Project 8 and Neutrino Mass

A frequency based approach to measure the neutrino mass

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CERN October 2019
# Paths to the Neutrino Mass Scale

<table>
<thead>
<tr>
<th>Observable</th>
<th>Cosmology</th>
<th>Search for $0\nu\beta\beta$</th>
<th>$\beta$-decay &amp; electron capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present upper limit</td>
<td>$M_\nu = \sum_i m_i$</td>
<td>$m^2_{\beta\beta} = \left</td>
<td>\sum_i U^2_{ei} m_i \right</td>
</tr>
<tr>
<td>Potential: near-term (long-term)</td>
<td>~0.1 – 0.6 eV</td>
<td>~0.1 – 0.4 eV</td>
<td>2 eV</td>
</tr>
<tr>
<td></td>
<td>60 meV (15 meV)</td>
<td>50 – 200 meV (20 – 40 meV)</td>
<td>200 meV (40 – 100 meV)</td>
</tr>
<tr>
<td>Model dependence</td>
<td>Multi-parameter cosmological model</td>
<td>- Majorana nature of $\nu$, lepton number violation</td>
<td>Direct, only kinematics; no cancellations in incoherent sum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- BSM contributions other than $m(\nu)$?</td>
<td>- Nuclear matrix elements</td>
</tr>
</tbody>
</table>

Valerius
Neutrino Mass Constraints

Cosmology measures \( \sum m_i \)

Double beta decay measures \( \left| \sum u^2_{ei} m_i \right| \)

Direct searches measure \( \left( \sum |u^2_{ei}| m_i^2 \right)^{1/2} \)

\( m_\nu \) measurable both by laboratory experiments and cosmology

a critical test of consistency
Neutrino Mass Constraints

Cosmology measures \( \sum m_i \)
Double beta decay measures \( |\sum u^2_{ei} m_i| \)
Direct searches measure \( (\sum |u^2_{ei}| m_i^2)^{1/2} \)

\( m_\nu \) measurable both by laboratory experiments and cosmology
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Neutrino Mass Constraints

Cosmology measures \( \sum m_i \)

Double beta decay measures \( \left| \sum u_{ei}^2 m_i \right| \)

Direct searches measure \( \left( \sum |u_{ei}^2 m_i|^2 \right)^{1/2} \)

\( m_\nu \) measurable both by laboratory experiments and cosmology

a critical test of consistency

"consistency would be spectacular confirmation!"
Neutrino Mass Constraints

Cosmology measures \( \sum m_i \)

Double beta decay measures \( \left| \frac{\sum u^2 \nu m_i}{|m_i|} \right| \)

Direct searches measure \( \left( \sum |u^2 \nu m_i| \right)^{1/2} \)

\( m_\nu \) measurable both by laboratory experiments and cosmology
a critical test of consistency

“inconsistency would be major discovery”

Mezetto
Future of Cosmological Neutrino Bounds

Example Forecast:
EUCLID + Planck + Simon’s Observatory

A. Boylea, E. Komatsua, JCAP 2018

Mertens
Complementary Neutrino Mass Limits

-inverted mass ordering-

-normal mass ordering-

β/EC decay experiments

Karsten Heeger, Yale University

CERN, October 9, 2019

S. Boeser with input from www.nu-fit.org
Complementary Neutrino Mass Limits

β-decay/EC experiments

normal mass ordering

inverted mass ordering

approx. current reach

0νββ decay experiments

β/EC decay experiment limits correlate with the exposure scale required for a definite observation of 0νββ in IMO scenario.

Neutrinos and Beta Spectrum

first evidence of neutrino from continuous beta spectrum

Chadwick, 1914

\[ N \rightarrow N' + e^- \] some nuclei emit electrons!

Fig. 5. Energy distribution curve of the beta-rays.

Pauli, 1930

a hypothesis

Karsten Heeger, Yale University

E. Fermi, Zeitschrift fur Physik 1934
Neutrino Mass and Tritium Beta Decay Endpoint

Finite neutrino mass modifies the decay electron spectrum!

