Progress towards a direct measurement of neutrino mass

BNO-50
Physics of Fundamental Interactions, Baksan
June, 2017

Hamish Robertson,
CENPA, University of Washington
Neutrinos DO have mass, and the average for the 3 must lie between 2 and 0.02 eV.

The **KATRIN** experiment.

A new idea: **CRES** (Cyclotron Radiation Emission Spectroscopy): *Project 8*.

but... nothing on sterile neutrinos, double beta decay, $^{163}$Ho, cosmology.
NEUTRINO MASSES AND FLAVOR CONTENT

“Normal”

\[ \Delta m_{23}^2 \]

Atmospheric

\[ 2 \times 10^{-3} \text{ eV}^2 \]

Solar

\[ \Delta m_{12}^2 \]

\[ 8 \times 10^{-5} \text{ eV}^2 \]

“Inverted”

E

mu

tau

\[ v_3 \]

\[ v_2 \]

\[ v_1 \]

3
PRESENT LABORATORY LIMIT FROM 2 TRITIUM EXPERIMENTS:

\[ m_\nu < 2 \text{ eV} \]

**Troitsk experiment**
- windowless gaseous tritium source

- 2011 re-analysis of selected data from 1994-2004: no evidence for Troitsk anomaly
  \[ m^2(\nu_e) = (-0.67 \pm 1.89 \pm 1.68) \text{ eV}^2 \]
  \[ m(\nu_e) < 2.05 \text{ eV} \]

**Mainz experiment**
- quench condensed tritium source

- 2004 final analysis of Mainz phase II data from 1998-2001: analysis of last 70 eV
  \[ m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1) \text{ eV}^2 \]
  \[ m(\nu_e) < 2.3 \text{ eV} \]
KATRIN: (KArlsruhe TRItium Neutrino experiment)

- October 2016 - **First light**
  Electrons traverse the 70 meter length of KATRIN
  First operation of entire beam line
- July 2017 – **$^{83}$mKr Spectrum**
  Precision measurement of a nuclear standard
  Test scanning principles of tritium operation
  Prototype of sterile neutrino search
- April 2018 – **Beginning of tritium operation**
  Goal: 350 meV discovery potential
  200 meV sensitivity
  Probe quasi-degenerate region
• Relative shape measurement of integrated β spectrum
• 4 fit parameters: $m^2$, $E_0$, $A_S$, $R_{Bg}$

3 yrs (5 cal. yrs) to balance statistics and systematics

optimal $m^2$ sensitivity at $S/B \approx 2$

[E. Otten, 1994]
THE LAST ORDER OF MAGNITUDE

If the mass is below 0.2 eV, how can we measure it? KATRIN may be the largest such experiment possible.

Size of experiment now: Diameter 10 m.

Next diameter: 300 m!

Ro-vibrational states of THe⁺, HHe⁺ molecule
Cyclotron motion:

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

\[ f_c = 27 992.491 10(6) \text{ MHz T}^{-1} \]

Radiated power \( \sim 1 \text{ fW} \) at 1 T for 18-keV electrons.

Surprisingly, this had never been observed for a single electron.
THE ENERGY IS MEASURED AS A FREQUENCY
ENERGY RESOLUTION

\[
\frac{E_{\text{kin}}}{E_{\text{kin}}} = 1 + \frac{m_e c^2}{E_{\text{kin}}} f
\]

\[\sim 30\]

• For 1 eV energy resolution, you need about 2 ppm frequency.
• For 2 ppm frequency, you need 500,000 cycles, or 15 μs.
• Electron travels 2 km.
• You need a trap!
Gas cell is a small section of WR-42 waveguide
WHAT WOULD A SIGNAL FROM AN ELECTRON LOOK LIKE?

Digitize the amplifier output. Make short-time Fourier transforms. Plot the spectra sequentially (a “spectrogram”).

In time-frequency space:

- Sudden onset of narrow band microwave power.
- Slowly rising frequency due to radiation losses.
- Ends after collision with rest gas.

Simulation: M. Leber
histPSfftw waterfall component 0

Frequency (Hz)

Time (s)

Entries: 1994752
Mean x: 0.002525
Mean y: 1.626e+08
RMS x: 0.001428
RMS y: 7.001e+06
ENERGY SPECTRUM

Project 8, PRL 114, 162501 (2015)
Energy Histogram (bin width = 0.2 eV) (10269 acqs) 20150227 Full Bath Tub Trap At 1A

- $L_1$ at 3.6 eV
- $L_2$ at 53 eV

Analyst: L. de Viveiros

Higher Resolution
Energy Histogram (bin width = 0.5 eV) (10235 acqs) 20150812T0041 BotCoil1000mA TopCoil1000mA CF1065MHz

Analyst: L. de Viveiros

Counts / keV / sec

Track Initial Energy [keV]

M1

M2

M3

8 eV

t = 1.0 - 1.5 ms
WHY IS THIS IMPORTANT?

