The Direct Road to Neutrino Mass

Hamish Robertson, CENPA, University of Washington

Physics Division seminar
Oak Ridge National Laboratory
“Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron.”

E. Fermi, 1934
“Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron.”

E. Fermi, 1934

This is the “direct” method.

F. Wilson, Am. J. Phys. 36, 1150 (1968)
First experiments with gaseous tritium!

\[ m_\nu < 500 \text{ eV} \]

\[ m_\nu < 1700 \text{ eV} \]
Neutrinos oscillate, have mass

Super-Kamiokande

KamLAND

SNO
• The story so far: 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).

• Cosmological comments.

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

\[ \Delta m_{12}^2 = 8 \times 10^{-5} \text{ eV}^2 \]

\[ \Delta m_{23}^2 = 2 \times 10^{-3} \text{ eV}^2 \]

“Normal”
\[ \nu_3 \]
\[ \nu_2 \]
\[ \nu_1 \]

“Inverted”
\[ \nu_2 \]
\[ \nu_1 \]
\[ \nu_3 \]

\[ \nu_e \quad \nu_{\mu} \quad \nu_{\tau} \]
What is the neutrino mass scale?

Some things are simply missing from the standard model (dark matter, gravity…) but neutrino mass is the only contradiction to the SM.
Perhaps neutrinos can help us understand the patterns of mass.
Neutrino oscillations discovered – neutrinos have mass!

\[ \nu_e (eV), \nu_{\mu} (keV), \nu_{\tau} (MeV) \]

\[ \mu \quad e \quad \tau \]

\[ \Omega = 1 \]

\[ v_1, v_2, v_3 \]

[Graph showing mass limits for neutrinos from 1950 to 2010 with different energy scales and data points for each type of neutrino.]
NEUTRINO MASS FROM BETA SPECTRA

With flavor mixing:

\[
\frac{dN}{dE} \approx 3rt(E_0 - E) \sum_{i=1,3} |U_{ei}|^2 [(E_0 - E)^2 - m_i^2]^{1/2} \Theta(E_0 - E - m_i)
\]

\[
= 3rt(E_0 - E)[(E_0 - E)^2 - m_\beta^2]^{1/2} \Theta(E_0 - E - m_\beta)
\]

\[
m_\beta^2 = m_1^2 + |U_{e2}|^2 \Delta m_{21}^2 + |U_{e3}|^2 \Delta m_{31}^2
\]

\[
m_\beta = m_1 = 3 \times 10^{-5} \text{ eV}^2 \quad \pm 6 \times 10^{-5} \text{ eV}^2
\]
3 masses and neutrino oscillation data give two possibilities, Inverted Order and Normal Order:
MASS RANGE ACCESSIBLE

\[ m_\beta [\text{eV}] \]

\[ \sum m_i [\text{eV}] \]

KATRIN 2019 (90\% C.L.)
Mainz & Troitsk (95\% C.L.)

Plot based on HERA 03-029 and NIMRT 41 (2009) external fraction models by P. Fleet

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MASS RANGE ACCESSIBLE
MASS
RANGE
ACCESSIBLE
MASS RANGE ACCESSIBLE
At Karlsruhe Institute of Technology unique facility for closed $T_2$ cycle:
Tritium Laboratory Karlsruhe

A direct, model-independent, kinematic method, based on $\beta$ decay of tritium.

~ 75 m long with 40 s.c. solenoids
Overview of KArlsruhe TRItium Neutrino Experiment

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

$10^{-3}$ mbar
$10^{-11}$ mbar
KATRIN forms integral spectrum with MAC-E filter

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

$\mu = E_\perp / B = \text{const.}$
KATRIN
March 18-19, 2019

305,000 events

Col dens: $2 \times 10^{17} \text{ cm}^{-2}$
[CDR: $5 \times 10^{17} \text{ cm}^{-2}$]

$E/dE = 42000/6.3$
$= 6670$
$\sim 2.8 \text{ eV base width}$
[CDR: 20000]

Bkg: 0.33 c/s
[CDR: 0.01 c/s]
KATRIN
April 10 - May 13
PRL 123, 221802 (2019)

\[
m_{\nu}^2 = (-1.0 \pm 0.9) \text{ eV}^2
\]

\(p = 0.56\)
Result is statistically probable

- best-fit result corresponds to a 1-σ statistical fluctuation to negative $m^2(\nu_e)$

