Detecting Neutrinos

Hamish Robertson, INT Summer School, Seattle 2009
A Brief History of Neutrinos

- 1930 – Pauli’s ‘desperate remedy’.
- 1938 – Bethe & Critchfield explain the sun’s power.
- 1956 – Parity violation discovered in $\beta$ decay.
- 1956 – The neutrino observed.
- 1958 – Neutrino helicity measured.
- 1961 – The $\mu$ neutrino discovered.
- 1975 – the $\tau$ neutrino makes 3.
“I have created a particle that can never be detected…” W. Pauli

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
Professor W. Pauli  
Zurich University  
Switzerland  
14 June 1956

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.

Frederick Reines & Clyde Cowan  
Box 1663 Los Alamos, New Mex

Nite letter
Frederick REINES and Clyde COVAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

LT. 15.6.18 / 15.38Z
The Wright letter
$6 \times 10^{-44} \text{ cm}^2$
NEUTRINO-ELECTRON SCATTERING

\[ \frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi} \left[ g_L^2 + g_R^2 \left(1 - \frac{T}{E_{\nu}}\right)^2 - g_L g_R \frac{m_e T}{E_{\nu}^2} \right] \]

T is electron kinetic energy, and:

\[ \frac{2G_F^2 m_e}{\pi} = 8.3 \times 10^{-45} \text{ cm}^2 \]

For \( E_{\nu} \gg m_e \),

\[ \frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi} \left[ g_L^2 + g_R^2 \left(1 - \frac{T}{E_{\nu}}\right)^2 \right] \]

Electron neutrinos:

\[ g_L = \sin^2 \theta_W + 1/2 = 0.727(3) \]
\[ g_R = \sin^2 \theta_W = 0.227(3) \]

Mu, tau neutrinos:

\[ g_L = \sin^2 \theta_W - 1/2 = -0.273(3) \]
\[ g_R = \sin^2 \theta_W = 0.227(3) \]

\[ \sigma_{\nu,e} \propto T \]
Helicity -- the Goldhaber-Grodzins-Sunyar experiment.

Mass from the electron spectrum in beta decay.

Neutrinoless Double Beta decay and the question of whether the neutrino and antineutrino are the same or different.
Helicity of the neutrino

Goldhaber, Grodzins, & Sunyar, PR 109, 1015 (1958)
Fermi 1932: Neutrinos could have mass, just like electrons, but seems much less.

Hanna & Pontecorvo 1949: Neutrino mass < 1/1000 electron mass.

1950’s: Parity violation discovered. Neutrino directly observed. Neutrino helicity measured. PV attributed to neutrinos.

Glashow, Weinberg, Salam late 1960’s: Can’t understand these things unless mass = 0. So, no RH neutrinos in the SM.
Determination of Neutrino Mass

- Neutrino Oscillations
- Beta Decay
  - Tritium
  - $^{187}\text{Re}$
- Double beta decay
- Cosmology

- The mass is needed for
  - Particle physics
  - Cosmology
Direct Mass Limits: the History
Neutrino mass is not a feature of the SM

A signal of unification? See-saw model:

\[
m_\nu = \frac{m_D^2}{M} \\
\nu_3 : 3 \times 10^{-6} \\
\nu_2 : 1 \times 10^{-8} \\
\nu_1 : 3 \times 10^{-13}
\]
And why is there matter but no antimatter?
Sakharov’s criteria:
Baryon number not conserved…
CP violated…
Universe not in equilibrium at some point…
Neutrinos and cosmology

- **Minimum mass:**
  \[ \Sigma m_\nu > 55 \text{ meV} \] (oscillations)

  \[ \omega_\nu = \Omega_\nu h^2 = \frac{\sum m_\nu}{94.2 \text{ eV}} \approx 0.0007 \]

  (total about 20% of the mass of stars)

- **Maximum mass:**
  \[ \Sigma m_\nu < 6900 \text{ meV} \] (tritium), about 8% of closure.