• Source is transparent to microwaves: can make it as big as necessary.

• Whole spectrum is recorded at once, not point-by-point.

• Excellent resolution should be obtainable.

• An atomic source of T (rather than molecular $T_2$) may be possible. Eliminates the final-state theory input.
Concept: B. Monreal and J. Formaggio, PRD 80:051301, 2009

Phase I

$^{83m}$Kr, waveguide cell

Proof of concept: PRL 114:162501, 2015

Phase 2

$T_2$, waveguide cell; Final states, $^3$H-$^3$He mass diff.

Good resolution: JPG 44:054004, 2017

Phase 3

$T_2$, 1000 cm$^3$ cell; 2 eV ν mass

Phase 4

Atomic T, 10 m$^3$ cell; $\ll$ 2 eV ν mass
Phase 3

Tritium experiment at Mainz/Troitsk scale: \(2\,\text{eV}\) goal

- Large MRI magnet
- \(200\,\text{cm}^3\) effective volume
- Ring array of antennas

Concept: M. Jones
Atomic tritium experiment:
Very large magnet $\sim 10 \text{ m}^3$
Trapped atomic T at $< 1 \text{ K}$

Phase 4

Final State Distributions

Atomic T
(at -8.1 eV)

$T_2$

Relative probability

Energy (eV)

Ioffe trap design:
A. Radovinsky

Ioffe trap design:
A. Lindman
PROJECT 8 SENSITIVITY

Existing mass limit

$T_2, 3 \times 10^{11} \text{ cm}^{-3}$

$T_2, 3 \times 10^{13} \text{ cm}^{-3}$

Normal vs inverted hierarchy

Current system volume

Atomic $T$, $1 \times 10^{12} \text{ cm}^{-3}$

90% CL mass limit, eV

Effective volume, m³

Standard deviation in $m_v$
SUMMARY

KATRIN

Construction complete except “tritium loops”

Full operation 2018

Project 8

Success of proof-of-concept.

Phase 2: “Microtritium” experiment, begins 2017

Phase 3: Molecular tritium neutrino mass to ~2 eV

Phase 4: Atomic tritium.
Fin
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COSMOLOGICAL SENSITIVITY

Within the ΛCDM model, constraints are now quite tight. Planck + BAO gives

\[ \sum m_\nu < 0.17 \text{ eV} \]

Di Valentino et al. PRD 93, 083527 (2016)
But some tensions ... Battye and Moss, PRL 112, 051303 (2014)

Some tensions in $\Lambda$CDM resolved with neutrino mass:

$$\sum m_\nu = (0.320 \pm 0.081) \text{ eV}$$
HUBBLE TENSION…

Tension with the HST galaxy low-z data can be resolved by relaxing $w$:

$$w \sim -1.14^{+0.12}_{-0.10}$$

$$\sum m_\nu \sim 0.35^{+0.16}_{-0.25} \text{ eV}$$

Di Valentino et al. PLB 761, 242 (2016)
## MASS AND MIXING PARAMETERS

<table>
<thead>
<tr>
<th></th>
<th>Oscillation</th>
<th>Kinematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.54^{+0.21}_{-0.21} \times 10^{-5}$ eV$^2$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{32}^2</td>
<td>$</td>
</tr>
<tr>
<td>$\Sigma m_i$</td>
<td>&gt; 0.055 eV (90% CL)</td>
<td>&lt; 5.4 eV (95% CL)*</td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>$34.1^{+0.9}_{-0.9}$ deg</td>
<td></td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>$39.2^{+1.8}_{-1.8}$ deg</td>
<td></td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>$9.1^{+0.6}_{-0.7}$ deg</td>
<td></td>
</tr>
<tr>
<td>$\sin^2\theta_{13}$</td>
<td>$0.025^{+.003}_{-.003}$</td>
<td></td>
</tr>
</tbody>
</table>

Marginalized 1-D 1-$\sigma$ uncertainties.

*C. Kraus et al., Eur. Phys. J. C40, 447 (2005); V. Aseev et al. PRD 84 (2011) 112003. Other refs, see Fogli et al. 1205.5254.*
Overview of KArlsruhe TRItium Neutrino Experiment

Windowless gaseous source  Transport section  Pre-spectrometer  Main-spectrometer  Detector

$10^{-3}$ mbar  $10^{-11}$ mbar

$\beta$ decay

$^{3} \text{H}$  $^{3} \text{He}$

$10^{10}$ $e^{-}/s$  $10^{10}$ $e^{-}/s$  $10^{3}$ $e^{-}/s$  $10^{3}$ $e^{-}/s$

Monitor-spectrometer

70 m
Idea: Cyclotron Radiation Emission Spectroscopy (CRES).

