Neutrino mass measurement with the KATRIN experiment

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Prague ν13, 24 May 2013

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Neutrino mass:

Particle physics: mass generation mechanism (fermion mass theory?)
Cosmology: contribution to matter density, model input

SM: left-handed and massless neutrinos

Neutrino oscillation experiments (solar, atmospheric, reactor, accelerator):
non-zero mass-squared differences \(\rightarrow\) at least two neutrinos have non-zero masses

No information about absolute mass scale from neutrino oscillation experiments
Indirect neutrino mass determination

Cosmology, neutrinoless double beta decay:

Sensitive to absolute neutrino mass scale (even below 0.1 eV possible in future)
But: model dependent

Example for $0^0\text{νβ}$:

It could be that the light massive neutrino mechanism is subdominant. Dominant mechanism could be f.e.: R-parity violating supersymmetry, right-handed couplings, leptoquark exchange, etc.

In that case neutrinoless double beta decay experiments give only upper limits for the absolute neutrino mass scale.

Also: sensitive to Dirac and Majorana phases $\rightarrow$ cancellation possibility
Direct neutrino mass experiments

Electron energy spectrum close to endpoint of single beta decay:

\[ w(E_e) \sim E_e p_e E_{\nu} p_{\nu} \]
\[ \sim E_e p_e (E_0 - E_e) \sqrt{(E_0 - E_e)^2 - m_{\nu}^2} \]

\[ T_2 (E_0=18.6 \text{ keV}): \]

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Electron energy spectrum with general neutrino mixing:

$$\nu_e = \sum_i U_{ei} \nu_i$$

$$w(E_e) \sim E_e \rho (E_0 - E_e) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m_{\nu i}^2} \Theta(E_0 - E_e - m_{\nu i})$$

3 active neutrinos: small $\Delta m_{\nu}^2$

$\rightarrow$ effective electron neutrino mass definition:

$$m_{\beta}^2 = \sum_{i=1}^3 |U_{ei}|^2 m_{\nu i}^2$$

Not sensitive to phases!
KATRIN experiment

Absolute neutrino mass scale determination down to 0.2 eV, with small model dependence.

Integral electron energy spectrum measurement (MAC-E filter method), close to endpoint of molecular tritium beta decay.

\[ {^3}\text{H}: \text{super-allowed} \]

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<table>
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<tbody>
<tr>
<td>( E_0 )</td>
<td>18.6 keV</td>
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<tr>
<td>( t_{1/2} )</td>
<td>12.3 yr</td>
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KIT (Karlsruhe Institute of Technology) campus north, Germany

KATRIN: at TLK (Tritium Laboratory Karlsruhe)

Collaboration:
Germany, USA, Russia, Czech Republic, Great Britain

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Advantages of tritium:

- **Superallowed transition:** matrix element $M$ is not energy dependent
- **Low endpoint energy:** relative decay fraction at the endpoint is comparatively high
- **Short half life:** specific activity is high, low amount of source material, low fraction of inelastic scattered electrons
- **Hydrogen isotope:** simple atomic shell, final states precisely calculable
Status of previous tritium experiments

Mainz & Troitsk have reached their intrinsic limit of sensitivity

Troitsk
windowless gaseous $T_2$ source
analysis 1994 to 1999, 2001

$$m_V^2 = -2.3 \pm 2.5 \pm 2.0 \text{ eV}^2$$
$$m_V \leq 2.2 \text{ eV (95\% CL.)}$$

Mainz
quench condensed solid $T_2$ source
analysis 1998/99, 2001/02

$$m_V^2 = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2$$
$$m_V \leq 2.2 \text{ eV (95\% CL.)}$$

Goal of KATRIN: factor 10 improvement
Simple energy spectrum measurement method

Problems:

- no electron detector with 1 eV resolution
- extremely large rate
The $\beta$-Spectrum of $\text{H}^3$

G. C. Hanna and B. Pontecorvo

Chalk River Laboratory, National Research Council of Canada,
Chalk River, Ontario, Canada

January 28, 1949

The proportional counter technique previously described$^{1,2}$ has been used to study the $\beta$-spectrum of $\text{H}^3$ an investi-

![Graph showing a "Kurie" plot of the end of the $\text{H}^3$ spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.]

