Direct measurements of neutrino mass

Pontecorvo100 – Symposium in honour of Bruno Pontecorvo for the centennial of the birth
Pisa/Italy, September 18-20, 2013

Christian Weinheimer

Institut für Kernphysik, Westfälische Wilhelms-Universität Münster
weinheimer@uni-muenster.de

Introduction

Direct neutrino mass determination

- Rhenium $\beta$ decay and EC experiments
- Tritium $\beta$ decay experiments

The Karlsruhe Tritium Neutrino experiment KATRIN

- some first data from the main spectrometer and detector commissioning

Summary and Outlook
Direct determination of $m(\nu_e)$ from $\beta$ decay

$\beta$ decay: $(A,Z) \rightarrow (A,Z+1)^+ + (e^-) + \bar{\nu}_e$

$\beta$ electron energy spectrum:

$$\frac{dN}{dE} = K \cdot F(E,Z) \cdot p \cdot E_{\text{tot}} \cdot (E_0 - E_e) \cdot \sqrt{(E_0 - E_e)^2 - \left|m(\nu_e)\right|^2}$$

(modified by electronic final states, recoil corrections, radiative corrections)

E.W. Otten & C. Weinheimer

G. Drexlin, V. Hannen, S. Mertens,

Need: low endpoint energy
very high energy resolution &
very high luminosity &
very low background

$\Rightarrow$ Tritium $^3$H, ($^{187}$Re)
$\Rightarrow$ MAC-E-Filter
(or bolometer for $^{187}$Re)
First measurements of the tritium $\beta$ spectrum searching for the neutrino mass

Tritium $\beta$-spectrum measured with proportional counter:

Curran, Angus, Cockroft, Phys. Rev. 76 (1949) 853

Tritium $\beta$-spectrums, measured with magnetic spectrometer

Langer, Moffat, Phys. Rev. 88 (1952) 689

$m_\nu < 250$ eV
Today's classical way: Tritium $\beta$-spectroscopy with a MAC-E-Filter

- Two supercond. solenoids compose magnetic guiding field
- Adiabatic transformation: $\mu = E_\perp / B = \text{const.}$
  $\Rightarrow$ parallel $e^-$ beam
- Energy analysis by electrostatic retarding field
  \[ \Delta E = E \cdot \frac{B_{\min}}{B_{\max}} = 0.93 \text{ eV (KATRIN)} \]

$\Rightarrow$ sharp integrating transmission function without tails

Magnetic Adiabatic Collimation + Electrostatic Filter
After all critical systematics measured by own experiment (atomic physics, surface and solid state physics: inelastic scattering, self-charging, neighbour excitation):

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

The Troitsk Neutrino Mass Experiment

- Windowless gaseous $T_2$ source, similar to LANL
- MAC-E-Filter, similar to Mainz

Energy resolution: $\Delta E = 3.5\text{eV}$

Luminosity: $L = 0.6\text{cm}^2$

$L = \frac{\Delta \Omega}{2\pi} * A_{\text{source}}$

3 electrode system in 1.5m diameter UHV vessel ($p<10^{-9}\text{ mbar}$)

Re-analysis of data
(better source thickness, better run selection)
Aseev et al, Phys. Rev. D 84, 112003 (2011)
$m_\beta < 2.05\text{ eV}, 95\% \text{ CL}$

Upgraded setup at Troitsk for KATRIN systematics and sterile keV neutrino search
$m(\nu_e)$ from tritium $\beta$ decay

![Graph showing $m_{\nu_e}$ from tritium $\beta$ decay](image)
$m(\nu_e)$ from tritium $\beta$ decay
and discovery of neutrino oscillation

1998: Super Kamiokande detector
discovered oscillation of atmospheric neutrinos

$\rightarrow m(\nu) \neq 0$
Cryogenic bolometers with $^{187}$Re
MIBETA (Milano/Como)

Measures all energy except that of the neutrino

detectors: 10 (AgReO$_4$)
rate each: 0.13 1/s
energy res.: $\Delta E = 28$ eV
pile-up frac.: $1.7 \times 10^{-4}$

$M_{\nu}^2 = -141 \pm 211$ (stat) $\pm 90$ (sys) eV$^2$

$M_{\nu} < 15.6$ eV (90% c.l.)

