Absolute scale of the active neutrino mass and the search of sterile neutrinos at KATRIN

Ecole Internationale Daniel Chalonge

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• Introduction
• Direct neutrino mass search
• Search for sterile neutrinos in $\beta$-endpoint spectra
• Time-of-flight method and 1st tests at the KATRIN main spectrometer
• Conclusions
Positive results from $\nu$ oscillation experiments

**atmospheric neutrinos**
(Kamiokande, Super-Kamiokande, ...)

**accelerator neutrinos**
(K2K, T2K, MINOS, OPERA, MiniBoone)

**solar neutrinos**
(Homestake, Gallex, Sage, Super-Kamiokande, SNO, Borexino)

**reactor neutrinos**
(KamLAND, CHOOZ, Daya Bay, DoubleCHOOZ, RENO, ...)

$\Rightarrow$ non-trivial $\nu$-mixing

\begin{align*}
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} &=
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\end{align*}

with:

- $0.34 < \sin^2(\theta_{23}) < 0.64$ maximal!
- $0.26 < \sin^2(\theta_{12}) < 0.36$ large!
- $\sin^2(\theta_{13}) = 0.089 +/- 0.010 +/- 0.005$
- $7.0 \times 10^{-5} \text{ eV}^2 < |\Delta m_{12}^2| < 8.2 \times 10^{-5} \text{ eV}^2$
- $2.1 \times 10^{-3} \text{ eV}^2 < |\Delta m_{13}^2| < 2.7 \times 10^{-3} \text{ eV}^2$

$\Rightarrow m(\nu_j) \neq 0$, but unknown!
1) **Cosmology**

very sensitive, but model dependent
compares power at different scales
current sensitivity: $\Sigma m(\nu_i) \approx 0.5$ eV

2) **Search for 0$\nu$\(\beta\beta\)**

Sensitive to Majorana neutrinos
Evidence for $m_{ee}(\nu) \approx 0.3$ eV?
GERDA, EXO-200 & KamLAND-ZEN have 1$^{st}$ results!

3) **Direct neutrino mass determination:**

No further assumptions needed. no model dependence
use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly
most sensitive method: endpoint spectrum of $\beta$-decay
Double $\beta$ decay

normal ($2\nu\beta\beta$)  

neutrinoless ($0\nu\beta\beta$)

needed:  
a) $\bar{\nu} = \nu$ (Majorana)  
b) helicity flip: $m(\nu) \neq 0$

or other new physics
First results from GERDA phase 1

New background reduction methods:
- phase 1: 18 kg enriched Ge detectors in LAr
- phase 2: point contact detectors p-type (BEGe) to identify multi-side events and use scintillation of LAr shield as veto

GERDA I result, arXiv:1307.4720

\[ T_{1/2} > 2.1 \times 10^{25} \text{ yr} \ (90\% \ C.L.) \]
\[ T_{1/2} > 3.0 \times 10^{25} \text{ yr} \ (90\% \ C.L.) \] (using all \(^{76}\text{Ge}\) experiments)

\[ m_{\beta\beta} < 0.2 - 0.4 \text{ eV} \] (using all \(^{76}\text{Ge}\) experiments)
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:

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

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

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

$\Rightarrow$ Tritium $^3H$, ($^{187}\text{Re}$)
$\Rightarrow$ MAC-E-Filter
(or bolometer for $^{187}\text{Re}$)

E.W. Otten & C. Weinheimer

G. Drexlin, V. Hannen, S. Mertens,
Cryogenic bolometers with $^{187}\text{Re}$
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.: $1.7 \times 10^{-4}$

$M_{\nu}^2 = -141 \pm 211_{\text{stat}} \pm 90_{\text{sys}}$ 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)
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; $\tau_R \approx 250$ $\mu$s
- experimental setup for up to 8 arrays completed
- starting with 72 pixels in 2011
- up to $10^{10}$ events in 4 years $\rightarrow$ $\sim 4$ eV sensitivity

MARE-1 @ Genova
- R&D effort for Re single crystals on transition edge sensors (TES)
  $\rightarrow$ improve rise time to $\sim \mu$s and energy resolution to few eV
- large arrays ($=10^3$ pixels) for $10^4$-$10^5$ detector experiment
- high bandwidth, multiplexed SQUID readout
- also used with $^{163}$Ho loaded absorbers
**ECHO neutrino mass project: $^{163}$Ho electron capture with metallic magnetic calorimeters**