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Integral energy spectrum measurement with spectrometer at negative potential between source and detector
Measured number of events: $N_1, N_2, N_3, \ldots \rightarrow$ integral spectrum; neutrino mass determination by fit
Integral energy spectrum measurement with spectrometer at negative potential between source and detector

**Problem:**

Tritium beta decays inside and beyond the negative potential region (no material window allowed between source and spectrometer: energy loss!)

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Reducing the tritium flow into the spectrometer by differential pumping system (large distance between source and spectrometer)

Problem: Most of the beta decay electrons do not get to detector (small solid angle)
Guiding the beta electrons by magnetic field

Electrons follow the magnetic field lines (in adiabatic approximation)

Problem:

Electric field can change only the longitudinal energy
→ most of the electrons with larger transversal energy do not get to detector

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Converting the transversal energy into longitudinal energy by inverse magnetic mirror effect

Adiabatic approx.: orbital magnetic moment $E_{\text{trans}} / B$ is constant

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principle of an electrostatic filter with magnetic adiabatic collimation (MAC-E)

-18.56 kV

Adiabatic guiding of electrons along magnetic field lines

Energy analysis: electric field can change longitudinal energy

Conversion of transversal energy into longitudinal: by inverse magnetic mirror effect

Constant magnetic flux, Bmin small: large spectrometer diameter (10m)

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Flux tube: defined by magnetic field lines going through the source

Magnetic flux constant in flux tube:

\[ d_s^2 B_s = d_A^2 B_A \]

KATRIN: \[ \frac{B_s}{B_A} \approx 10000 \]
\[ d_s = 9 \text{ cm} \quad d_A = 9 \text{ m} \]

MAC-E filter: high energy resolution (no tail at the low energy part), high luminosity, low background

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gaseous T2, 30 K

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KATRIN setup

- CMS
- tritium source
- transport and pumping section
- pre-spectrometer
- main spectrometer
- detector

Electrons

B-field [T]

magnetic field

65 coils

Electric potential [kV]

-18.3 kV

0 V

-18.6 kV

distance from analysing plane [m]

-40 -30 -20 -10 0 +10

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WGTS
Windowless Gaseous Tritium Source

7 sc. magnet modules (3.6 T, 5.6 T); axisymmetric + dipole coils
12 turbomolecular pumps
Tritium gas temperature: 30 K
Tritium purity: > 95 %
Column density: $5 \times 10^{17}$ mol/cm$^2$
Beta decay rate: $10^{11}$/s
WGTS – magnetic field

Differential pumping

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WGTS Demonstrator at KIT-TLK: to test cooling concept (without sc magnets)  
Temperature stability: 3 mK  
(requirement: 30 mK)

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Plasma effects

Beta decay and ionization:

\[ T_2 \rightarrow (^3HeT)^+ + e^- + \bar{\nu}_e \]
\[ e_p^- + T_2 \rightarrow e_p^- + e_s^- + T_2^+ \]
\[ e_p^- + T_2 \rightarrow e_p^- + e_s^- + T^+ + T \]

From simulation: secondary electrons cool down to gas temperature \( \rightarrow \) average electron energy: few meV \( \rightarrow \) space charge potential cannot be much larger than few mV \( \rightarrow \) systematic effect to neutrino mass probably not significant

Experimental information:

- \(^{83}\text{m}\text{Kr}\) in tritium source (change of Kr lines due to plasma effects)
- e- gun electrons through tritium source (change of energy due to plasma instabilities)
Pre-spectrometer

- Optimize the background by its potential
- Additional tritium pump
- Prototype for main spectrometer (important !)

Delivered : 2003  
Length: 3.4 m, diameter: 1.5 m

First measurements: 2006

Sc. magnet max.  
4.5 T
First pre-spectrometer measurements:

**Strong Penning discharge:**
- increasing magnetic field $\rightarrow$
- pressure and leakage current increase, electric breakdown

Caused by deep (few kV) Penning traps

Eliminating the Penning traps (by a new shielding electrode)
$\rightarrow$ strong Penning discharge disappeared!