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**Neutrino Power Spectrum**

- Cosmic Microwave Background
- SDSS galaxies
- Cluster abundance
- Weak lensing
- Lyman Alpha Forest

Tegmark & Zaldarriaga, astro-ph/0207047 + updates
Even small $m_\nu$ influences structure

$\Sigma m_\nu$

280 meV

1500 meV

Barger et al. hep-ph/0312065

SDSS + 2dFGRS
Minimum mass: \( \Sigma m_\nu > 60 \text{ meV} \) (oscillations)

\( \Sigma m_\nu, \text{ eV}^2 \)

2\( \sigma \) bounds from:
- \( \nu \) oscillation data
- \( \beta \) decay
- cosmology

KATRIN

<table>
<thead>
<tr>
<th>Case</th>
<th>Cosmological data set</th>
<th>( \Sigma ) bound (2( \sigma ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WMAP</td>
<td>&lt; 2.3 eV</td>
</tr>
<tr>
<td>2</td>
<td>WMAP + SDSS</td>
<td>&lt; 1.2 eV</td>
</tr>
<tr>
<td>3</td>
<td>WMAP + SDSS + SN\text{Riess} + HST + BBN</td>
<td>&lt; 0.78 eV</td>
</tr>
<tr>
<td>4</td>
<td>CMB + LSS + SN\text{Astier}</td>
<td>&lt; 0.75 eV</td>
</tr>
<tr>
<td>5</td>
<td>CMB + LSS + SN\text{Astier} + BAO</td>
<td>&lt; 0.58 eV</td>
</tr>
<tr>
<td>6</td>
<td>CMB + LSS + SN\text{Astier} + Ly-( \alpha )</td>
<td>&lt; 0.21 eV</td>
</tr>
<tr>
<td>7</td>
<td>CMB + LSS + SN\text{Astier} + BAO + Ly-( \alpha )</td>
<td>&lt; 0.17 eV</td>
</tr>
</tbody>
</table>

Fogli et al.

Planck will provide 3 separate $\Lambda$CDM constraints on $\Sigma m_\nu$:

1. Planck + SDSS  $\quad 0.2$ eV
2. Planck only $\quad 0.26$ eV
3. CMBR + grav. lensing $\quad 0.15$ eV

From Planck “Bluebook”
\[ \beta \text{-decay electron spectrum...} \]

... shape determines the absolute neutrino mass squared:

\[ N(E) = \frac{dN}{dE} = K \times F(E,Z) \times p_e \times E_e \times p_\nu \times E_\nu \]

\[ = K \times F(E,Z) \times p \times E \times \sqrt{(E_0 - E)^2 - m_\nu^2} \times (E_0 - E) \]

\[ K \sim \left[ g_v^2 |M_F|^2 + g_A^2 |M_{GT}|^2 \right] \quad F(E,Z) = \text{Fermi function} \]

\[ m_\nu = \text{“mass” of electron (anti-)neutrino} = \sum |U_{ei}|^2 \text{ } m_i = m_\nu \text{ in quasi-degenerate region.} \]

Present Limit:
2.3 eV (95% CL)
Kraus et al.
hep-ex/0412056
After all critical systematics measured by own experiment (inelastic scattering, self-charging, neighbor excitation):

\[ m^2(\nu) = -0.6 \pm 2.2 \pm 2.1 \text{ eV}^2 \quad \Rightarrow \quad m(\nu) < 2.3 \text{ eV} \quad (95\% \text{ C.L.}) \]

Kinematics of $\beta$-decay

Model-independent determination of mass.
Independent of:
- whether neutrinos Dirac or Majorana,
- nuclear matrix elements,
- phases,
- cosmological models.
Writing the transition probability as the matrix element of some operator $T$,

$$\frac{dN}{dE} = |<l| < \nu_l | T | I >|^2 = \left| \sum_i U_{li}^* <l| < \nu_i | T | I > \right|^2$$

In the degenerate regime where all the masses are the same, the unitarity of $U$ gives us back the original expression for a single massive neutrino, an “electron neutrino with mass”

$$\propto p_e E (E - E_0)^2 \left[ 1 - \frac{m_\nu^2}{(E - E_0)^2} \right]^{1/2}$$

In fact, because $U_{e3}$ is so small, this expression is good all the way down to about 10 meV!
KATRIN at Forschungszentrum Karlsruhe
unique facility for closed $T_2$ cycle:
Tritium Laboratory Karlsruhe

~ 75 m long with 40 s.c. solenoids

5 countries
13 institutions
100 scientists
Mass Range Accessible

Normal Hierarchy
\[ \Delta m_{12}^2 = 8 \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{23}^2 = 3 \times 10^{-3} \text{ eV}^2 \]

