Search for keV sterile neutrinos

16th PATRAS Workshop
Thibaut Houdy, Susanne Mertens
18th of June, 2021
What are neutrinos?

Neutrinos oscillate → they are massive

Standard Model (SM)

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left 2/3 $u$</td>
<td>Left $\nu_e$</td>
</tr>
<tr>
<td>Right 2/3 $u$</td>
<td>Right $\nu_e$</td>
</tr>
<tr>
<td>Right $d$</td>
<td>Right $\nu_\mu$</td>
</tr>
<tr>
<td>Left $d$</td>
<td>Left $\nu_\tau$</td>
</tr>
<tr>
<td>Right $s$</td>
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</tr>
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<td>Left $t$</td>
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</tr>
</tbody>
</table>

2015
What are neutrinos?

Neutrinos oscillate → they are massive

2015

What is their mass?

$m_\nu < 0.9 \text{ eV at } 90\% \text{ CL}$

Los Alamos (91)
Tokyo (91)
Zürich (92)
Mainz (93)
Beijing (93)
Livermore (95)
Troitsk (95)
Mainz (99)
Troitsk (99)
Mainz (05)
Troitsk (11)
KATRIN (19)
KATRIN (21)
KATRIN (comb.)
What are neutrinos?

Neutrinos oscillate → they are massive

How is it generated?

What is their mass?

$\Phi$

Higgs

$e_L$

$e_R$

$\nu_L$

$\nu_R$

$m_\nu < 0.9 \text{ eV at } 90\% \text{ CL}$
What are neutrinos?

Neutrinos oscillate → they are massive
Mass generation → existence of a sterile neutrino? (ex: See-Saw mechanism)
What are neutrinos?

Neutrinos oscillate → they are massive
Mass generation → existence of a sterile neutrino? (ex: See-Saw mechanism)
Simple extension of the standard model (ex: νMSM$^1$)

Is there a sterile neutrino?

**keV-scale:**
Dark Matter candidate

**eV-scale:**
Resolve anomalies in oscillation experiments

**GeV-scale:**
See-saw candidate
Is there a sterile neutrino?

**eV-scale:**
Resolve anomalies in oscillation experiments

**keV-scale:**
Dark Matter candidate

**Journal of Cosmology and Astroparticle Physics**

R. Adhikari et al JCAP01(2017)025

A White Paper on keV sterile neutrino
Dark Matter
keV-sterile neutrinos as Dark Matter

https://arxiv.org/abs/2104.07634
keV–sterile neutrinos as Dark Matter

Production mechanisms:

- Thermal production
- Oscillation from active $\nu$ via scattering (Dodelson-Widrow)
- Enhancement via lepton number (Shi-Fuller)
- Decay of heavy scalar
- and many others...

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Overproduction (model-dependent)

Phase-space argument
Experimental searches

Direct Detection:
e.g. DyNO

Indirect Detection:
e.g. XMM Newton

Production:
e.g. KATRIN/TRISTAN
Experimental searches

Indirect Detection:
e.g. XMM Newton

Production:
e.g. KATRIN/ TRISTAN

Direct Detection:
e.g. DyNO
Indirect searches

- Structure formations
- Radiative decay
  Looking for keV x-ray signals emitted in high density DM locations via radiative decay of sterile neutrino

→ signal at 3.5 keV observed by stacking galaxy clusters (XMM-Newton, Suzaku, Chandra), in Andromeda and Milky Way

Some results are contradictory (Hitomi)

Atomic transition is still discussed

Bulbulet al1402.2301, Boyarsky et al1402.4119
Dessert et al, Science 367 (2020)
keV-sterile neutrinos as Dark Matter

See Boyarski et al, Progress in Particle and Nuclear Physics 104, 1-45 (2019)
Experimental searches

Direct Detection:
e.g. DyNO

Indirect Detection:
e.g. XMM Newton

Production:
e.g. KATRIN/ TRISTAN

Experimental searches
Direct detection

• Electronic recoil in massive DM exp.

XENON1T, XENONNT, DARWIN


• Neutrino capture on stable isotope

Dyno:
Neutrino capture on \(^{163}\)Dy to produce \(^{163}\)Ho. Extraction and measure of Ho/Do

Experimental searches

Indirect Detection: e.g. XMM Newton

Production: e.g. KATRIN/TRISTAN

Direct Detection: e.g. DyNO

Total Energy-Momentum reconstruction

**HUNTER**

(a) Beta decay with electron emission

\[ m_{\nu}^2 = [Q - E_a - E_\gamma - E_N]^2 - [p_\gamma + p_e + p_N]^2 \]

\[ \beta\text{-decay atom in trap} \]

(b) Beta decay by K-capture

\[ m_{\nu}^2 = [Q - E_a - E_\gamma - E_N]^2 - [p_\gamma + p_e + p_N]^2 \]

