Direct neutrino mass determination

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Introduction

• Neutrino mass in particle physics / cosmology
• Current knowledge
• Experimental methods

Tritium $\beta$-decay experiments

• KATRIN
• Project 8

Holmium EC-decay experiments

• ECHO
• HOLMES

Summary
Neutrino mass in particle physics

- Nature of the neutrino: Majorana or Dirac particle, i.e. is the neutrino it's own anti-particle?

- How to explain the many orders of magnitude difference between neutrino mass limits and masses of the charged fermions of the standard model → sea-saw type I and type II mechanisms

- Possible connection to the generation of the observed matter - antimatter asymmetry in the universe → leptogenesis
Neutrino mass in cosmology

- Neutrinos are (after γ's) the second most abundant particle species in the universe.
- As part of the hot dark matter, neutrinos have a significant influence on structure formation.

For large $\Sigma m_\nu$ values fine grained structures are washed out by the free streaming neutrinos.

$\Sigma m_\nu = 0$ eV
$\Sigma m_\nu = 1$ eV
$\Sigma m_\nu = 7$ eV
$\Sigma m_\nu = 4$ eV

Chung-Pei Ma 1996
What we know (from ν oscillations):

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and Δm² values known (with varying accuracies)

What we don't know:

- Normal or inverted hierarchy?
- Dirac or Majorana particle?
- CP violating phases in mixing matrix?
- No information about absolute mass scale! (only upper limits)
- Existence of sterile neutrinos?
Search for neutrino mass

**β-decay: absolute ν-mass**
model independent, kinematics
status: $m_\nu < 2.3$ eV
potential: $m_\nu \approx 0.2$ eV
e.g.: KATRIN, Project-8, ECHO HOLMES, NuMECS

**0νββ-decay: eff. Majorana mass**
model-dependent (CP-phases)
status: $m_{\beta\beta} < 0.31$ eV
potential: $m_{\beta\beta} \approx 20$-50 meV
e.g.: GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA, KamLAND-Zen

**cosmology: ν hot dark matter $\Omega_\nu$**
model dependent, analysis of CMB and structure formation data
status: $\Sigma m_\nu < 0.23$ eV

possible signal: $\Sigma m_\nu = 0.11 \pm 0.03$eV
(Emami et al., arXiv:1711.05210)
Kinematic determination of $m(\nu_e)$

\[
\frac{d\Gamma}{dE} = C \ p(E + m_e)(E_0 - E) \sqrt{(E_0 - E)^2 - m_{\nu_e}^2} \ F(Z + 1, E) \ \Theta(E_0 - E - m_{\nu_e}) \ S(E)
\]

\[
C = \frac{G_F^2}{2\pi^3} \cos^2 \theta_C |M|^2
\]

(modified by final state distribution, recoil corrections, radiative corrections, ...)

\[
m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}
\]

Suitable Isotopes:

**Tritium**
- $E_0 = 18.6$ keV, $T_{1/2} = 12.3$ a
- $S(E) = 1$ (super-allowed)

**Rhenium**
- $E_0 = 2.47$ keV, $T_{1/2} = 43.2$ Gy

alternative approach:

**Holmium** (EC decay)
- $Q_{EC} \approx 2.5$ keV, $T_{1/2} = 4570$ y
Detector requirements:

- large solid angle or source=detector approach
- high energy resolution
- low background
- low dead time / no pile up

Tritium based experiments

- **KATRIN**: gaseous tritium source with MAC-E type integrating spectrometer determining kinetic energy spectrum of $\beta$-decay electrons
- **Project 8**: gaseous tritium source determining kinetic energy spectrum of $\beta$-decay electrons by measuring cyclotron radiation emitted in a magnetic field

Holmium based experiments

- **ECHO**: Calorimetric measurement of energy released in EC decay of $^{163}$Ho using Metallic Magnetic Calorimeters (MMC)
- **HOLMES**: Calorimetric measurement of energy released in EC decay of $^{163}$Ho using Transition Edge Sensors (TES), successor of MARE effort
- **NuMECS**: similar experimental approach as HOLMES
KATRIN experiment at KIT

- Tritium source
  - \( ^3\text{H} \) \( \beta \) decay
  - \( \bar{\nu}_e \)
  - \( 10^{10} \text{ e}^- / \text{s} \)
  - \( ^3\text{He} \)
  - \( E = 18600 \text{ eV} \)