- p-value is derived from 13 000 MC samples with $m^2(\nu_e) = 0$ and properly fluctuated $\sigma_{\text{stat}}$ and $\sigma_{\text{syst}}$

p-value = 0.16

exp. result: $-1.0 \text{ eV}^2$

MC ensemble

$N_{\nu} = 0 \text{ eV}$

$\text{Best fit}$
Derivation of mass limit

**Lokhov-Tkachov**
- $m_\nu < 1.1 \text{ eV (90\% CL)} = \text{sensitivity}$

**Feldman-Cousins**
- $m_\nu < 0.8 \text{ eV (90\% CL)}$

Bayesian Confidence Interval ($m_\nu^2 > 0$, flat)
- $m_\nu < 0.9 \text{ eV (90\% CI)}$
Still mainly statistical

- total statistical uncertainty budget $\sigma_{\text{stat}} = 0.97 \text{ eV}^2$
- total systematic uncertainty budget $\sigma_{\text{syst}} = 0.32 \text{ eV}^2$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (eV$^2$)</th>
</tr>
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<tbody>
<tr>
<td>Stat. only</td>
<td>0.97</td>
</tr>
<tr>
<td>Non-Poisson bkg.</td>
<td>0.30</td>
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<tr>
<td>Background slope</td>
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<tr>
<td>Source properties</td>
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<tr>
<td>Magnetic fields</td>
<td>0.05</td>
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<tr>
<td>Scan fluctuations</td>
<td>0.05</td>
</tr>
<tr>
<td>Final states</td>
<td>0.02</td>
</tr>
</tbody>
</table>

→ since May 2020
improved radon-retention system

(S. Mertens)
Problems, always problems

- Background
- Plasma
- Pandemic
Backgrounds predominantly originate from main spectrometer: stored particles from radon decays, ionisation of Rydberg states.

$$\sigma(m_\nu^2) = k \frac{b^{1/6}}{r^{2/3}t^{1/2}},$$

Design: 0.01 c/s
Actual: 0.5 c/s

K. Valerius, Heraeus 2019
Run KNM1 is published, KNM2 under analysis, KNM3 mainly systematic studies, KNM4 now running.

Destination: 0.2 eV
The road is direct, but long!
Neutrinos in the cosmos

Throwing in everything, Planck finds

$$\sum m_\nu < 0.12 \text{ eV}$$

But they used degenerate approximation. Actually:

$$\sum m_\nu < 0.26 \text{ eV}$$

Loureiro et al. PRL 123, 081301 (2019)
Neutrinos in the cosmos

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)
The Hubble Constant Problem

The Hubble constant measures the current expansion rate of the universe. When cosmologists calculate its value based on data from the early universe, they predict a lower value than when they measure objects in the present-day universe. A new analysis of “tip of the red giant branch” (TRGB) stars finds an intermediate Hubble value, complicating the debate.
Neutrinos in the cosmos

Planck CMB Lensing (1807.06209)

Project 8 Goal

Abazajian et al., “CMB-S4 Science” 1907.04473
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!

\[ \sigma(m^2) = k \frac{b^{1/6}}{r^{2/3} t^{1/2}}, \]

Molecular rotation and vibration

Theory: Saenz et al. 2000

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

Arthur Schawlow

Surprisingly, this had never been observed for a single electron.

Cyclotron motion:

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

\[ f_c = 27,992.491 \pm 0.010 \, \text{MHz} \, \text{T}^{-1} \]

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

\[ P(17.8 \, \text{keV}, 90^\circ, 1 \, \text{T}) = 1 \, \text{fW} \]
$^{83m}{\text{Kr}}$: NICE TEST SOURCE

$E_\gamma = 32152 \text{ eV}$

Conversion e$^-$
K: 17824.3 eV
L$_2$: 30424.4 eV
L$_3$: 30477.2 eV
...
ENERGY RESOLUTION & TRAPS

\[ \frac{\Delta E_{\text{kin}}}{E_{\text{kin}}} = \left(1 + \frac{m_e c^2}{E_{\text{kin}}}\right) \frac{\Delta f}{f} \]

- For 1 eV energy resolution, you need about 2 ppm frequency.
- For 2 ppm frequency, you need 500,000 cycles, or 15 \( \mu \)s.
- Electron travels 2 km.
- You need a trap!
G-M cooler (35K)
26-GHz amplifiers
$^{83m}\text{Kr}$ source (behind)

Superconducting Magnet (0.96 T)

WR-42 waveguide
ESR cell
Gas lines
Trap coils

University of Washington: Phase I
First CRES event (from $^{83m}Kr$)

Waveguide to low-noise amplifier

1 T Weak magnetic trap

Coil

Gas

1 MHz $\approx$ 20 eV
start frequency of the first track gives kinetic energy.

frequency chirps linearly, corresponding to ~1 fW radiative loss.

electron scatters inelastically, losing energy and changing pitch angle.

Eventually, scatters to an untrapped angle

First CRES event (from $^{83m}$Kr)
Data in a shallow trap demonstrates 4 eV FWHM, including 2.83 eV natural width of $^{83m}$Kr 17.8 keV K conversion electron.

