet understood
- The neutrinos’ absolute mass scale and ordering are unknown
- Precision beta decay and electron capture experiments can make direct mass measurements
Neutrino mass from tritium $\beta^-$ spectroscopy

Tritium $\beta^-$ spectroscopy is the leading technique for direct neutrino mass measurements.
State of the art: KATRIN

- New result! Upper limit of $1.1 \text{ eV/}c^2$ (90% CL) (arXiv: 1909.06048, M. Aker et. al.)
- KATRIN is designed to achieve an ultimate sensitivity of $\sim 200 \text{ meV/}c^2$.
- If neutrino mass is smaller, how can we surpass 200 meV limit?
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- Statistical and systematic barriers to greater sensitivity with KATRIN’s MAC-E filter method include:
  - Integral spectrometer
  - Resolution area; difficult to scale up more
  - Interactions during electron transport
  - The irreducible final state distribution in ³HeT + final state after decay of molecular tritium complicates the extraction of neutrino mass from the spectrum
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Cyclotron Radiation Emission Spectroscopy (CRES)
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1 fW @ 25 GHz
Cyclotron Radiation Emission Spectroscopy (CRES)

Fourier-transform

1 fW @ 25 GHz

Project 8 - Event 0

Frequency [GHz]

Time [s]

Scaled signal to noise ratio (linear)
Cyclotron Radiation Emission Spectroscopy (CRES)

\[ f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}/c^2} \]
Cyclotron Radiation Emission Spectroscopy (CRES)

1 fW @ 25 GHz

Project 8 - Event 0

$\frac{f_c}{f_{c,0}} = \frac{1}{2\pi m_e + E_{kin}/c^2}$
Cyclotron Radiation Emission Spectroscopy (CRES)

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

\[ m_\nu = \sqrt{\sum_i |U_{ei}|^2 m_i^2} \]
Cyclotron Radiation Emission Spectroscopy (CRES)

Advantages of CRES

• Frequency measurement ➔ high precision

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

1 fW @ 25 GHz

"m_e = 0 eV"

"m_e = 0.2 eV"
Cyclotron Radiation Emission Spectroscopy (CRES)

Advantages of CRES
- Frequency measurement ➔ high precision
- Differential spectrometer ➔ increased statistical efficiency

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

\[ m_v = \sqrt{\sum_i |U_{ei}|^2 m_i^2} \]
Cyclotron Radiation Emission Spectroscopy (CRES)

Advantages of CRES

• Frequency measurement ➔ high precision
• Differential spectrometer ➔ increased statistical efficiency
• Source is transparent to microwave radiation ➔ no electron transport ➔ volume scaling

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

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Project 8 - Event 0

1 fW @ 25 GHz
Cyclotron Radiation Emission Spectroscopy (CRES)

Advantages of CRES
• Frequency measurement  ➔ high precision
• Differential spectrometer  ➔ increased statistical efficiency
• Source is transparent to microwave radiation  ➔ no electron transport  ➔ volume scaling
• Compatible with atomic tritium  ➔ avoids final-state spectral broadening of $T_2$

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi m_e} \frac{eB}{E_{\text{kin}}/c^2}$$
Pushing direct neutrino mass limits with Project 8

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

1 fW @ 25 GHz

Mainz & Troitsk limits (95% CL)

KATRIN 2019 (90% CL)

nu-fit v3.1

KATRIN design sensitivity (90% CL)

Project 8 design sensitivity (90% CL)