- Transport section
  - \( \text{e}^- \)
  - \( 10^{10} \text{ e}^- / \text{s} \)
  - \( 10^3 \text{ e}^- / \text{s} \)

- Pre-Spectrometer
  - \( E > 18.3 \text{ keV} \)
  - \( \Delta E = 0.92 \text{ eV} \)

- Spectrometer

- Detector
  - \( \text{e}^- \)
  - 1 e\(^-\) / s

- 70 m
- adiabatic transport $\rightarrow \mu = \frac{E_\perp}{B} = \text{const.}$
- $B$ drops by $2 \cdot 10^4$ from solenoid to analyzing plane $\rightarrow E_\perp \rightarrow E_\parallel$
- only electrons with $E_\parallel > eU_0$ can pass the retardation potential
- Energy resolution $\Delta E = E_{\perp,\text{max, start}} \cdot \frac{B_{\text{min}}}{B_{\text{max}}} < 1 \text{ eV}$

A. Picard et al., NIM B 63 (1992)
Windowless Gaseous Tritium Source

- Beam tube: \( \varnothing = 9 \text{ cm} \), \( L = 10 \text{ m} \)
- Guiding field: 3.6 T
- Temperature: \( T = 30 \text{ K} \pm 30 \text{ mK} \)
- \( \text{T}_2 \) flow rate: \( 5 \cdot 10^{19} \) molecules/s (40 g of \( \text{T}_2 / \text{day} \))
- \( \text{T}_2 \) purity: 95\% \pm 0.1 \%
- \( \text{T}_2 \) inlet pressure: \( 10^{-3} \text{ mbar} \pm 0.1 \% \)
- Column density: \( 5 \cdot 10^{17} \text{ } \text{T}_2/\text{cm}^2 \)
- Luminosity: \( 1.7 \cdot 10^{11} \text{ Bq} \)

WGTS at Tritium Laboratory Karlsruhe
Pumping sections

Differential Pumping Section (DPS2-F)
- magnetic guiding field $B = 5.6$ T
- differential pumping using 2000 l/s TMPs
  $\rightarrow$ tritium reduction factor: $1 \cdot 10^5$
- ion monitoring by FTICR
- ion manipulation by electrodes

Cryogenic Pumping Section (CPS)
- magnetic guiding field $B = 5.6$ T
- cryosorption of $T_2$ on Ar frost at $\approx 3$ K
  $\rightarrow$ tritium reduction factor $1 \cdot 10^{-7}$
- within 60 days: accumulation of 1 Ci
Main-Spectrometer

- 18.6 kV retardation voltage, $\sigma < 60$ meV
- 0.93 eV resolution
- pressure $< 10^{-11}$ mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping

$\sigma_E = 50$ meV
(single angular emittance)
Focal Plane Detector

Focal plane detection system

- segmented Si PIN diode: 90 mm Ø, 148 pixels, 50 nm dead layer
- energy resolution ≈ 1 keV
- pinch and detector magnets up to 6 T
- post acceleration up to 30kV
- active veto shield

pre-amplifier wheel

detector magnets at KIT

segmented Si-PIN wafer
Beam line commissioning

Technical start of KATRIN: „1st light“, photo-electrons from rear wall & and ions

Testing complete 70m long beamline with electrons:
- alignment
- magn. steering of pencil beam

and with ions:
- ion removal

no tritium yet
July 2017: calibration and commissioning campaign using gaseous, condensed and implanted $^{83m}\text{Kr}$ sources

$^{83m}\text{Kr}$ from 1 GBq $^{83}\text{Rb}$ source

→ quasi-monoenergetic electron lines between 7 keV and 32 keV
July 2017: calibration and commissioning campaign using gaseous, condensed and implanted $^{83m}$Kr sources

- Condensed $^{83m}$Kr source, point-like, can be scanned over full flux tube
- Implanted $^{83}$Rb/$^{83m}$Kr

Preliminary, small part of statistics only!
1. Inelastic scattering of β´s in the source (WGTS)
   - calibration measurements with e-gun necessary
   - deconvolution of electron energy loss function