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

First $^{163}$Ho spectrum with MMC

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

courtesy L. Gastaldo
Tritium experiments: source $\neq$ spectrometer

MAC-E-Filter

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

$\Delta \Omega = 2\pi$

$B_{S_{\text{max}}}$  $B_{\text{min}}$  $B_{\text{max}}$  $B_D$

$T_2$ source  electrodes  detector

$\rho_e$ (without $E$ field)

$\Rightarrow$ sharp integrating transmission function without tails $\Rightarrow$

Magnetic Adiabatic Collimation + Electrostatic Filter
The KATRIN experiment at KIT

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

- very high energy resolution ($\Delta E \leq 1$ eV, i.e. $\sigma = 0.3$ eV)
  $\Rightarrow$ source $\neq$ spectrometer concept
- strong, opaque source
  $\Rightarrow$ $dN/dt \sim A_{\text{source}}$
- magnetic flux conservation (Liouville)
  $\Rightarrow$ scaling law:
  
  $A_{\text{spectrometer}} / A_{\text{source}} = B_{\text{source}} / B_{\text{spectrometer}} = E / \Delta E = 20000 / 1$

KATRIN Design Report
Scientific Report FZKA 7090)
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KATRIN Design Report
Scientific Report FZKA 7090)

windowless gaseous molecular tritium source

see dedicated talk by Guido Drexlin in open session

70 m
Electromagnetic design: magnetic fields

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

Requirements
- detection of β-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 (145 pixels)
  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities
KATRIN detector has been commissioned at KIT
Main spectrometer – transport to Karlsruhe Institute of Technology

Leopoldshafen, 25.11.06
Main spectrometer with air coil system
Wire electrode system inside: bg reduction, field shaping, ...
Example of KATRIN simulation & fit (last 25eV below endpoint, reference):

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

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

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

Sensitivity is still statistically limited,
because with more statistics would go closer to the endpoint,
where most systematics nearly vanish

Sensitivity still has to proven, but there might be even some more improvements
Example of KATRIN simulation & fit
(last 25eV below endpoint, conf.)

⇒ KATRIN will improve the sensitivity by 1 order of magnitude
will check the whole cosmological relevant mass range
will detect degenerate neutrinos (if they are degen.)

KATRIN can also searching sterile neutrinos
by looking for a kink in the decay spectrum:

\[
dN/dE = K \ F(E,Z) \ p \ E_{\text{tot}} \ (E_0-E_e) \ \sum_{i=1}^{n_{\text{active}} + n_{\text{sterile}}} |U_{ei}|^2 \ \sqrt{(E_0-E_e)^2 - m(v_i)^2}
\]

eV scale (reactor anomaly):
  J. A. Formaggio, J. Barret, PLB 706 (2011) 68
  A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
  A. Esmaili, O.L.G. Peres, arXiv:1203.2632

keV scale (dark matter): under study

Sensitivity still has to proven, but there might be even some more improvements
Is there a fourth sterile neutrino state?

Re-evaluation of reactor neutrinos fluxes and use of GALLEX/SAGE calibration measurements: “reactor antineutrino anomaly”: $P_{ee} = 0.943 \pm 0.023$

\[ \sin^2(2\theta) \approx 0.1 \]

\[ \Delta m^2 > 1 \text{ eV}^2 \]

Hints for a 2\textsuperscript{nd} sterile neutrino: Warm Dark Matter in the universe

ΛCDM (Cold Dark Matter with cosmological constant) models (masses of about 100 GeV) predict too much structure at galactic scales (too many satellite galaxies)

(e.g. Lovell et al. at Meudon Workshop 2012)

In contrast to observations! (here only artist view on the right)

Warm Dark Matter (masses of a few keV, e.g. sterile neutrinos) would smear out these structures

http://chandra.harvard.edu/graphics/resources/illustrations/milkyWay/milkyway_magellanic_clouds.jpg
Neutrino mixing with 3 active neutrinos:
active = coupling to $Z^0$ and $W^{\pm/-}$

$\nu_e \nu_\mu \nu_\tau$

$U_{e1} U_{e2} U_{e3} U_{\mu_1} U_{\mu_2} U_{\mu_3} U_{\tau_1} U_{\tau_2} U_{\tau_3}$

$\nu_1 \nu_2 \nu_3$

$U$ is unitary 3 x 3 matrix
3 active neutrinos plus a sterile neutrino

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_{\text{sterile}}
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & 0 \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & 0 \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}
\]

\(\nu_{\text{sterile}}\) does not couple to \(Z^0\) and \(W^{+/−}\).