(M. Sisti et al., NIMA520 (2004) 125)

MANU (Genova)

- Re metallic crystal (1.5 mg)
- BEFS observed (F. Gatti et al., Nature 397 (1999) 137)
MARE neutrino mass project: $^{187}$Re beta decay with cryogenic bolometers

Advantages of cryogenic bolometers:
- measures all released energy except that of the neutrino
- no final atomic/molecular states
- no energy losses
- no back-scattering

Challenges of cryogenic bolometers:
- measures the full spectrum (pile-up)
- need large arrays to get statistics
- understanding spectrum
- still energy losses or trapping possible
- beta environmental fine structure

MARE-1 @ Milano-Bicocca
- 6x6 array of Si-implanted thermistors (NASA/GSFC)
- 0.5 mg AgReO$_4$ crystals
- $\Delta E \approx 30$ eV, $\tau_R \approx 250$ µs
- experimental setup for up to 8 arrays completed
- starting with 72 pixels in 2011
- up to $10^6$ events in 4 years $\rightarrow \sim 4$ eV sensitivity

MARE-2 aims for $10^4$ to $10^5$ detectors with much more advanced time & energy resolution
- R&D effort for Re single crystals on transition edge sensors (TES) $\rightarrow$ improve rise time to $\sim$ µs and energy resolution to few eV
- large arrays ($\approx 10^3$ pixels) for $10^4$-$10^5$ detector experiment
- high bandwidth, multiplexed SQUID readout
- also used with $^{163}$Ho loaded absorbers

MARE-1 @ Genova
ECHO neutrino mass project: $^{163}\text{Ho}$ electron capture with metallic magnetic calorimeters

$^{163}\text{Ho} + e^- \rightarrow ^{163}\text{Dy}^* + \nu_e \rightarrow ^{163}\text{Dy} + \gamma/e^- + \nu_e$

First $^{163}\text{Ho}$ spectrum with MMC

P.C.-O. Ranitzsch et al.,
J Low Temp Phys 167 (2012) 1004

other cryo-bolometer projects with EC($^{163}\text{Ho}$) as well: MARE, Holmes, ...
The KATRIN experiment at KIT

Aim: \( m(\nu_e) \) sensitivity of 200 meV (currently 2 eV)

- very high energy resolution \((\Delta E \leq 1\text{eV}, \text{i.e. } \sigma = 0.3 \text{ eV})\)
- strong, opaque source
- magnetic flux conservation (Liouville)

\[ \frac{A_{\text{spectrometer}}}{A_{\text{source}}} = \frac{B_{\text{source}}}{B_{\text{spectrometer}}} = \frac{E}{\Delta E} = \frac{20000}{1} \]

\( \Rightarrow \) source \( \neq \) spectrometer concept

\( \Rightarrow \) \( \frac{dN}{dt} \sim A_{\text{source}} \)

\( \Rightarrow \) scaling law:

KATRIN Design Report
Scientific Report FZKA 7090)

windowless gaseous molecular tritium source
Molecular Windowless Gaseous Tritium Source WGTS

WGTS: tub in long superconducting solenoids
Ø 9cm, length: 10m, T = 30 K

Tritium recirculation (and purification)
\( p_{\text{inj}} = 0.003 \text{ mbar}, q_{\text{inj}} = 4.7\text{Ci/s} \)

allows to measure with near to maximum count rate using
\( \rho d = 5 \cdot 10^{17}/\text{cm}^2 \)
with small systematics

check column density by e-gun, \( T_2 \) purity by laser Raman
Very successful cool-down and stability tests of the WGTS demonstrator

**Cooling concept of WGTS:**
Pressurized 2-phase Ne

**Per mill stability source strength request:**
\[ \frac{dN}{dt} \sim f_T \cdot \frac{N}{\tau} \sim n = f_T \cdot \frac{p \cdot V}{R \cdot T} \]

Tritium fraction \( f_T \) & ideal gas law

**Recently:**
Tests of sc magnets, constructing of WGTS out of demonstrator

**S. Grohmann et al., Cryogenics, (2013, in press)**

Very successful cool-down and stability tests of the WGTS demonstrator

**Graph:**
Average temperature \( T_{av} \) = 30.243 K
Maximum peak-to-peak variation \( \Delta T_{max} \) = 43.005 K
Standard deviation \( \sigma \) = 15.004 K
Transport and differential & cryo pumping sections

Molecular windowless gaseous tritium source

Differential pumping
new set-up

Cryogenic pumping
with Argon snow
at LHe temperatures
(successfully tested with the TRAP experiment)