Measurements with detector: large background (few 100 Hz)
at high magnetic field

Caused again by Penning traps (at the ground electrode, few mm dimensions)

New ground electrode: no Penning traps $\rightarrow$ background reduction by factor 100000!
Background from radon decays

- Background from high energy stored electrons
- High energy electrons come from Rn decays
- Rn comes from getter

Background reduction (from few 10 mHz to few mHz):
- Removing getter from pump ports
- Cooled baffle, preventing radon transport from getter into spectrometer
Baffle Setup at Pre-Spectrometer

Radon emanating from the getter freeze to the cold surface of the Baffle

with liquid nitrogen cooled surface

no line of sight between pump and vacuum chamber

Baffle

PRE-Spectrometer vessel

NEG-Pump

219Rn

45° pump port

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Background in pre-spectrometer with warm baffle

Background in pre-spectrometer with cold baffle
KATRIN main spectrometer
24 m long, 10 m diameter, stainless steel: 3 cm thick, 200 t. Vacuum inside: $10^{-11}$ mbar.
Air coils

earth magnetic field compensation coils

axisymmetric air coils
Flux tube magnetic field lines without air coils:
shift of field lines due to earth magnetic field

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Flux tube magnetic field lines without axisymmetric air coils, but with earth magnetic field compensation: axisymmetric air coils are also needed.
Flux tube magnetic field lines with axisymmetric air coils and with earth magnetic field compensation

aircoil amperturns:


flux tube, 190 Tcm²

main spectrometer

detector

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Aim of air coils:

- to optimize the axisymmetric magnetic field inside the tank (field of supercond. coils alone is not optimal for electron transmission)
- to compensate the earth magnetic field

low field coil system (LFCS)
earth magnetic field compensation system (EMCS) → cosine coil system

12.6 m
24 m
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Electric shielding with wire electrodes: background reduction

Wires more negative than tank → small energy secondary electrons are reflected by the wires

Wires:
- 0.2 and 0.3 mm diameter
- total length: 42 km
- tank surface: 700 m²

Σ = 248 modules (+ spares)

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Wire modules:
University of Münster

Scaffolding:
KIT

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Detector system

Assembled and commissioned:
University of Washington, Seattle

Focal-Plane detector:

- segmented Si-PIN diode array (148 pixels: to record radial and azimuthal profile of signal and background electrons)
- energy resolution: 1.5 keV
- minimal electron energy: 5 keV
- detector region background: few mHz possible (with muon veto: MIT)
Detector system installed near main spectrometer

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Wire electrode installation ready, main spectrometer vessel was baked up to 300 °C (Jan. 2013).

Main spectrometer commissioning experiments start next week

- first background experiments with low potential
- electron transmission experiments (with egun)
- radon background with warm and cold baffle; removing stored electrons by electric dipole field and magnetic pulse (fast decrease of magnetic field)
- high voltage experiments (field emission, Penning discharge, background from secondary electron emission)
Variation of the retarding potential in main spectrometer

Unaccounted variation of the analyzing plane potential in middle of the main spectrometer $\rightarrow$ shift of measured neutrino mass squared

$$\Delta m^2_{\nu} = -2\sigma_{\Delta U}^2 \quad \Delta U = U_A - U_S$$

$U_A, U_S$ : analyzing plane and source potentials

better than 60 mV stability of analyzing plane potential is required during spectrum scanning

Absolute value of the analyzing plane potential is not critical (since endpoint is free parameter)
Retarding potential monitoring:

- direct voltage measurement (18 kV → 10 V by high-precision voltage divider)
- direct calibration of analyzing plane potential of main spectrometer, with conversion electrons from $^{83m}$Kr or photoelectrons from $^{241}$Am/Co source; not possible during data taking
- main spectrometer potential connected to monitor spectrometer; continuous calibration of monitor spectrometer potential by photoelectron or conversion electron sources

Quench condensed Kr source, high-precision voltage divider:
Münster (group of Ch. Weinheimer)

$^{241}$Am/Co source: Rez, group of O. Dragoun
Precise monitoring of the main spectrometer energy scale:
precise measurement of retarding potential
+ comparison to reference energy

Mainz spectrometer modified to 1 eV resolution

Monitor Spectrometer

β-particles

pre spectrometer

main spectrometer

detector

HV-supply

monitor spectrometer (magnified)

reference source of nuclear or atomic transition

reference detector

voltage divider/voltage measurement
A window to work in

Molecular Excitations

Saenz et al. PRL 84, 242

Rovibrational Structure of Ground State

First Electronic Excitation

Energy loss function

quench condensed $D_2$

Mainz

gaseous $T_2$, Troitsk

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

energy loss $\varepsilon$ [eV]