If you are going to measure anything with precision, measure frequency.

-- Arthur Schawlow
• Uses frequency-based Cyclotron Resonance Emission Spectroscopy (CRES) for energy measurements of betas from gaseous source.

• Measurement via microwave photon emission (26 GHz @ 1 Tesla): allows for extraction of electron energies without removing them from the source.
Phase 1 at University of Washington

- G-M cooler (35K)
- 26-GHz amplifiers
- $^{83\text{m}}$Kr source (behind)
- SC Magnet (0.95 T)
Short Time Fourier Transform (32.8 μs, 30.52 kHz),
Power cut 8.12 dB above noise floor
Ratios
Short-time Fourier transform spectrogram

Find tracks

Join segments vertically to map complete electron event
Larmor formula for emitted power

\[ P(\gamma, \theta) = \frac{1}{4\pi\varepsilon_0} \frac{2}{3} \frac{e^4}{m_e^2 c^2} B^2 (\gamma^2 - 1) \sin^2 \theta , \]

with \( \gamma = \left( 1 + \frac{E_{\text{kin}}}{m_e c^2} \right) \) and \( \theta \) the pitch angle.

\[ P(90^\circ) = 1.0 \text{ fW for 17.8 keV } e^- \]

\[ P(90^\circ) = 1.7 \text{ fW for 30.2 keV } e^- \]
$^{83m}\text{Kr}$: NICE TEST SOURCE

$^{83}\text{Rb}$

$E_Y = 32152$ eV

Principal conversion e$^-$:
- K: 17824.3 eV
- L$_2$: 30424.4 eV
- L$_3$: 30477.2 eV
- M$_2$: 31934.2 eV
- M$_3$: 31941.9 eV
Phases and Goals of Project 8

<table>
<thead>
<tr>
<th>Phase</th>
<th>Timeline</th>
<th>Source</th>
<th>R&amp;D Milestones</th>
<th>Science Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2010–2017</td>
<td>$^{83m}\text{Kr}$</td>
<td>single electron detection proof of concept</td>
<td>conversion electron spectrum of $^{83m}\text{Kr}$</td>
</tr>
<tr>
<td>II</td>
<td>2015–2018</td>
<td>T$_2$</td>
<td>Kurie plot systematic studies</td>
<td>Final-state spectrum test, $^3\text{H}–^3\text{He}$ mass difference, $m_\nu \lesssim 10–100$ eV/c$^2$</td>
</tr>
<tr>
<td>III</td>
<td>2016–2021</td>
<td>T$_2$</td>
<td>high-rate sensitivity $B$ field mapping</td>
<td>$m_\nu \lesssim 2$ eV/c$^2$</td>
</tr>
<tr>
<td>IV</td>
<td>2017...</td>
<td>T</td>
<td>atomic tritium source</td>
<td>$m_\nu \lesssim 40$ meV/c$^2$ measure $m_\nu$ or determine normal hierarchy</td>
</tr>
</tbody>
</table>

Currently commissioning Phase II waveguide prototype with $^{83m}\text{Kr}$.

First tritium operations in Summer 2017.

Design of Phase III ongoing.

Early R&D for Phase IV with atomic tritium.
Phase 2

“Microtritium” – a very small tritium experiment.

Changes from Phase 1:
- WR-42 → 1-cm circular waveguide cell
- Kapton windows → CaF₂
- External ESR calibrations of field
- 5-coil “bathtub” trap
- RSA → ROACH streaming digitizer
- Isolator for better SNR

Design: M. Fertl
Addition of cryogenic isolator (circulator with one port terminated) reduces frequency dependence of noise floor.

Analyst: R. Cervantes
A spectrogram from the ROACH Digitizer

Analyst: C. Claessens
"JUMP" SPECTRUM

$^{83m}$Kr 30.4 keV line

Most probable jump is 14 eV.
# Neutrino Mass Physics Impact

<table>
<thead>
<tr>
<th>Neutrino Mass Sensitivity</th>
<th>Scale</th>
<th>Possible Experiments</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\nu &lt; 2 \text{ eV}$</td>
<td>eV</td>
<td>Mainz, Troitsk, Project 8 (Phase II)</td>
<td>Neutrinos ruled out as primary dark matter</td>
</tr>
<tr>
<td>(current sensitivity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_\nu &gt; 0.2 \text{ eV}$</td>
<td>Degeneracy</td>
<td>KATRIN, Project 8 (Phase III)</td>
<td>Cosmology, $0\nu\beta\beta$ reach</td>
</tr>
<tr>
<td>$m_\nu &gt; 0.05 \text{ eV}$</td>
<td>Inverted Hierarchy</td>
<td>Project 8 (Phase IV)</td>
<td>Resolve hierarchy if null result, Cosmology, $0\nu\beta\beta$ reach</td>
</tr>
<tr>
<td>$m_\nu &gt; 0.01 \text{ eV}$</td>
<td>Normal Hierarchy</td>
<td>Unknown</td>
<td>Oscillation limit, possible relic neutrino sensitivity</td>
</tr>
</tbody>
</table>
Antenna array concept for Phase III: phased array(s) with digital beam forming

