KATRIN-2017:
Background studies, sensitivity.

N.Titov, INR RAS
for the KATRIN Collaboration

International Session-Conference of SNP PSD RAS
"Physics of Fundamental Interactions"

Dedicated to 50th anniversary of Baksan Neutrino Observatory

Kabardino-Balkarian State University. June 6, 2017. Nalchik
Outline:

1. The 83-year long search for neutrino mass.
   - Tritium $\beta$-decay spectrum analysis – best choice
   - Era of Electrostatic Spectrometer with Adiabatic Magnetic Collimation (MAC-E filter)
     - New challenge: Project KATRIN
2. October 14, 2016 - KATRIN ”First light”
3. KATRIN background studies, new players:
   - Radon
   - Rydberg states
4. KATRIN sensitivity
   - Final state spectrum – new calculations
   - Current expectations
1934: Neutrino mass could be evaluated from nuclear $\beta$- decay spectrum
1948: First experiment with tritium

\[ T \rightarrow ^3\text{He} + e^- + 18.6\text{ keV} \]

\[ m_\nu < 1\text{ keV/c}^2 \]

Hanna G.C. and Pontecorvo B., Phys. Rev. 75 (1949) 983
1983: Electrostatic spectrometer with adiabatic magnetic collimation „Troitsk ν-mass” experiment

Petr Spivak
24.03.1911 - 30.03.1991

Vladimir Lobashev
29.07.1934 – 3.08.2011

Electrostatic spectrometer with adiabatic magnetic collimation

Charged particle in a slowly varying magnetic field moves \textit{adiabatically}.

- During transition into weaker magnetic field velocity vectors are aligned along the magnetic field – electrostatic analysis is applicable
- Spectrometer resolution is decoupled from the source dimensions
- Electrons from decay on the walls can’t reach detector
“Great minds think alike”

Mainz Neutrino Mass Experiment

Robert B. Moore
Physics Department,
McGill University
Montreal, Canada

Ernst Otten

Jochen Bonn
7.04.1944 – 27.08.2012
Physics Institute
Johannes Gutenberg University
Mainz, Germany

≈1998: New challenge:
Mainz and Troitsk reached their limits but it is possible to improve neutrino mass limit by another order of magnitude.

Confirm or excludes quasi-degenerate mass regime

Test cosmological neutrino mass limit
Forschungszentrum Karlsruhe

Tritium laboratory with license for 40g of Tritium
2001: Workshop at Bad Liebenzell

5 groups from 4 countries:
  •Karlsruhe
  •Mainz
  •Troitsk
  •Seattle
  •NPI Rezz near Prague

Letter of Intent

KATRIN: A next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass

A. Osipowicz$^a$, H. Blümer$^{b,f}$, G. Drexlin$^b$, K. Eitel$^b$, G. Meisel$^b$, P. Plischke$^b$, F. Schwamm$^b$, M. Steidl$^b$, H. Gemmeke$^c$, C. Day$^d$, R. Gehring$^d$, R. Heller$^d$, K.-P. Jüngst$^d$, P. Komarek$^d$, W. Leemann$^d$, A. Mack$^d$, H. Neumann$^d$, M. Noe$^d$, T. Schneider$^d$, L. Dörr$^e$, M. Glugla$^e$, R. Lässer$^e$, T. Kepecija$^f$, J. Wolf$^f$, J. Bonn$^g$, B. Bornschein$^g$, L. Bornschein$^g$, B. Flatt$^g$, C. Kraus$^g$, B. Müller$^g$, E.W. Otten$^g$, J.-P. Schall$^g$, T. Thümmler$^g$, C. Weinheimer$^g$, V. Aseev$^h$, A. Belesev$^h$, A. Berlev$^h$, E. Geraskin$^h$, A. Golubev$^h$, O. Kazachenko$^h$, V. Lobashev$^h$, N. Titov$^h$, V. Usanov$^h$, S. Zadoroghny$^h$, O. Dragoun$^i$, A. Kovalik$^i$, M. Ryšavý$^i$, A. Špalek$^i$, P.J. Doe$^j$, S.R. Elliott$^j$, R.G.H. Robertson$^j$, J.F. Wilkerson$^j$
2001: Project KATRIN

Co-spokesperson
Prof. Dr. Guido Drexlín
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Institut für Experimentelle Kernphysik

First Head of collaboration board
Prof. Dr. Johannes Blümer
Director of the Institute for Nuclear Physics
Karlsruhe Institute of Technology

Co-spokesperson
Prof. Dr. Christian Weinheimer
Universität Münster
Institut für Kernphysik
Among KATRIN senior fellows

Prof. Dr. Hamish Robertson  
Center for Experimental Nuclear Physics and Astrophysics, CENPA  
University of Washington, Seattle, WA, USA