Possible source: atoms in a Magneto-Optical Trap (e.g. $^{203}\text{Hg}$, $^{131}\text{Cs}$, $^7\text{Be}$)

Possible detector: Cold Target Recoil Ion Momentum Spectroscopy, COLTRIMS

Peter F Smith 2019 New J. Phys.21 053022
Total Energy-Momentum reconstruction

HUNTER

(a) Beta decay with electron emission

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m_{\nu}^2 = \left[ Q - E_e - E_{\gamma} - E_N \right]^2 \rightleftharpoons \left[ p_{\gamma} + p_e + p_N \right]^2
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Peter F Smith 2019 New J. Phys.21 053022
Studying $\beta$-decay

Existence of a new mass eigenstate distorts the shape of the $\beta$-decay

$$\frac{d\Gamma}{dE} = \cos 2\theta \frac{d\Gamma}{dE}(m_\beta) + \sin 2\theta \frac{d\Gamma}{dE}(m_s)$$

Characteristic kink-like signature and spectral distortion
Studying $\beta$-decay

Different mass sensitivities, complexity of modelling, experimental challenges
Studying $\beta$-decay

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

- Metallic Magnetic Calorimeter with SQUID multiplexing read-out
- 5 eV FWHM resolution
- 4 pixels with 0.18 Bq

$^{163}\text{Ho} ightarrow ^{163}\text{Dy}^* + \nu_e$

Studying $\beta$-decay

$^{163}$Ho $\rightarrow$ $^{163}$Dy* + $\nu_e$

- Metallic Magnetic Calorimeter with SQUID multiplexing read-out
- 5 eV FWHM resolution
- 4 pixels with 0.18 Bq

**Target of ECHo-1k**
- Total activity of 1 kBq
- 1 eV resolution
- 10 eV sensitivity on $m_\nu$

**Challenges:**
- pile-up, multiplexing, statistics, background, theoretical description of the spectrum
Studying $\beta$-decay

Tritium

Holmium

\[ m_\nu = 0 \]
\[ m_\nu = 10 \text{ keV, } \sin^2 \theta = 0.2 \]
\[ m_\nu = 1.75 \text{ keV, } \sin^2 \theta = 0.2 \]
KArlsruhe TRItium Neutrino Experiment : KATRIN

- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Design sensitivity: 0.2 eV (90% CL)
General Idea

- Ultra-strong $\beta$-source \( 10^{11} \) decays/s
- Low background level \(< 0.1 \) cps
- Excellent energy resolution \(~ 1\) eV
- Precise understanding of spectrum
**KATRIN Working Principle**

Windowless gaseous tritium source
- molecular tritium in closed loop system
- \(10^{11}\) decays/s

\[ \beta\text{-decay} \]
**KATRIN Working Principle**

**Transport section**
- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by $> 10^{14}$ + tritium ion removal
Spectrometer section
• high resolution \(\sim 1\) eV
• large angle acceptance 0 - 51°
Focal plane detector
• 148-pixel Si-PIN detector
• counting of electrons

β-decay
keV-sterile signature in $\beta$-decay

$\sin^2 \theta \leftarrow m_4 = 10$ keV

Active branch

Sterile branch

~ $1$ e$^-$/s at the detector
keV-sterile signature in $\beta$-decay

- Active branch
- Sterile branch
- $\sin^2 \theta$
- $m_4 = 10 \text{ keV}$

8 order of magnitude higher rate
keV-sterile signature in $\beta$-decay

Stringent limit from astrophysical and cosmological observations ($\sin^2(\theta)<10^{-7}$):

$\rightarrow$ Dramatic increase of the count rate (up to $3\times10^8$ Hz)

$\rightarrow$ Integral and differential phases (detector with good resolution)

$\rightarrow$ Highly pixelised

$\rightarrow$ new detector is needed: the TRISTAN project
TRISTAN Project

Capability of handling high rates ($> 3 \times 10^8$ cps)  
+ Excellent energy resolution (300 eV @ 20 keV)

- Silicon Drift Detector (SDD) Technology
- Novelty: large number of pixels (about 3500)
- Novelty: application to high-precision $\beta$-spectroscopy
TRISTAN : Development of a large area SDD array and read-out system to look for keV-sterile neutrino with the KATRIN experiment

The graph shows the relationship between $\sin^2 \theta$ and $m_{\text{heavy}}$ (keV) for different experimental setups and limits. The red dashed line represents the current KATRIN setup, the red solid line represents KATRIN with TRISTAN, and other lines represent various statistical limits and experimental results.