Now we have an unitary 4 x 4 matrix, but still the 3 x 3 submatrix is unitary.

\(\nu_{\text{sterile}}\) and \(\nu_4\) do not play any physical role (except for gravitation).
3 active neutrinos plus a sterile neutrino with non-vanishing mixing

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_{\text{sterile}}
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}
\]

\(\nu_{\text{sterile}}\) does not couple to \(Z^0\) and \(W^{+/-}\).

Now we have an unitary 4 x 4 matrix, but usually \(U_{s1}, U_{s2}, U_{s3}, U_{e4}, U_{\mu4}, U_{\tau4} \ll 1\)

But the 3 x 3 submatrix is not unitary anymore!

\(\nu_{\text{sterile}}\) and \(\nu_4\) do play a physical role by their mixing:

\[
\nu_e = \sum_{i=1}^{3} U_{ei} \nu_i + U_{e4} \nu_4
\]

\[
m^2(\nu_e) := \sum_{i=1}^{3} |U_{ei}|^2 m^2(\nu_i) + |U_{e4}|^2 m^2(\nu_4)
\approx \cos^2(\theta) m(\nu_{1,2,3})^2 + \sin^2(\theta) m(\nu_4)^2
\]
3 active neutrinos plus a sterile neutrino with non-vanishing mixing

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_{\text{sterile}}
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}
\]

Are sterile neutrinos a crazy idea?
Not a all:
We expect 3 right-handed ("sterile") neutrinos from the sea-saw mechanism to create the light neutrino masses $\nu_1$, $\nu_2$, $\nu_3$

The only new thing is, that one ($\nu_4$) or two neutrinos ($\nu_4$, $\nu_5$) do not have masses of $10^x$ GeV but are very light
Influence of a 4\textsuperscript{th} sterile neutrino near the endpoint $E_0$

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

Remark: Neutrinoless double $\beta$ decay:

\[
m_{\beta\beta}(\nu) = \left| \sum_{i=1}^{n_a+n_s} |U_{ei}|^2 e^{i\alpha(i)} m(\nu_i) \right| \quad \text{(coherent)}
\]

measures only "one number" → cannot distinguish sterile neutrinos if $U_{ei}$ is small

e.g.
\[
m(\nu_4) = 2 \text{ eV}
\]

\[
\sin^2(\theta) = 0.3
\]

e.g.
\[
m(\nu_{123}) \approx 0 \text{ eV}
\]

\[
\cos^2(\theta) = 0.7
\]
Sterile neutrino limits from the Mainz Neutrino Mass Experiment

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

Do same analysis (same data sets, same programs, same way to treat systematic uncertainties) on Mainz phase 2 data as in C. Kraus et al., Euro. Phys. J. C40 (2005) 447


similar analysis by Troitsk: preliminary arXiv:1211.7193, final one will come soon
Sensitivity on sterile neutrinos of the next direct neutrino mass experiments

→ KATRIN can check parameter space of reactor anomaly!

J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

→ Need certainly a new strategy!

A. Nucciotti, Meudon Workshop, June 2011

KATRIN

MARE II
Search for a tiny kink of a keV neutrino

Main questions:

1) How to measure this tiny kink a few keV below the endpoint?
   In parallel, in addition or after KATRIN's m(νe) mission?

2) How to get enough statistics?

3) How to fight against the systematics?
Normal ("differential") or integral $\beta$-spectrum

e.g. $m_{\text{sterile}} = 2.5$ keV
$\sin^2(\theta) = 0.25$
(unrealistically high for Warm Dark Matter)

$\rightarrow$ obviously much better signal-to-background-ratio for differential $\beta$-spectrum w.r.t. integral $\beta$-spectrum
Second gain of integral versus differential:
Avoid many steps in MAC-E-Filter mode

Integral – MAC-E-Filter method

Differential measurement

need many retardation voltages to obtain spectral information

need one retardation voltage and other means (detector, TOF) to obtain spectral information
Statistical sensitivity for integral and differential measurement

90% CL level

Susanne Mertens, Chalonge 2013, Meudon

→ statistical uncertainty is not a problem but the systematics!
Possible implementations of a differential $\beta$-spectrum measurement with KATRIN

Detector measures $\beta$-spectrum with energy resolution $\Delta E \sim 1\text{keV}$ (FWHM) above a retarding energy $qU_0 = \text{const.}$

Problems:
- tails of resolution function
- high count rate capability (pile-up)
Possible implementations of a differential $\beta$-spectrum measurement with KATRIN

“Instrumented rear-wall“ (detector)
measures $\beta$-spectrum
with energy resolution
$\Delta E \sim 1\text{keV (FWHM)}$
completely and
all the time parasitically

Problems:
tails of resolution function
ultra-high count rate capability (pile-up, ...)