Idealized situation:
1. Super-allowed $\beta^-$-decay of isolated atom
2. Single neutrino mass state

With Coulomb distortion for $T_{\text{nuc}}$ and neutrino mixing:

$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2 \theta_C}{2\pi^3 \hbar^7} \left| M_{\text{nuc}} \right|^2 F_c(Z, E_e) p_e (E_e + m_e) \sum_i |U_{ei}|^2 (E_{\text{max}} - E_e)$$

$$\times \sqrt{(E_{\text{max}} - E_e)^2 - m_{\nu_i}^2} \cdot \Theta (E_{\text{max}} - E_e - m_{\nu_i})$$
State-of-the-art Technology for T2: MAC-E filter

**Magnetic Adiabatic Collimation with Electrostatic filter**

**Diagram:**
- Magnetic Adiabatic Collimation & Electrostatic Filter: adiabatic conversion $E_\perp \rightarrow E_\parallel$

**Integral measurement with retarding electric field:**
Only count decay electrons above threshold!

Karsten Heeger, Yale University

CERN, October 9, 2019
Neutrino Mass from Tritium Experiments

Tritium spectrometers have been workhorse of endpoint measurements for decades

Complicated molecular final states and incomplete de-excitation has yielded non-real mass values

More recent improved theory calculations can correct select previous results

L. Bodine et al. PRC 91 035505 (2015)
KATRIN Overview

Windowless Gaseous Tritium Source cryostat

Main Spectrometer

cryogenic
differential
cracking
pumping

RS
KATRIN  tritium scanning – fitting of spectrum

- fit of integrated experimental energy spectrum to theoretical model with 4 free parameters
  - leave parameters $A_s$ and $E_0$ unconstrained ‘shape-only’ fit
- merged data set
  - combine all 274 scans:
    - excellent stability of all fitted $\beta$-decay endpoints $E_0$ ($\sigma = 0.25$ eV)
    - “stacking” of events at mean HV set-point (excellent reproducability: RMS = 34 mV)

Drexlin, TAUP 2019
Integral tritium $\beta$-decay spectrum

- High-statistics $\beta$-spectrum
  - 2 million events in 90-eV-wide interval (522 h of scanning)
  - excellent goodness-of-fit
    $\chi^2 = 21.4$ for 23 d.o.f.
    (p-value = 0.56)

- bias-free analysis
  - blinding of FSD
  - full analysis chain first on MC data sets
  - final step: unblinded FSD for experimental data

- $\nu$-mass and $E_\theta$: best fit results

$$m^2(\nu_e) = \left(-1.0 \pm 0.9 \right) \text{eV}^2 \ (90\% \ CL)$$

Drexlin, TAUP 2019
Direct Neutrino Mass Searches

Tritium experiments define the mass limit. Where will we be in 2030?

Mainz (2005, final result)
\( m(\nu_e) < 2.3 \text{ eV} \) (95% CL)
C. Kraus et al., EPJ C40:447

Troitsk (2011, re-analysis)
\( m(\nu_e) < 2.05 \text{ eV} \) (95% CL)
V. N. Aseev et al., PRD 84:112003

Schloesser

Tritium experiments define the mass limit. Where will we be in 2030?
Challenges for Sensitivity Beyond KATRIN

Source intrinsic limitation:
Irreducible excitation of ro-vibrational initial and final states of $T_2$ molecule.

Technical challenges:
1. Statistical nature of $e^-$ scattering in gas column
2. $e^-$ can be scattered into angular acceptance cone of the MAC-E filter
3. Rydberg atoms as background source
Project 8: Cyclotron Radiation Emission Spectroscopy of T2

1. Start with an enclosed volume
2. Fill with tritium gas
3. Add a magnetic field
4. Decay electrons spiral around field lines
5. Add antennas to detect the cyclotron radiation

Project 8: Cyclotron Radiation Emission Spectroscopy of T2

- Cyclotron radiation from single electrons
- Source transparent to microwave radiation
- No e⁻ transport from source to detector
- Highly precise frequency measurement

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

\[ P(E_{\text{kin}}, m, \theta) = \frac{1}{4\pi\epsilon_0} \frac{2}{3} \frac{e^4}{m^4c^5} B^2 \left( E_{\text{kin}}^2 + 2 E_{\text{kin}} m e^2 \right) \sin^2 \theta \]

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

Small but readily detectable with state of the art detectors.
Project 8 in a waveguide with magnetic trap

Energy resolution vs. frequency resolution

\[
\frac{\Delta E_{\text{kin}}}{E_{\text{kin}}} = \left(1 + \frac{m_e c^2}{E_{\text{kin}}} \right) \frac{\Delta \nu_c}{\nu_c} \\
\approx 28 \text{ for } 18.6 \text{ keV electron}
\]

\[\Delta E_{\text{kin}} \approx 0.2 \text{ eV} \rightarrow \frac{\Delta \nu_c}{\nu_c} \approx 4 \times 10^{-7}\]

\[\nu_c \approx 27 \text{ GHz} \rightarrow \Delta \nu_c \approx 11 \text{ kHz}\]