2. Fluctuations of WGTS column density (required < 0.1%)
   - rear wall detector, Laser - Raman spectroscopy,
     T=30K stabilization, e-gun measurements

3. Transmission function
   - spatially resolved e-gun measurements

4. WGTS charging due to decay ions (MC: \( \phi < 20 \text{mV} \))
   - Injection of low energy (meV) electrons from the
     rear end, diagnostic tools available

5. Final state distribution
   - reliable quantum chem. calculations

6. HV stability of retarding potential on 3ppm level required
   - precise HV-Divider (PTB), monitor spectrometer, calibration sources

\[ \Delta m^2 = -2 \sigma^2 \]

fluctuations \( \sigma^2 \) lead to a downward shift in \( m^2 \)

allow only few contributions with
\[ \Delta m^2 \leq 0.007 \text{ eV}^2 \]

\[ \frac{\Delta U}{U} = \frac{0.06}{18575} \approx 3 \cdot 10^{-6} \]

\[ \Rightarrow 3 \text{ ppm long term stability} \]
1. Inelastic scattering of $\beta$´s in the source (WGTS)
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KATRIN sensitivity:
5 year measurement (eff. 3 y of data)

- statistical uncertainty
- systematic uncertainty

$\rightarrow$ sensitivity for upper limit: $0.2 \text{ eV/c}^2$ (90% C.L.)
$m(\nu_e) = 0.35 \text{ eV}$ observable with $5\sigma$

- fluctuations $\sigma^2$ lead to a downward shift in $m^2_{\nu}$

$\Delta m^2_{\nu} = -2 \sigma^2$

- $\sigma_{\text{stat}} \approx 0.018 \text{ eV}^2$
- $\sigma_{\text{sys,tot}} \approx 0.017 \text{ eV}^2$

$\frac{\Delta U}{U} = \frac{0.06}{18575} \approx 3 \cdot 10^{-6}$
$\Rightarrow 3$ ppm long term stability
Project 8: measuring energy by radiation

Measurement of coherent cyclotron radiation of tritium $\beta$ electrons

- Source similar to KATRIN: guiding magnetic field + low pressure $T_2$ gas

- $\beta$ electrons radiate coherent cyclotron radiation with frequency:
  \[
  \omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E_k + m_e}
  \]

- Antenna array for cyclotron radiation detection

B. Monreal and J. Formaggio, PRD 80:051301, 2009

UW (Seattle), MIT, UCSB (Santa Barbara), Yale, Pacific NW, Livermore, NRAO, KIT
Phase 1: detecting single electrons from $^{83\text{m}}\text{Kr}$

Prototype for $^{83\text{m}}\text{Kr}$ measurements

- $^{83\text{m}}\text{Kr}$ moving within a waveguide
- Cyclotron radiation picked up by cascaded cryogenic low noise amplifiers
- B-field: 1 Tesla
- $\omega(18 \text{ keV}) \sim 26 \text{ GHz}$
- $P(18 \text{ keV}) = 1.2 \text{ fW}$
Phase 1: detecting single electrons from $^{83m}$Kr

First detection of cyclotron radiation from a single trapped electron


Phase 2: start of tritium spectroscopy

Project 8 outlook:

- $^3$He spectroscopy with Project 8 should enable a similar or slightly better sensitivity as with KATRIN (assuming $10^{11}$ molecules/cm$^3$, 10 m$^3$ sensitive volume and 1 year measuring time optimistically 100 meV could be reached)

- Need to consider new systematics (Doppler shift, magnetic field drifts/inhomogeneities, scattering, pile-up, ...) → lots of R&D work necessary!

- If a large (100 m$^3$) atomic tritium source could be realized sensitivities down to 40 meV might be possible (see A. A. Esfahani et al., J. Phys. G 44 (2017) 5)
Electron capture in $^{163}\text{Ho}$

$^{163}_{67}\text{Ho} \rightarrow ^{163}_{66}\text{Dy}^* + \nu_e$

$^{163}_{66}\text{Dy}^* \rightarrow ^{163}_{66}\text{Dy} + E_C$

- $^{163}\text{Ho}$ decays by electron capture (EC) with $T_{1/2} \approx 4570$ y
  (2 x $10^{11}$ atoms for 1 Bq)

- Atomic de-excitation by:
  - X-ray emission
  - Auger electrons
  - Coster-Kronig transitions