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Possible implementations of a differential $\beta$-spectrum measurement with KATRIN

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Problems:
- tails of resolution function
- ultra-high count rate capability (pile-up, ...)

TOF by pulsing retarding potential of pre spectrometer applying short on & long off pulses

Problems:
- can we pulse the pre spectrometer potential within less than 1 $\mu$s by up to 3kV?

Detector measures $\beta$-spectrum with energy resolution $\Delta E \sim 1\text{keV (FWHM)}$ above a retarding energy $qU_0 = \text{const.}$

Problems:
- tails of resolution function
- ultra-high count rate capability (pile-up)
Systematic uncertainties

1. β-decay spectrum:
   a) β-decay and nuclear physics: radiative decays, weak magnetism, size of the nucleus
      recoil corrections: all effects are small, e.g. $\mathcal{O}(10^{-5})$, and follow smooth functions
      S. Mertens et al., checked systematic uncertainties: $\Delta\sin^2(\theta) < 10^{-7}$
      (see S. Mertens, talk at Chalonge 2013, Meudon)
   b) β-decay and atomic and molecular physics
      Fermi function: quite well-known, smooth function
      electronic final states of $T_2$-decay:
      43% of all decays go to excited or ionized states: $\mathcal{O}(1)$ effect!

2. tritium source:
   a) energy loss by inelastic scattering
   b) stability column density: KATRIN $10^{-3}$ ($10^{-4}$ reachable)
   \[ \mathcal{O}(1) \text{ effect!} \]

3. transmission of the spectrometer:
   a) constancy of transmission at large surplus energies $\mathcal{O}(\text{keV})$
   requires full conservation of adiabaticity by larger magnetic fields

4) detection system:
   a) tails of response functions, pile-up, time resolution, stabilities, …
Electronic final states of tritium $\beta$-decay: $T_2 \rightarrow (^3\text{He}T)^+, ^3\text{He} + T^+, \ldots$

Including electronic excited final states of excitation energy $V_j$ with probability $W_j$

$$W_j = |\langle \Psi_0 | \Psi_{f,j} \rangle|^2$$

Using $\varepsilon_j = E_0 - V_j - E$

$$\frac{d^2 N}{dt \, dE} = A \cdot F(E, Z + 1) \cdot p \cdot (E + m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \sqrt{\varepsilon_j^2 - m^2(\nu_c)} \cdot \Theta(\varepsilon_j - m(\nu_c))$$

Quantum-chemical calculations of electronic final states of $T_2 \beta$-decay:


Can access the electronic final state spectrum quite accurately by sum rules and at higher excitation energies by the quasi-free electron extension

Precise enough for WDM searches?

only $57.4\%$ \Rightarrow electronic final states are important
Inelastic scattering x transmission fcn

Standard KATRIN:

\[ P_0 = 41\% \]

→ need to lower tritium column density to get \( P_0 \gg 90\% \)

\( \mathcal{O}(1) \rightarrow \mathcal{O}(0.1 - 0.01) \) effect

And there is still enough statistics!

Energy loss function:
apply sum rules and high energy extrapolation by quasi-free electrons measurements @ KATRIN
Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer

Time-of-flight spectrum is sensitive to the neutrino mass
require one retardation potential only
not integral but differential β-spectrum
Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer

Comparison of TOF spectra for different neutrino masses $\nu_e$

Electric potential on main spectrometer z axis

Sensitivity on spectral shape originates from strongly retarding the electrons by retarding potential
Sensitivity improvement on $m^2(\nu_e)$ by ideal TOF determination

Measure at 2 (instead of $\approx 30$) different retarding potentials since TOF spectra contain all the information

Coincidence request between start and stop signal $\rightarrow$ nice background suppression

$\rightarrow$ Factor 5 improvement in $m_\nu^2$ w.r.t. standard KATRIN!

\[ E_\nu = 18374.996622 \pm 0.001338 \text{ eV} \]
\[ m_\nu^2 = -0.004045 \pm 0.000090 \text{ (eV)}^2 \]
\[ \chi^2/\text{d.o.f.} = 1635.45/1855.000000 \]

N. Steinbrink et al., to appear on arXiv within the next days
1) Can measure time-of-arrival with KATRIN detector with $\Delta t = 50 \text{ ns} \rightarrow \text{ok}$

2) Need to determine time-of-passing-by of beta electron before main spectrometer without disturbing energy and momentum by more than 10 meV !