(Bean & Bell PRD 65,113009)

Average mass > 20 meV

\[ \Delta m_{12}^2 \]
\[ \Delta m_{23}^2 \]

Mass of Lightest state \( (m_1) \), eV

Mass of Eigenstate, eV

Present Lab Limit 2.3 eV

KATRIN
## Experimental Arrangement

**Rear System:**
Monitor source parameters

**Source:**
Provide the required tritium column density

**Transp. & Pump system:**
Transport the electrons, adiabatically and reduce the tritium density significantly

**Pre-spectrometer:**
Rejection of low-energy electrons and adiabatic guiding of electrons

**Main-spectrometer:**
Rejection of electrons below endpoint and adiabatic guiding of electrons

**Detector:**
Count electrons and measure their energy
Arrival in Leopoldshafen: Nov 24, 2006
Adiabatic magnetic guiding of $\beta$'s along field lines in stray B-field of s.c. solenoids:
- $B_{\text{max}} = 6 \, \text{T}$
- $B_{\text{min}} = 3 \times 10^{-4} \, \text{T}$

Energy analysis by static retarding E-field with varying strength:

High pass filter with integral $\beta$ transmission for $E>qU$

adiabatic transformation $E_\perp \rightarrow E_\parallel$
**Principle of the MAC-E-Filter**

Magnetic Adiabatic Collimation + Electrostatic Filter


\[ \Delta E = E \cdot \frac{B_{\text{min}}}{B_{\text{max}}} = E \cdot \frac{A_{\text{s,eff}}}{A_{\text{analyse}}} = 0.93 \text{ eV}, \text{ KATRIN} \]

(4.8 eV, Mainz)

⇒ sharp integrating transmission function without tails:
Check of transmission function (Mainz Expt.)

Conversion electrons from $^{83m}\text{Kr}$

(e.g. A. Picard et al., Z. Phys. A 342 (1992) 71)

transmission function convoluted with Lorentzian ($\Gamma = 2.83$ eV)
A window to work in

Molecular Excitations

Energy loss function

Rovibrational Structure of Ground State

First Electronic Excitation

Excitation in $^3\text{HeT}^+$ (eV)

energy loss $\varepsilon$ [eV]

Saenz et al. PRL 84, 242

quench condensed $D_2$
Mainz
gaseous $T_2$, Troitsk
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>source of systematic shift</th>
<th>achievable/projected accuracy</th>
<th>systematic shift $\sigma_{\text{syst}}(m_{\nu}^2)[10^{-3}\text{eV}^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>description of final states</td>
<td>$f &lt; 1.01$</td>
<td>$&lt; 6$</td>
</tr>
<tr>
<td>$T^-$ ion concentration $n(T^-)/n(T_2)$</td>
<td>$&lt; 2 \cdot 10^{-8}$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>unfolding of the energy loss function (determination of $f_{\text{res}}$)</td>
<td>$&lt; 2$ (including a more realistic e-gun model)</td>
<td></td>
</tr>
</tbody>
</table>
| monitoring of $\rho d$ $[E_0 - 40\text{eV}, E_0 + 5\text{eV}]$ | $\Delta \varepsilon_T/\varepsilon_T < 2 \cdot 10^{-3}$  
$\Delta T/T < 2 \cdot 10^{-3}$  
$\Delta \Gamma/\Gamma < 2 \cdot 10^{-3}$  
$\Delta p_{\text{inj}}/p_{\text{inj}} < 2 \cdot 10^{-3}$  
$\Delta p_{\text{ex}}/p_{\text{ex}} < 0.06$ | $< \frac{\sqrt{5.6.5}}{10}$ |
| background slope | $< 0.5\text{mHz}/\text{keV}$ (Troitsk) | $< 1.2$ |
| HV variations | $\Delta \text{HV}/\text{HV} < 3\text{ppm}$ | $< 5$ |
| potential variations in the WGTS | $\Delta U < 10\text{meV}$ | $< 0.2$ |
| magnetic field variations in WGTS | $\Delta B_S/B_S < 2 \cdot 10^{-3}$ | $< 2$ |
| elastic $e^- - T_2$ scattering | | $< 5$ |

Identified syst. uncertainties

$$\sigma_{\text{syst, tot}} = \sqrt{\sum \sigma_{\text{syst}}^2} \approx 0.01\text{eV}^2$$