Cosmology disfavored

Planck limit
Project 8: a phased approach to neutrino mass

Science Goals

- $m_\nu < 40 \text{ meV/c}^2$
- Mass hierarchy

Phase I
- CRES Demonstration
  - PRL 114:162501, 2015
- ~eV Resolution

Phase II

Phase III

Phase IV

Project 8, Phase I: first demonstration of CRES

R&D Milestone
- Single-electron detection
- Spectroscopy

Science Goals
$^{83m}$Kr conversion-electron spectrum

Phase I
- CRES Demonstration
  - PRL 114:162501, 2015
- ~eV Resolution

Phase II

Phase III

Phase IV

Project 8, Phase II: tritium, systematics

R&D Milestone

- $T_2$ spectrum
- Systematic studies

Science Goals
Tritium endpoint
Background assessment

Phase I

CRES Demonstration
PRL 114:162501, 2015

~eV Resolution

Phase II

Phase III

Phase IV

Phase II of Project 8

Cryocooler

Cryogenic Amplifiers

T_2/^{83}Kr Gas System

Waveguide

Superconducting Solenoid Magnet

Gas Cell and e^- Trapping Coils

5 mT

1 T

Image: Project 8, A. Lindman
Energy resolution demonstrated with $^{83}$mKr

- 18, 30, and 32 keV conversion peaks observed
- Natural linewidth of 18 keV line: $2.8 \pm 0.1$ eV (FWHM)
- Best demonstrated instrumental width, in a shallow trap (shown at right): $2.0 \pm 0.5$ eV (FWHM)
- Tail is primarily due to scattering, described well by an analytical model
- Deeper trap with lower resolution used for tritium data in Phase II to increase statistics, to compensate for small 1 mm$^3$ effective volume
Track and event reconstruction performance

- Reconstruction must distinguish tracks from noise, group tracks into events, extract event start frequencies
- Reconstruction performance evaluated with $^{83m}$Kr data and simulated data
- Efficient detection of electron tracks as short as 120 μs

- Predicted background from misreconstructed noise: <1 event in planned Phase II 100-day $T_2$ data campaign
Track and event reconstruction challenges

- Complex event morphologies arise due to
  - Doppler shifts
  - Interference effects
  - Electron motion through magnetic field inhomogeneities
- Understanding the phenomenology of these effects: Phys. Rev. C. 99, 2019
- RF configuration and choice of trap geometry reduce interference and give rise to simpler event structures in final Phase II data

Sidebands & disappearing tracks

Wide tracks
Understanding detection efficiency

- If detection efficiency were to vary with frequency, the tritium spectrum would be distorted.
- Uncorrected, this would interfere with accurate physics results (endpoint, neutrino mass).
- If variations are present, we must understand and correct for them!
Determining detection efficiency vs. frequency
Determining detection efficiency vs. frequency

Systematics data

Counts vs. Frequency

35 cm

event rate vs. frequency
Determining detection efficiency vs. frequency

\[ P = \frac{1}{6 \pi \epsilon_0} \frac{e^4}{m_e^2 c} B^2 (y^2 - 1) \sin^2 \theta \]

\[ y = 1 + \frac{K}{m_e c^2} \]

Systematics data

Event rate vs. frequency

not directly applicable to tritium data
Determining detection efficiency vs. frequency

Systematics data

Counts

Frequency

CRES event properties (e.g., SNR) vs. frequency

event rate vs. frequency
Determining detection efficiency vs. frequency

Systematics data

Counts

Frequency

35 cm

CRES event properties (e.g., SNR)

vs. frequency

Event rate vs. frequency

Simulations

Efficiency

Signal-to-noise ratio (SNR)

reconstruction efficiency vs. CRES event properties (e.g., SNR)
Determining detection efficiency vs. frequency

- Systematics data
- Simulations
- CRES event properties (e.g., SNR)
- Efficiency vs. frequency
- Event rate vs. frequency
- Reconstruction efficiency vs. CRES event properties (e.g., SNR)
- Combine to get
Determining detection efficiency vs. frequency

Systematics data

Counts

Frequency

35 cm

CRES event properties
(e.g., SNR)

vs. frequency

event rate vs. frequency

Simulations

Signal-to-noise ratio (SNR)