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Simulation codes

Various C and C++ codes

Standard C++ simulation package of KATRIN: KASSIOPEIA

- relativistic charged particle tracking: 8th order Runge-Kutta
- electric field calculations: BEM, direct and iterative solvers, zonal harmonic expansion
- magnetic field: zonal harmonic expansion, elliptic integrals, integrated Biot-Savart
- gas flow
- various statistical simulation methods
After 3 years data (5y realtime):

discovery potential
\[ m(\nu) = 0.35 \text{ eV (5}\sigma) \]
sensitivity (90\% CL)
\[ m(\nu) < 0.2 \text{ eV} \]

Planned start of data taking with tritium: 2015
Sterile neutrinos: chiral right-handed singlets, no weak interaction

But they can mix with left-handed active neutrinos (if massive)

LSND anomaly: short-baseline $\bar{\nu}_e$ appearence from $\bar{\nu}_\mu$ beam

Reactor antineutrino anomaly: short-baseline detected $\bar{\nu}_e$ rate smaller than calculated rate

Gallium anomaly: detected $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$ rate from artificial $\nu_e$ EC sources ($^{51}\text{Cr}, ^{37}\text{Ar}$) smaller than calculated rate

large mixing: $\sin^2(2\theta) \approx 0.1$

large masses: $\Delta m^2 > 1 \text{ eV}^2$
\[ \nu_e = \sum_{i=1}^{3} U_{ei} \nu_i + U_{e4} \nu_4 \]

\[ \sum_{i=1}^{3} |U_{ei}|^2 = \cos^2(\theta) \]

\[ |U_{e4}|^2 = \sin^2(\theta) \]

\[ \frac{dN}{dE} = K' F(E,Z) \rho E_{\text{tot}} (E_0-E_e) \left( \cos^2(\theta) \sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta) \sqrt{(E_0-E_e)^2 - m(\nu_4)^2} \right) \]

- **e.g. sterile neutrino**
  - \( m(\nu_4) = 2 \text{ eV} \)
  - \( \sin^2(\theta) = 0.3 \)

- **e.g. active neutrinos**
  - \( m(\nu_{123}) \approx 0 \text{ eV} \)
  - \( \cos^2(\theta) = 0.7 \)
KATRIN 90 % exclusion possibility for light sterile neutrino above the yellow line

allowed regions from reactor antineutrino fits

Riis, Hannerstad, JCAP 1102 (2011) 011
Formaggio, Barrett, PLB 706 (2011) 68
Esmaili, Peres, arXiv 1203.2632
Warm dark matter (WDM) and keV sterile neutrinos

- $\nu_L$, hot dark matter
- $\nu_R$, warm dark matter candidate
- $\tilde{\chi}_0$, cold dark matter candidate

- $1$ eV
- $1$ keV
- $1$ TeV

- $\lambda_{\text{free}}$, $1$ Gpc
- $10$ kpc
- $1$ pc
Some problems with CDM (e.g.: too many satellite dwarf galaxies predicted)

keV mass sterile neutrinos: possible WDM candidates

Predictions: \textbf{mass:} 1-15 keV, \textbf{mixing angle:} \sin^2 \Theta_s < 10^{-7}
Tritium beta decay spectrum with sterile neutrino (example)

\[ \frac{dN}{dE_e} \propto \sum_i |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m_{v_i}^2} \cdot \Theta(E_0 - E - m_{v_i}) \]

\[ \propto \cos^2(\theta) \frac{dN}{dE_e}(m_{v_{light}}) + \sin^2(\theta) \frac{dN}{dE_e}(m_{v_{heavy}}) \]

\[ \sin^2 \theta_s = 0.1 \]

\[ m_s = 10 \text{ keV} \]
KATRIN statistical 90 % exclusion possibility for WDM sterile neutrino

Sterile neutrino mass (eV) vs. $\sin^2 \Theta_s$

Allowed region from astrophysics

Systematics ???