Rear wall to stabilize WGTS potential
Egun to measure column density

\[ T_2 \text{-injection } 1.8 \text{ mbar l/s (STP)} = 1.7 \times 10^{11} \text{ Bq/s} = 40 \text{ g/d} \]

\[ \approx 10^{-7} \text{ mbar l/s} \]

\[ < 2.5 \times 10^{-14} \text{ mbar l/s} \]

\[ \Rightarrow \text{adiabatic electron guiding & } T_2 \text{ reduction factor of } \approx 10^{14} \]
Electromagnetic design: magnetic fields

\[ \Rightarrow \Delta E = E \cdot \frac{B_{\text{min}}}{B_{\text{max}}} = E \cdot \frac{1}{20000} = 0.93 \text{ eV} \]

- Aircoils: axial field shaping + earth field compensation

Distance from analysing plane [m]
Main Spectrometer
Suppress secondary electron background from walls on high potential

Secondary electrons from wall/electrode by cosmic rays, environmental radioactivity, ...

New: double layer wire electrode on slightly more negative potential (ca. 23,000 wires, 200 µm precision, UHV compatible)

Background suppression successfully tested at the Mainz MAC-E filter:

- Detector background: 1.6 mHz
- Total background rate: 2.8 mHz

Background from stored electrons: methods to avoid or to eliminate them

Stored electron by magnetic mirrors
F. Fränkle et al., Astropart. Phys. 35 (2011) 128

Radon suppression by LN\(_2\) cooled baffle
S. Görhardt, diploma thesis, KIT

Nulling magnetic field by magn. pulse
B. Hillen, PhD thesis, Münster

radial E x B drift due to electric dipole pulse
G. Drexlin et al., arXiv:1205.3729

Mechanical eliminating stored particles:
The detector

Requirements

- detection of $\beta$-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz) (passive and active shielding)
- good energy resolution (< 1 keV)

Properties

- 90 mm Ø Si PIN diode
- thin entry window (50nm)
- detector magnet 3 - 6 T
- post acceleration (30kV) (to lower background in signal region)
- segmented wafer (148 pixels)
  - record azimuthal and radial profile of the flux tube
  - investigate systematic effects
  - compensate field inhomogeneities
SDS commissioning - objectives

**Primary objectives:**
- test of individual hardware, software and slow control components
- provide ultra high vacuum conditions at the $p \approx 10^{-11}$ mbar level
- detailed understanding of the transmission properties of this MAC-E-Filter ($E = 18.6$ keV with $\Delta E = 0.93$ eV resolution) and compare to simulation with Kasseiopeia
- detailed understanding and passive & active control of background processes
Could switch on main spectrometer without large background rate
all other MAC-E-Filters (Troitsk, Mainz, KATRIN pre spectrometer)
exhibited rates $> 10^5$ cps when switched on for the first time
→ No large Penning traps (advanced KATRIN design works)

This first measurement without wire electrode on screening potential,
LN$_2$ baffles cold and active counter measures against stored electrons

But still KATRIN requires a background rate of $10^{-2}$ cps
Test of transmission function

vessel on ground

vessel on high voltage

Electron Rate (cph)

preliminary
First tests of active background removal by E x B drift

- Enhanced bg rate by igniting Penning trap between egun & spec
- Applying dipole voltage of 10 V between east and west half of wire electrode system → E x B drift
KATRIN´s sensitivity

Example of KATRIN simulation & fit (last 25eV below endpoint, reference):

sensitivity:
\[ m_\nu < 0.2 \text{eV} \ (90\% CL) \]

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

Expectation for 3 full data taking years: \( \sigma_{\text{syst}} \sim \sigma_{\text{stat}} \)

\[ \Rightarrow \text{KATRIN will improve the sensitivity by 1 order of magnitude} \]
\[ \text{will check the whole cosmological relevant mass range} \]
\[ \text{will detect degenerate neutrinos (if they are degen.)} \]
Different ways for a direct neutrino mass measurement from $\beta$-decay
- cryogenic bolometers investigating $^{187}$Re $\beta$-decay ($\rightarrow$ MARE)
- cryogenic bolometers investigating $^{163}$Ho EC ($\rightarrow$ MARE, Holmes (new), ECHO)
- tritium $\beta$-decay using MAC-E-Filter ($\rightarrow$ KATRIN)
- …

KATRIN is using a complex but established method:
→ sensitivity: 2 eV → 200 meV
main spectrometer & detector are being commissioned looking quite promising
expect start of tritium data taking in 2015

Cryo-microcalorimeters have a large potential
but need large arrays → multiplexing
what are the systematics?
The KATRIN 148-pixel detector is smiling when being hit by electrons from 11 subsequent positions of the scanning photoelectron source.