Efficiency

reconstruction efficiency

vs. CRES event properties (e.g., SNR)

combine to get

efficiency vs. frequency

compare as cross-check
Determining detection efficiency vs. frequency

<table>
<thead>
<tr>
<th>Counts</th>
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CRES event properties (e.g., SNR) vs. frequency

reconstruction efficiency vs. CRES event properties (e.g., SNR)

combine to get efficiency vs. frequency

compare as cross-check

10/24/19

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Determining detection efficiency vs. frequency

Systematics data

Counts vs. Frequency

35 cm

CRES event properties (e.g., SNR) vs. frequency

Efficiency vs. SNR

Simulations

reconstruction efficiency vs. CRES event properties (e.g., SNR)

combine to get

efficiency vs. frequency

compare as cross-check

Adapt efficiency vs. frequency for tritium data
(slightly different SNR vs. frequency from Kr data...)

event rate vs. frequency
Determining detection efficiency vs. frequency

Systematics data

Counts

Frequency

35 cm

Simulations

Efficiency

Signal-to-noise ratio (SNR)

reconstruction efficiency

vs. CRES event properties (e.g., SNR)

CRES event properties (e.g., SNR)

vs. frequency

event rate vs. frequency

Combine to get

efficiency vs. frequency

compare as cross-check

Adapt efficiency vs. frequency for tritium data

(slightly different SNR vs. frequency from Kr data...)

Correction to tritium spectrum!
First CRES tritium spectrum

- Data from 7-day $T_2$ campaign
- Endpoint fit uses preliminary detection efficiency data and analysis framework
- Since then, more extensive systematics data have been taken and analysis has developed, allowing for more precise corrections in upcoming campaign
- 100-day $T_2$ run planned to begin later this month
Phase III: Large-volume CRES demonstration

CRES Demonstration
PRL 114:162501, 2015

~eV Resolution

Phase I

Phase II

Phase III
RF Demonstration
Atomic T Demonstration

Phase IV

Phase III: Large-volume CRES demonstration

CRES Demonstration
PRL 114:162501, 2015

~eV Resolution

Phase I

Phase II

Phase III
RF Demonstration
Atomic T Demonstration

Phase IV

R&D Milestone
- 200 cm³ active volume
- Antenna array
- B-field homogeneity

Science Goals
mν < 2 eV/c²
Antenna array for large-volume CRES detector

- Cyclotron radiation detected by an array of patch or slot antennas
- Multichannel, high-volume (up to a few PB) datataking will require real-time digital beamforming and track reconstruction
- Spatial tracking of electrons will enable local magnetic field corrections and counteract effects of pileup at higher gas densities
- Patch array design informed by simulations of RF detector response to time-dependent CRES fields using Project 8 Locust software (arXiv:1907.11124, 2019) and HFSS
Phase III RF demonstrator

- MRI magnet at UW gives 1 ppm B homogeneity over 200 cm$^3$ volume
- An insert with gas cell, cryogenics, e$^-$ trapping coils, antenna array, and field-mapping tools is under development
Phase III: Atomic tritium demonstration

- **Phase I**
  - CRES Demonstration
  - PRL 114:162501, 2015

- **Phase II**
  - ~eV Resolution

- **Phase III**
  - RF Demonstration
  - Atomic T Demonstration

- **R&D Milestone**
  - Dissociator (cracker)
  - Accomodator
  - Velocity and state selector
  - Atomic Ioffe trap

- **Phase IV**

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Relative probability vs. Relative Extrapolated Endpoint (eV)

- Atomic T
- T2
Dissociator (cracker) development

• Need cracker that
  – produces T atoms from T\textsubscript{2} at ~100x the flux demonstrated by commercially available crackers for H\textsubscript{2}→ 2H
  – is compatible with tritium (cannot use RF discharge sources)
• We are exploring higher-flux ways of running commercial crackers, as well as custom crackers that increase atom flux
Cooling and choosing T atoms

1) Cracker
2) Accommodator
3) Nozzle
4) Velocity and state selector
5) Climb potential well into trap