**TABLE IV:** Summary of sources of systematic errors on $m_{\nu}^2$, the achievable or projected accuracy of experimental parameters (stabilization) and the individual effect on $m_{\nu}^2$ for an analysis interval of $[E_0 - 30\text{eV}, E_0 + 5\text{eV}]$ if not stated otherwise.
KATRIN: sensitivity and discovery potential

Expectation for 3 full beam years:
\[ \sigma_{\text{syst}} \sim \sigma_{\text{stat}} \]

- "5\sigma" discovery potential:
  - \( m_\nu = 0.35\text{eV} \) (5\sigma)
  - \( m_\nu = 0.3\text{eV} \) (3\sigma)

- Sensitivity:
  - \( m_\nu < 0.2\text{eV} \) (90\%CL)

"KATRIN will search 1 order of magnitude below present upper bound."
Sensitivity with run time

(a) 

$\sigma_{\text{stat}(m_{\nu}^2)} [eV^2]$ vs. full beam time [months]

(b) 

90\% up. lim. on $m_{\nu}$ [eV] vs. full beam time [months]
Mass Range Accessible

Normal Hierarchy
\[ \Delta m_{12}^2 = 8 \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{23}^2 = 3 \times 10^{-3} \text{ eV}^2 \]
(Beacom & Bell PRD 65, 113009)

Average mass
\[ > 20 \text{ meV} \]

KATRIN
Present Lab Limit
\[ 2.3 \text{ eV} \]
If the mass is NOT in the 200-2200 meV window, but the 20-200 meV window instead, how can we measure it? KATRIN may be the largest such experiment possible.

Size of experiment now: Diameter 10 m.

Source $T_2$ column density near max

Next diameter: 300 m!
**Microcalorimeters for $^{187}$Re $\beta$-decay**

**MIBETA:** Kurie plot of $6.2 \times 10^6$ $^{187}$Re $\beta$-decay events ($E > 700$ eV)

![Kurie plot](image)

10 crystals: $8751$ hours $\times$ mg (AgReO$_4$)

$E_0 = (2465.3 \pm 0.5_{\text{stat}} \pm 1.6_{\text{syst}})$ eV

$m_\nu^2 = (-112 \pm 207 \pm 90)$ eV$^2$

**MANU2 (Genoa)**
metallic Rhenium
$m(\nu) < 26$ eV


**MIBETA (Milano)**
AgReO$_4$
$m(\nu) < 15$ eV


**MARE (Milano, Como, Genoa, Trento, US, D)**
Phase I: $m(\nu) < 2.5$ eV

hep-ex/0509038
KATRIN-type experiment limit: Source and detector are separate. Can evade by making them the same. MARE $^{187}\text{Re}$ uses microcalorimeters: source=detector. BUT pileup limits size of each to $\sim 100 \mu g$.

<table>
<thead>
<tr>
<th></th>
<th>Tritium</th>
<th>$^{187}\text{Re}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endpoint</td>
<td>18.58 keV</td>
<td>2.47 keV</td>
</tr>
<tr>
<td>Branch to last eV</td>
<td>$2 \times 10^{-13}$</td>
<td>$6 \times 10^{-11}$</td>
</tr>
<tr>
<td>Half-life</td>
<td>12.32 y</td>
<td>$4.32 \times 10^{10}$ y</td>
</tr>
<tr>
<td>Mass (1 dis/d in last 200 meV)</td>
<td>20 $\mu$g</td>
<td>13 kg</td>
</tr>
<tr>
<td>Mass (1 dis/d in last 20 meV)</td>
<td>20 mg</td>
<td>13000 kg</td>
</tr>
</tbody>
</table>
New schemes

◆ Decay of $^{187}$Re ($Q = 2.47$ keV) observed in bolometers.
  • For 20 meV, need 13 T of Re or 20 mg of $^3$H.

◆ Atomic T in a trap, full kinematic reconstruction: arXiv 0901:3111
  • For 200 meV, need 1,000’s of separate sources.

◆ Decay of radioactive ions in a storage ring at a specific momentum: arXiv 0904:1089
  • For 200 meV, need $10^{18} – 10^{20}$ decays in beam.

◆ Detection of RF cyclotron radiation from $\beta$ orbiting in B-field: arXiv 0904:2860
  • Needs further thought, might be feasible.
Cyclotron motion of electrons in B field