- A non-zero neutrino mass affects the de-excitation energy spectrum

$Q_{EC} = 2.8$ keV
Calorimetric measurements

Calorimetric measurement:
All the energy released in the electron capture process minus the one of the electron neutrino is measured by the detector

Advantages:
- Source = detector
- All energy is detected

Challenges:
- Sufficient and clean isotope production
- $\Delta E_{FWHM} < 10$ eV
- $\tau_{\text{risetime}} < 1$ μs
- Multiplexed read-out of a large number of detectors

To reach sub-eV sensitivity:
$10^{14}$ decays in 1 year
10 Bq / detector $\rightarrow 10^5$ detectors
ECHO: Electron Capture $^{163}$Ho Experiment

- Measurement of de-excitation energy using Metallic Magnetic Calorimeters (MMC)
  \[ \Delta \Phi_s \propto \frac{\partial M}{\partial T} \Delta T \rightarrow \Delta \Phi_s \propto \frac{\partial M}{\partial T} \frac{E}{C_{\text{sens}} + C_{\text{abs}}} \]
- Operated at 30 mK
- Rise Time ~ 130 ns
- $E_{\text{FWHM}} = 7.6$ eV @ 6 keV (2013)
- Non-Linearity < 1% @ 6keV

Heidelberg (Univ., MPI-K), U Mainz, U Tübingen, TU Dresden, U Bratislava, INR Debrecen, ITEP Moscow, PNPI St Petersburg, IIT Roorkee, Saha Inst. Kolkata

courtesy L. Gastaldo
Current status of ECHO

- High purity $^{163}$Ho source has been produced
- $^{163}$Ho ions have been successfully implanted in offline process
  - @ISOLDE-CERN in 32 pixels
  - @RISIKO in 8 pixels
  - @RISIKO in 64 pixels
- Large MMC arrays have been tested and microwave SQUID multiplexing has been successfully demonstrated
- Independent Q-value measurement:
  $$ Q_{EC} = (2.858 \pm 0.010_{\text{stat}} \pm 0.05_{\text{syst}}) \text{ keV} $$


courtesy L. Gastaldo
Prove scalability with medium large experiment **ECHO-1K (2015-2018)**

- total activity 1000 Bq, high purity $^{163}$Ho source (produced at reactor)
  - $\Delta E_{FWHM} < 5$ eV
  - $\tau_{rise} < 1$ µs
- multiplexed arrays
  → microwave SQUID multiplexing
- 1 year measuring time
  → $10^{10}$ counts
  → neutrino mass sensitivity $m < 10$ eV

**Future: ECHO-10M** for sub-eV sensitivity

In addition: high energy resolution and high statistics $^{163}$Ho spectra allow to investigate the existence of **sterile neutrinos** in the eV-scale and keV-scale

courtesy L. Gastaldo
HOLMES: EC experiment with TES readout

- $^{163}\text{Ho}$ implanted in Au absorber with transition edge sensor (TES) readout
- Frequency multiplexing approach for readout of multi-pixel detector
  - Custom chip $\mu$MUX17A
  - 33 resonances in 500 MHz interval with a width of 2 MHz and 14 MHz separation
- Sampling frequency 400 kS/s
- Energy resolution at endpoint $\Delta E_0 = 4$ eV
- Rise time 35 $\mu$s, decay time 141 $\mu$s

Project status

- TES array and DAQ ready
- Ion implanter setup in progress
- First $^{163}\text{Ho}$ implantation coming shortly
- First spectrum late in 2017

→ 32 pixels for 1 month
→ $m_\nu$ sensitivity $\approx 10$ eV

Courtesy A. Nucciotti
Summary

- Studies of $\beta$-decay kinematics offer a model-independent way to determine the neutrino mass, complementary to cosmology and $0\nu\beta\beta$ searches

- Besides neutrino mass the experiments in preparation are also sensitive to sterile neutrinos

- KATRIN will probe the neutrino mass range down to 0.2 eV

- Start of tritium data taking with KATRIN: June 2018

- Calorimetric experiments (ECHO, HOLMES) will provide an independent look at kinematic neutrino mass limits. The scalable approach and further R&D work will allow to reach a competitive level of sensitivity.

- New ideas and a lot of R&D work are required to go beyond 100 meV!