Possible velocity and state selector designs under consideration:

Images: A. Lindman
Phase III atom trapping demonstrator

- Magnetically trapping neutral tritium atoms with a Ioffe trap: need a large volume, a high B field wall, and high field homogeneity ($\Delta B/B < 10^{-7}$)
- ~1 m$^3$ demonstrator planned to validate atom production, cooling, selection, and trapping methods
Phase IV: Putting it all together to reach target sensitivity

- Phase I
  - CRES Demonstration
  - PRL 114:162501, 2015

- Phase II
  - ~eV Resolution

- Phase III

- Phase IV
  - Science Goals
  - $m_\nu < 40$ meV/c²
  - Mass hierarchy

Timeline:
- 2015
- 2016
- 2017
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
Conceptual design of Phase IV for 40 meV/c²

A: Atomic tritium production
B: Transport and preparation
C: Trapping and measurement

A. Lindman
The Project 8 collaboration

Case Western Reserve University
- Laura Gladstone, Benjamin Monreal, Yu-Hao Sun

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Johannes Gutenberg-Universität Mainz
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- Thomas Thümmler

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Massachusetts Institute of Technology
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- Luiz de Viveiros, Timothy Wendler, Andrew Ziegler

University of Washington

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- Karsten Heeger, James Nikkel, Luis Saldaña, Penny Slocum, Pranava Teja Surukuchi, Arina Telles

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See Martin Fertl (Mainz) for postdoc and graduate student opportunities!
Searching for chirality-flipping interactions with CRES

- Search for tensor couplings not present in the Standard Model, which distort β-decay spectra.
- Goal: determine shape of $^6$He β- spectrum to measure “little $b$” Fierz interference term to better than $10^{-3}$.
- Requires extending the CRES technique to higher energy betas and to a precision determination of a continuum spectrum. Non-trivial: under development.
- Monte Carlo simulations predict 1 day of running would determine $b$ one order of magnitude better than any previous experiment.
- Measurements on $^{14}$O and $^{19}$Ne, with different $b$s, give handle on systematic effects.

$^6$He β spectrum, with regions planned to be covered in 18-24 GHz range by scanning B field.

Distortion due to new physics would go like $1/E$. 

\[ \text{dN/dE} \times 10^6 \]

K/m

\[
\begin{align*}
B = 1 \text{T} & \quad \text{Green} \\
B = 2 \text{T} & \quad \text{Blue} \\
B = 4 \text{T} & \quad \text{Red} \\
B = 6 \text{T} & \quad \text{Pink}
\end{align*}
\]
Searching for chirality-flipping interactions with CRES

- $^6$He experiment under construction at CENPA at the University of Washington
  $^1$University of Washington, $^2$Argonne National Lab, $^3$North Carolina State University, $^4$Pacific Northwest National Laboratory, $^5$Tulane University

- **Phase I:** proof of principle of CRES using $^6$He
- **Phase II:** first measurement ($b < 10^{-3}$)
- **Phase III:** ultimate measurement ($b < 10^{-4}$)
Takeaways

- Cyclotron Radiation Emission Spectroscopy (CRES) is a promising new frequency-based technique with applications in precision $\beta^-$ spectroscopy.
- Project 8 uses CRES for a direct neutrino mass measurement:
  - Phase II: Demonstration of high resolution, low background, understanding of systematic effects, and preliminary measurement of continuous $\beta^-$ spectrum from $T_2$ in a small-scale waveguide-based apparatus.
  - Phase III: Demonstration of free-space RF detection techniques for larger volumes, as well as production, cooling, selection, and trapping methods for atomic tritium.
  - Phase IV: Aiming for 40 meV/c$^2$ sensitivity direct neutrino mass measurement.
- CRES search for chirality-flipping interactions in higher-energy $^6$He $\beta^-$ decay promises to improve measurement of Fierz interference term “little $b$” to better than $10^{-3}$.