Main line shape consistent with a Voigt profile

Shakeup and shakeoff in Kr, and scattering before detection, leads to high-(low-)f (low-E) tail.

Asner et al. PRL 114, 162501 (2015)
Most probable jump is 14 eV.
CRES WORKS: 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.

• Low backgrounds are expected.

• An atomic source of T (rather than molecular T\textsubscript{2}) may be possible. Eliminates the molecular broadening.
To determine neutrino mass from T$_2$ decay (KATRIN), the final-state distribution must be known.
$b = 10^{-6} / \text{eV/s}$

$\sigma_B = 0.3 \text{ ppm}$

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

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

Standard deviation in $m_v^2, \text{eV}^2$

$90\% \text{ CL mass limit, eV}$
Phased approach to a neutrino mass measurement

Goal: a mass measurement sensitive to 40 meV
Phase II

Kr/T$_2$ gas handling system attached

Insert cryostat

NMR magnet providing background magnetic field

Picture: Alec Lindman
Phase II high resolution
83mKr data (shallow trap)

Two trap coils
Small acceptance: 90.0(1)°
0.2 + 0.2 mm³
Natural width of line: 2.8(1) eV
Instrumental Resolution: 2.0(1) eV

Magnetic field - 959 (mT)

Distance from lower window (mm)

Main field
Traps on:
r = 1,2,3,4 mm

12 17.85 mA

Intensities (%/eV)

Energy (eV)

3d so
3d su
4s so
4s su
4p so
4p su

Kr shake spectrum:
HR & V. Venkatapathy;
PRC 102, 035502 (2020)

Shake spectrum +
H₂ scattering

Energy (keV)
Counts

Preliminary!
Phase II Waveguide Cell

Improvements:
- Cylindrical waveguide (more volume)
- 4 deep trap coils (more statistics)
- Amplifiers colder (less noise)
- Terminator replaces short
- CaF₂ windows for tritium

Instrumental
33 eV FWHM

53 eV FWHM
Phase II Kr & $T_2$ gas system

$T_2$ inventory: 2 Ci
KATRIN

1.5 M events

Project 8

3770 events

preliminary

Zero background events in 82 days!
KATRIN spectrometer

Project 8 Phase II spectrometer (to scale)
Phase III

1. Demonstrate free-space CRES detection
2. Demonstrate atomic trapping

Tritium experiment at Mainz/Troitsk scale.

Changes from Phase II:
- Large MRI magnet
- 200 cm³ effective volume
- Ring array of antennas

Concept: M. Jones
MAGNETIC TRAP FOR T

Ioffe-Pritchard trap

Halbach magneto-gravitational trap


PHASE IV CONCEPT

Cracker 2500 K
Accommodator 160 K
Nozzle ~10 K

Velocity and State Selector
Straight Quadrupole

Molecular tritium supply and recirculation

Atoms slow by 60 m/s across 1 T step

1 T Solenoid

0.03 K Tritium Atoms
Fiducial Volume
B = 1 T
B = 3 T

Antenna array for digital beamforming and position reconstruction

Atom-Trapping Quadrupole
Atom-Trapping Multipole

(A. Lindman)
PROJECT 8 SENSITIVITY

Technical Readiness Levels

<table>
<thead>
<tr>
<th>TRL</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Can’t prove laws of physics violated.</td>
</tr>
<tr>
<td>2</td>
<td>Reasonable to think laws of physics aren’t violated.</td>
</tr>
<tr>
<td>3</td>
<td>Proof-of-principle demonstrated.</td>
</tr>
<tr>
<td>4</td>
<td>Low-fidelity prototype successfully tested.</td>
</tr>
<tr>
<td>5</td>
<td>High-fidelity prototype successfully tested.</td>
</tr>
<tr>
<td>6</td>
<td>Standalone final component successfully tested.</td>
</tr>
<tr>
<td>7</td>
<td>Integrated subsystem successfully tested.</td>
</tr>
<tr>
<td>8</td>
<td>First physics data collected.</td>
</tr>
<tr>
<td>9</td>
<td>Results published.</td>
</tr>
</tbody>
</table>

Phase I: 9  
Phase II: 8  
Phase III: 2  
Phase IV: 1
DIRECT MASS MEASUREMENTS...

... are largely model independent:

- Majorana or Dirac
- No nuclear matrix element complications
- No complex phases
- No cosmological degrees of freedom

KATRIN is running! New mass limit 1.1 eV (90% CL)

Success of Project 8 proof-of-concept.

- New spectroscopy based on frequency
- Potential atomic T source: eliminate molecular broadening. Design and testing underway.
Fin