$\rightarrow$ Need „detector“ with 10 meV threshold

This seems not to be prohibited in principle but it is unrealistic for the near future !

2') Use pre spectrometer as a „gated-filter“ by switching fast the retarding voltage


no problem with transmission properties: M. Prall et al., NJP 14 (2012) 073054

About as sensitive on the neutrino mass as standard KATRIN:

N. Steinbrink et al., to appear on arXiv within the next days
A possible strategy to detect a few keV sterile neutrinos by TOF with KATRIN

- Set (a few) retarding potentials below kink position
- Use gating filter with short on- and long off-times to have optimal time resolution
- Differentiate spectrum by measuring time-of-flight
- Use low column density
- Fight final states uncertainties and energy losses by sum rules, parameterisations and extrapolations

\(\sin^2(\theta) = 0.025\) (unrealistically high for Warm Dark Matter)
Preliminary results of a first study

TOF spectra for $m_s = 1$ keV, $U = 17$ kV, different mixing angles

- $\sin^2 \theta_s = 0.0$
- $\sin^2 \theta_s = 0.05$
- $\sin^2 \theta_s = 0.1$
- $\sin^2 \theta_s = 0.2$
- $\sin^2 \theta_s = 0.5$
- $\sin^2 \theta_s = 1.0$

N. Steinbrink, Chalange 2013, Meudon
Preliminary results

preliminary: statistical sensitivity about $10^{-7}$
no sophisticated statistical analysis yet

N. Steinbrink, Chalonge 2013, Meudon
Test of TOR method at KATRIN main spectrometer during SDS commissioning

Angular-selective pulsed UV laser photoelectron source at main spectrometer & detector
Test of tof method at main spectrometer during SDS commissioning

Integral transmission function at -200 V

measured TOF agrees with calculated TOF by N. Steinbrink from electrical potential and magnetic field maps
Conclusions

Neutrinos do oscillate → non-zero neutrino mass which is very important for nuclear & particle physics (which model beyond the Standard Model ?) for cosmology & astrophysics (evolution of the universe)

KATRIN is the next generation direct neutrino mass experiment with 200 meV sens.
main spectr. + detector commissioning is running, tritium data from 2015 on

MARE, ECHO: cryo-bolometers may achieve similar sensitivity after a lot of successful R&D

Sterile neutrinos are well motivated by the "reactor neutrino anomaly" (eV-scale) and "Warm Dark Matter" (keV-scale)

KATRIN will check the reactor anomaly and could in principle search for Warm Dark Matter in a dedicated run
To yield optimal sensitivity, it requires taking differential spectra a few keV below $E_0$,
e.g. by time-of-flight spectroscopy in gated-filter mode or analysing detector spectra
detailed studies by S. Mertens, N. Steinbrink et al.

see dedicated talk by Guido Drexlin in open session
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KATRIN will check the reactor anomaly and could in principle search for Warm Dark Matter in a dedicated run

To yield optimal sensitivity, it requires taking differential spectra a few keV below $E_0$, e.g. by time-of-flight spectroscopy in gated-filter mode or analysing detector spectra
detailed studies by S. Mertens, N. Steinbrink et al.

The KATRIN 148-pixel detector is smiling when being hit by electrons from 11 subsequent positions of the scanning photoelectron source

see dedicated talk by Guido Drexlin in open session
The Troitsk Neutrino Mass Experiment

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

- Luminosity: $L = 0.6\text{cm}^2$
  
  $L = \frac{\Delta \Omega}{2\pi} \times A_{\text{source}}$

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

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

- Re-analysis of Troitsk data
  
  (better source thickness, better run selection)

  Aseev et al, Phys. Rev. D 84, 112003 (2011)

  $m_\beta < 2.05\text{ eV}, 95\% \text{ CL}$

- Upgrade of Troitsk exp.
  
  aim to investigate KATRIN systematics and keV neutrinos