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Summary

• absolute neutrino mass scale determination: important task for particle physics and cosmology
• KATRIN: direct, model independent absolute neutrino mass scale determination by electron energy spectrum measurement of tritium $\beta$ decay
• Spectrometer method; gaseous tritium source far from detector; magnetic guiding; integral spectrum (MAC-E filter); high statistics, high resolution, small background; complicated system; data taking start: not before 2015
• goal: 0.2 eV neutrino mass limit (90 % CL)
• possibility of light and WDM keV sterile neutrino detection
Egun:

- electrons with sharp energy and angular distribution
- transmission function measurements
- source thickness monitoring
- plasma effects

Rear wall:

- source potential definition and stabilization
- source activity monitoring
- gold-plated
Advantages of tritium:

- Superallowed transition: matrix element $M$ is not energy dependent
- Low endpoint energy: relative decay fraction at the endpoint is comparatively high
- Short half life: specific activity is high, low amount of source material, low fraction of inelastic scattered electrons
- Hydrogen isotope: simple atomic shell, final states precisely calculable

Final state distribution calculation is needed for differential spectrum of $T_2$ decay:

$$w_{diff}(E) = \sum_j W_j \cdot E_{\nu j} \sqrt{E_{\nu j}^2 - m_\nu^2}$$

$$E_{\nu j} = E_0 - V_j - E$$

(assuming degenerate neutrino masses)

Ground state probability: 0.57

mean: 1.7 eV

$\sigma = 0.4$ eV
WGTS demonstrator

- beam tube cooling system: $T_{BT} = 28-32$ K
  $\Delta T = \pm 30$ mK - stability (1h) & homogeneity

- initial stability results: proof-of-principle ✓

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<tr>
<th>Parameter</th>
<th>$\Delta T$ (4h)</th>
<th>$\Delta T$ (24h)</th>
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<tbody>
<tr>
<td>peak-to-peak variation</td>
<td>3 mK</td>
<td>9 mK</td>
</tr>
<tr>
<td>standard deviation $\sigma_t$</td>
<td>1.4 mK</td>
<td>3.6 mK</td>
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- implications: $\Delta T_{BT} \ll 10^{-3}$, $\Delta p_{in} < 10^{-3}$
  - super-stable $\beta$-emitting source
  - reduced systematics from source
  - demonstrator $\Rightarrow$ WGTS cryostat (2013)
WGTS
Windowless Gaseous Tritium Source

• T² gas:
  - high luminosity and high stability
  - differential pumping (TMPs); closed tritium loop
  - high tritium purity; measurement of T², DT etc. isotopic composition (with Laser Raman spectroscopy)

• Homogeneous magnetic field and adiabatic guiding of electrons

• Systematic effects for neutrino mass: as small as possible

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Focal Plane Detector System

VACUUM, CALIBRATIONS

PINCH MAGNET 6T

electrons

VETO, SHIELD (Cu/Pb)

detector magnet

ELECTRONICS

POST-ACCELERATION ELECTRODE

DETECTOR MAGNET 3.6 – 6T

SUPPORT STRUCTURE

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Tritium retention: DPS1-F, DPS2-F and CPS

Only very small amount of tritium allowed to enter the main spectrometer (background !)

WGTS DPS CPS

DPS1-F

R ≈ 10^2

R ≈ 10^5

R > 10^7

DPS
differential pumping section

CPS
cryogenic pumping section

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First test experiments at KATRIN pre-spectrometer (end of 2006):

Tank and electrodes at -18 kV, increase of magnetic field; at 0.15 T

- increase of vacuum pressure from \(10^{-9}\) mbar to \(10^{-6}\) mbar

- increase of leakage current from 0.2 \(\mu\)A to few mA (limit of power supply)

- drop of high voltage from -18 kV down to -3 kV (electric breakdown)

Penning discharge!
Penning traps

Cathode-to-cathode magnetic field lines, potential penetration from anode (ground electrode)
Electric potential on various magnetic field lines at the entrance of pre-spectrometer
Solution of the Penning discharge problem in the pre-spectrometer

by shielding the Penning trap region against potential penetration from the anode by an additional electrode \(\rightarrow\) no deep Penning traps
After installation of the new electrodes (Sept 2007):

No pressure and leakage current increase, no electric breakdown (up to -30 kV, 4.5 T)

large Penning discharge disappeared!

It was then possible to start background measurements with the segmented PIN-diode detector.
Measurements at high (>2 T) magnetic field:

background:
order of few 100 Hz

Again Penning traps:
at the end ring of the ground electrode,
small dimensions (few mm)
Solution:
new ground electrode design, with detailed simulations, Penning traps eliminated

Using the new ground electrode:
Background decreased from few 100 Hz to few 10 mHz (factor 10000)

After reducing background from radon decays:
Background: few mHz (reduction factor of new ground electrode: 100000)
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