Prof. John Wilkerson  
Department of Physics and Astronomy  
University of North Carolina, NC, USA

**Limit on \( \bar{\nu}_e \) Mass from Observation of the \( \beta \) Decay of Molecular Tritium**

R. G. H. Robertson, T. J. Bowles, G. J. Stephenson, Jr., D. L. Wark, (a) and J. F. Wilkerson  
*Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*

D. A. Knapp  
*Physics Division, Lawrence Livermore National Laboratory, Livermore, California 94550*  
(Received 6 May 1991)

\[ m_\nu < 9.3 \text{ eV (95\% c.l.)} \]
Among KATRIN senior fellows
Rezz near Prague, Czech Republic

Drahoslav Vénos
Otokar Dragoun
Miloš Ryšavý
Alojz Kovalík
Antonín Špalek
KATRIN collaboration at 2015

**Collaboration:**
- 130 scientists
- 5 countries
- 14 institutions

**Experimental objective:**
- model-independent neutrino mass
- sensitivity: 0.2 eV/c²
- source: gaseous tritium (β-decay)
KATRIN collaboration at 2017

Collaboration:
- 130 scientists
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Experimental objective:
- model-independent neutrino mass
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- source: gaseous tritium (β-decay)
**KATRIN project**

**Main parameters:**

- Total installation length 70 m
- 40 superconducting solenoids
- Spectrometer diameter 10 m
- Inner source diameter 90 mm
- Source column density $5 \cdot 10^{17}$ mol/cm$^2$
- Total source activity $\approx 100$ GBk (3Ci)
- Resolution $\Delta E = 0.9$ eV at 18 keV
- Neutrino mass sensitivity
  (after 3 years of data taking):
  \[ m_\nu < 0.2 \text{ eV}/c^2 \]
Electrons with 100 eV energy uniformly emitted from “Rear Wall” were detected by focal plane multipixel detector placed at the opposite end of installation at 70 m distance.
Background studies summary
(F. Fraenkle talk at CM 09.03.2016)
will be published soon
Radon induced background ($\approx 400$ mHz)

Fabian Harms talk at KATRIN CM, March 2017, will be published soon

KATRIN Main Spectrometer has about 100% detection efficiency for Rn decay when it happens in the volume.
Radon background was reduced by 97% after baffles at nitrogen temperature were installed in pumping ports.

Two known sources of Rn:

- $^{219}$Rn from NEG getter pump
  *Interception efficiency by cold baffles 97%*

- $^{220}$Rn from welding
  *excluded*
  *Interception efficiency by cold baffles 90%*
New type of background was observed

Observations:
1. Background is generated uniformly in spectr. volume.
2. Background rate is independent on vacuum level.

Long term puzzle:
A background exists that is generated by low energy (below 1 keV) electrons that appear in the center of spectrometer vessel. It was theoretically and experimentally proven that because of magnetic collimation electrons with such a low energy couldn’t be emitted from the vessel wall or any solid electrode.
206Pb-induced H*-Rydbergs – a coherent spectrometer background model

G. Drexlin at KATRIN CM, March 2016
will be published soon

Rydberg states act as long-lived neutral messengers from surface processes
KATRIN spectrometer surface is about 100 larger than in Mainz/Troitsk cases

A Rydberg atom is an excited atom with one or more electrons that have a very high principal quantum number \( n \), and \( r \sim n^2, E_{\text{ion}} \sim 1/n^3 \)

Thus Rydberg atom is extremely large with loosely bound valence electrons, easily perturbed or ionized by collisions or external fields (Wikipedia).
New observation method - a surface microscope by asymmetric B fields

G. Drexlin at KATRIN CM, March 2016

Large number of 2-hit cluster (20-50 electrons per event) [master A. Müller]

generation of Rydberg states H*
Rn-222 from forced spectrometer venting

G. Drexlin at KATRIN CM, March 2016

- Rn-222 decays in inner volume
- short-lived progenies decay to Pb-210
- complex transport (aerosols, electrostatic fields)

U-238 decay chain
Rb-210 deposition on inner surface

G. Drexlin at KATRIN CM, March 2016

- implantation: maximum depth of Pb-210 d < 40 nm [PhD F. Harms]
- incorporation into aerosols: sticking to inner surface

- $^{208}$Pb-decay on the wall was identified via conversion electrons

- Pb-210 implanted in stainless steel
- Pb-210 incorporated in aerosols
$^{206}\text{Pb}$ ions from $^{210}\text{Pb}$ chain

G. Drexlin at KATRIN CM, March 2016

- measured rate (in $2\pi$) $\sim A_{\text{Pb-210}} \sim (900 \pm 100) \text{ s}^{-1}$ [PhD F. Harms, 2015]
- $A_{\text{Pb-210}}$ upper limit for $A_{\text{Pb-206}}$: $^{206}\text{Pb}$ recoil ions with $E_{\text{kin}} < 100 \text{ keV}$