Frequency resolution vs. observation time

\[\Delta \nu_c \times t_{\text{obs}} \geq \frac{1}{2\pi} \rightarrow t_{\text{obs}} \geq 14 \mu\text{s}\]

→ Need for a magnetic (no work) trap!
Project 8: Single Electron Detection

First Detection of Cyclotron Radiation from single keV electron

- Scattering off residual gas: energy loss & change of pitch angle
- $\Delta E = 14$ eV
- 1 fW synchrotron energy loss
- Onset $\Rightarrow$ initial $^{83m}$Kr electron $E_\perp$ (30 keV)

$^{83m}$Kr

17.8 keV

PRELIMINARY

Krypton line from tritium-ready system

18.0 keV
Project 8 - A Staged Approach

1 Phase – I: 2010-2016 – proof-of-principle test measurements with $^{83m}$Kr CRES observed for first time

2 Phase – II: 2015-2019 - tritium CRES demonstrator
  first tritium data 2018
  several days of runs
  fitted $\beta$-decay endpoint: $E_0 = (18.526 \pm 0.09)$ keV
  new 2019 campaign to begin soon (100 d)
The newly assembled instrument

Kr/T₂ gas handling system attached

Insert cryostat

NMR magnet providing background magnetic field

Picture: Alec Lindman
Project 8: A High Precision Measurement

17.8 keV $^{83m}$Kr peak

- Preliminary model includes intrinsic line width and Gaussian instrument resolution
- Line width: $2.8 \pm 0.1$ eV (FWHM)
- Instrumental width: $2.0 \pm 0.5$ eV (FWHM)
Project 8 Phase II: First Observation of Tritium Events

First T₂ Electron Event

T₂ energy spectrum

Preliminary
Project 8 - The Future

3 Phase – III: … – a large volume demonstrator based on multi-antenna array in MRI tritium spectrum for $m(\nu_e) \sim 2$ eV

4 Phase – IV: … – towards an atomic tritium source
R&D for an atomic tritium source (loffe trap)
goal: inverted mass hierarchy for $m(\nu_e)$
Project 8: Phase III

> Inwards-looking antenna array watches electrons radiating cyclotron power in free space
Project 8: Phase III

> Single electrons resolvable in simulation

see also:
A. Ashtari Esfahani et al.
arXiv:1907.11124
Atomic Tritium

> Sensitivity beyond inverted hierarchy requires atomic tritium

![Graph showing probability distribution of Atomic T and T2 molecules with annotations on rotation and vibration.]
Phase IV Concept

> Use magnetic moment of atomic species to guide and trap
  – Unpaired electron of atomic T (or H, D) gives it magnetic moment

A: Atomic tritium production
B: Transport and preparation
C: Trapping and measurement
Towards the Future - Next Discoveries

Planning for discovery experiments!
Towards the Future - Next Discoveries

“There are two possible outcomes: if the result confirms the hypothesis then you’ve made a measurement. If the result is contrary to the hypothesis then you’ve made a discovery”, Enrico Fermi.

Planning for discovery experiments!
Summary

We have demonstrated Cyclotron Radiation Emission Spectroscopy as a novel technique with a promising future in a next-generation neutrino mass experiment

**Phase I** achieved few-eV resolution of $^{83m}$Kr spectrum
  • Approaching natural linewidth of $^{83m}$Kr source

– **Phase II tritium** data taking ongoing
  • Challenges of continuous spectrum measurement being met

**R&D underway** towards scaling CRES technique, atomic tritium for next generation endpoint measurement
Project 8 Collaboration

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

Harvard-Smithsonian Center for Astrophysics
- Sheperd Doeleman, Jonathan Weintraub, André Young

Johannes Gutenberg-Universität Mainz
- Sebastian Böser, Christine Claessens, Martin Fertl, Michael Gödel, Alec Lindman

Karlsruher Institut für Technologie
- Thomas Thümmler

Lawrence Livermore National Laboratory
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Massachusetts Institute of Technology
- Zachary Bogorad, Nicholas Buzinsky, Joseph Formaggio, Evan Zayas

Pacific Northwest National Laboratory
- Mathieu Guigue, Mark Jones, Benjamin LaRoque, Erin Morrison, Noah Oblath, Malachi Schram, Jonathan Tedeschi, Brent VanDevender, Mathew Thomas, Mauro Grando

Pennsylvania State University
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University of Washington

Yale University
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This work was supported by the US DOE Office of Nuclear Physics, the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all collaborating institutions.

P8 slides on behalf of collaboration