- Phase III can set $m_{\nu} < 2 \text{ eV}$
- Total tritium source volume ~100 cm$^3$
- Ring-shaped phased arrays with focus determined by digital beam forming

Phase IV Ioffe Trap concept: Atomic tritium $f(x, y) = (0 \text{ cm}, 0 \text{ cm})$
AN EARLY H TRAP (AT&T, MIT)

Effect of dipolar spin flips

$6 \times 10^{12} \text{ cm}^{-3}$

40 mK

400 s

Hess et al. PRL 59, 672 [1987]
ALPHA’S ANTIHYDROGEN TRAP

MOLECULAR FINAL-STATE SPECTRUM

T\textsubscript{2} \rightarrow ^3\text{HeT}^+

Q_A = 18.6 keV

Saenz et al. PRL 84 (2000)
MOLECULAR FINAL-STATE SPECTRUM

Saenz et al. PRL 84 (2000)
Fackler et al. PRL 55 (1985)

694 eV²

LANL 1991, LLNL 1995
TABLE IX. Atomic mass difference and neutrino mass squared extracted from two experiments, in one case with the original 1985 theoretical calculations of the FSD and in the second case with a more modern calculation.

<table>
<thead>
<tr>
<th></th>
<th>LANL [15]</th>
<th>LLNL [16]</th>
</tr>
</thead>
<tbody>
<tr>
<td>As published</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta_{00}$</td>
<td>18570.5(20)</td>
<td>18568.5(20)</td>
</tr>
<tr>
<td>$Q_A$</td>
<td>18588.6(20)</td>
<td>18586.6(25)</td>
</tr>
<tr>
<td>$m^2_{\nu}$</td>
<td>-147(79)</td>
<td>-130(25)</td>
</tr>
<tr>
<td>Re-evaluated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta_{00}$</td>
<td>18571.2(20)</td>
<td>18569.2(20)</td>
</tr>
<tr>
<td>$Q_A$</td>
<td>18589.3(20)</td>
<td>18587.3(25)</td>
</tr>
<tr>
<td>$m^2_{\nu}$</td>
<td>20(79)</td>
<td>37(25)</td>
</tr>
</tbody>
</table>

Bodine, Parno, HR; PRC 91 035505 (2015)
MOLECULAR FINAL-STATE SPECTRUM

Saenz et al. PRL 84 (2000)
Fackler et al. PRL 55 (1985)

0.2 eV²
694 eV²

KATRIN

LANL 1991, LLNL 1995
Formaggio and Monreal, Phys. Rev. D 80, 051301(R), 2009
MAGNETIC CONFIGURATION OF TRAP

Solenoidal uniform field for electron cyclotron motion

Pinch coils to reflect electrons

Ioffe conductors (multipole magnetic field) to reflect radially moving atoms.

The ALPHA antihydrogen trap parameters:
- Magnetic well depth 0.54 K (50 μeV)
- Trap density initially ~10^7 cm^-3
- Trap lifetime ~ 1000 s
Molecular excitations

Energy loss

Saenz et al. PRL 84, 242

Rovibrational Structure of Ground State

First Electronic Excitation

Excitation in $^3$HeT$^+$ (eV)

quench condensed $D_2$

Mainz

gaseous $T_2$, Troitsk

energy loss $\varepsilon$ [eV]
Present Lab Limit 2 eV

Effective (beta) mass, eV

Sum of Masses, eV

Normal

Inverted

KATRIN

starting 2017

MASS RANGE ACCESSIBLE
If the mass is below 0.2 eV, how can we measure it?

KATRIN may be the largest such experiment possible.
NEUTRINO MASS LIMITS FROM BETA DECAY

HDM $\Omega = 1$

IH lower limit

NH lower limit

Year

FIRST OBSERVATION OF SINGLE-ELECTRON CYCLOTRON RADIATION

June 6, 2014

Analyst: N. Oblath

Project 8, PRL 114, 162501 (2015)
June 6, 2014

Electron scatters off gas molecules, losing energy, possibly changing pitch angle

Electron slowly loses energy from cyclotron emission
~ 1 fW radiative loss

Track start gives initial electron kinetic energy