$^{206}\text{Pb}$ recoils

$^{206}\text{Pb}$ chain

$^{206}\text{Hg}$

$^{206}\text{Pb}$ $E_{\text{kin}} = 100 \text{ keV}$
Pb-ions are proposed to generate:
- low-energy electrons (E<1eV) with exponential multiplicity distribution
- large number of Rydberg H*-atoms (~100) & Fe, Ni, Cr, O atoms (~20)

Flat kinetic energy spectrum [SRIM] 0-100 keV, A. Osipowicz 2015
New Final States Spectrum calculations

Alejandro Saenz, Institute of Physics Humboldt-University of Berlin

Summary and outlook

- Cross-check of the old calculation using a completely new approach for both electronic and nuclear part.
- Automatized set-up for arbitrary isotope mixtures, temperatures, and fit ranges.

Outlook:

- Continue convergence studies $\rightarrow$ error estimate.
- Inclusion of non-adiabatic corrections for all states.
- Analysis of final molecular products/fragments (for TRIMS experiment).
- Energy loss (electron scattering).
- Consider non-$\Sigma$ states (non-adiabatic effects, recoil effect, corrections to sudden approximation).

Talk at KATRIN CM, March 2017
Will be published soon
Electronic part of the Final States Spectrum

Picture from
L. I. Bodine, D. S. Parno,
and R. G. H. Robertson
Phys. Rev. C 91, 035505

Calculations by
Saenz, S. Jonsell, and P. Froelich,
– red
O. Fackler, B. Jeziorski, W. Kolos,
H. J. Monkhorst, and K. Szalewicz,
– blue

$({}^3\text{HeT})^+$
Electronic part of the Final States Spectrum

Provided that calculation of Final States Spectrum electronic part is robust data analysis interval could be extended.
KATRIN sensitivity with increased background
240 meV (90% c.l.) after 3 years
(K. Valerius at “Neutrino – 2016”)

Background reduction measures were studied:
- optimized scanning strategy
- increased range of spectral analysis
- flux tube compression by increasing $B_{\text{analysis}}$

Background rate in mcps

sensitivity on $m_{\nu}$ in meV (90% C.L.)

- $E_0 = 30$ eV
- $E_0 = 45$ eV
- $E_0 = 60$ eV

558 mcps non-optimized

one option

$\Delta E \sim 2.5$ eV
Thank you for your attention!
Back up slides
$^{219}\text{Rn}$ vs $^{220}\text{Rn}$

Baffle efficiency
MolFlow+ simulations

G. Drexlin et al., Vacuum, Volume 138, Pages 165 – 172, 2017
Электростатический спектрометр с адиабатической магнитной коллимацией
Принцип работы

Высокое разрешение спектрометра не зависит от размера источника

\[ \Delta E = |eU_0| \frac{B_{\text{analyser}}}{B_{\text{pinch}}} \]
Электростатический спектрометр с магнитной адиабатической коллимацией
Фундаментальные основы

Критерий адиабатичности $\varepsilon$:

$$\varepsilon = \left| \frac{\text{grad}B}{B} \right| \frac{r_H}{B} \ll 1$$

или

$$\varepsilon = \frac{1}{\omega_H} \cdot \frac{B}{B} \ll 1$$

где $r_H, \omega_H$ – радиус и частота Ларморовской прецессии

Адиабатический инвариант сохраняется экспоненциально:

$$\frac{\Delta \mu}{\mu} \sim e^{-\frac{1}{\varepsilon}}$$

Л.А. Арцимович, Р.А. Сагдеев Физика плазмы для физиков. Атомиздат, 1979

При соблюдении критерия адиабатичности разрешение спектрометра не зависит от радиуса и кривизны траектории!
Установка «Троицк ню-масс»

Спектрометр
длина 6,5 м
диаметр электрода 1,2 м
разрешение 3,7 эВ
Диаметр источника 20 мм
tолщина 1·10^{17} моль/см²

Первые данные опубликованы в 1994 г:

The search for the neutrino mass by direct method in the tritium beta-decay and perspectives of study it in the project KATRIN

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The updated results of the search for neutrino mass in the tritium beta-decay on the Troitsk nυ-mass and Neutrino Mainz set-ups are presented. Both groups give an upper limit for the neutrino mass at 95% $m_\nu < 2.05 \text{ eV}/c^2$ in Troitsk and $m_\nu < 2.2 \text{ eV}/c^2$ in Mainz. Further improvement is limited both by statistic and systematic errors. In order to enter in the cosmologically important sub-electronvolt area the collaboration of groups from Karlsruhe Forschungszentrum, Mainz, Troitsk et al. proposed a new advanced project KATRIN. The status of the project is presented.