Key points:
- Current KATRIN: Red dashed line
- KATRIN with TRISTAN: Red solid line
- Statistical limit: Dotted line
- Holzschuh 99: Dashed-dot line
- Hiddemann 95: Dashed line
- Troitsk 17: Dotted line

The graph indicates that KATRIN with TRISTAN has improved sensitivity compared to the current KATRIN setup, especially at lower $m_{\text{heavy}}$ values.
Staged approach

Prototypes \( \times 24 \) Module \( \times 9 \) Phase 1 \( \times 2.5 \) Phase 2
Staged approach

Prototypes

Module

Phase 1

Phase 2

TRISTAN prototype

• 7-pixels with external CMOS
Prototype results

**Photon response**
- 130 eV (FWHM) at 6 keV
- <150 eV (FWHM) for <1 us shaping time
- 0.1 % linearity over 60 keV range

**Electron response**
- Semi empirical model in construction
- Dead-layer measurements using e-gun (tilting the detector) and $^{241}$Am sources
Prototype applications

2017-2019:
TRISTAN 7-pixels prototype implemented in Troitsk nu mass spectrometer → differential and integral measurements

2019-2020:
TRISTAN 7-pixels prototype implemented in KATRIN as Forward Beam Monitor. Monitoring since KNM2.
Staged approach

Prototypes

Module

Phase 1

Phase 2

TRISTAN module
- 166-pixels with integrated JFET
Operating 166-pix SDD in UHV ($10^{-8}$ mbar), cool (-80°C), intense B field (~1 T), low noise (<300 eV FWHM)

- Large SDD matrix with integrated FET
- CeSiC: carbon-fiber reinforced silicon carbide
- Rigid-flex with high density
- Dedicated ASIC
- 1-m long Kapton flex cable
1st operation of a 47-pix TRISTAN SDD on Oct 2020

- Kerberos, TRISTAN peak sensing ADC
- Cooling liquid circulation
- Planar Design 47-pixels SDD with nFET
- 48-ch bias board
- 400 pins micro-D CF100 flange
TRISTAN Module Integration

Insertion of a 47-pix planar design → test the full chain of acquisition

Test in **realistic conditions**
- Ultra High Vacuum
- Magnetic Fields
- Cooling system
TRISTAN Module Integration

**55Fe x-rays**
- Test with integrated set-up
- Homogeneous
- Stable
TRISTAN Module Integration

1st electron light with a 47-pix TRISTAN inside MoS KATRIN on April 2021

$^{83m}$Kr electrons from MoS
- Monoenergetic
- Vacuum (10$^{-8}$ mbar)
- Operating at -50°C
• Studying of the electron response
• Analyzing plane HV to 30 kV to focus on L32 line
• Size of the source ~ size of the detector
Staged approach

Prototypes

Module

Phase 1

Mini-TRISTAN
- 9 x modules
  → 1500 pixels

Phase 2

Full TRISTAN
- 21 x modules
  → 3500 pixels
Next milestones:

- **New DAQ system**
- **Full model of the tritium spectrum**
- First physics runs with **9 modules** in the KATRIN beamline (~ 2022)
Deep Tritium Model

Terra incognita

Differential decay rate (a.u.)

Energy (keV)
Deep Tritium Model: effects to consider

Effect can be different for differential and integral mode

<table>
<thead>
<tr>
<th>Rear-Wall</th>
<th>Source</th>
<th>Transport - Spectrometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Back-scattering</td>
<td>• Scattering</td>
<td>• Non-adiabaticity transport</td>
</tr>
<tr>
<td>• Auger electron emission</td>
<td>• Magnetic traps</td>
<td>• Synchrotron radiation</td>
</tr>
<tr>
<td>• Residual beta-activity</td>
<td>• Plasma effects</td>
<td>• HV stability</td>
</tr>
<tr>
<td></td>
<td>• Stability</td>
<td>• Background</td>
</tr>
<tr>
<td></td>
<td>• Gas composition and impurities</td>
<td>• B-field stab.</td>
</tr>
</tbody>
</table>

- all these effects have been estimated individually
- Global model on construction

**Detector**
- SDD response
- Read-out resp
- ADC NL
- Post acceleration electrode
- Pile-up, backscattering
- Penning traps
- Stability
Deep Tritium Model: illustration

![Graph showing the measured spectrum with energy on the x-axis and rate per bin [1/s] on the y-axis. The graph illustrates the distribution of tritium emissions at different energies.]
Deep Tritium Model : illustration
Deep Tritium Model: illustration
Deep Tritium Model: illustration
Deep Tritium Model: illustration

- Measured spectrum
- Tritium decay
- + deadlayer
- + charge sharing
- + pile up
Deep Tritium Model: illustration

- Development of a full model for complete sensitivity studies
- **1h of nominal mass campaign**
- Total count rate: 16079 cps
- Count rate in ROI: 7496 cps
- Counts: $2.3 \times 10^6$ electrons
Conclusion

- Sterile neutrinos are a natural extension of the SM
- keV-sterile neutrinos are a viable dark matter candidate
- New ideas are being explored to search for these particles. Exciting new measurements are coming!

**KATRIN** now holds the best direct limit on the neutrino mass

**TRISTAN** is getting ready to allow KATRIN to search for keV-sterile neutrinos
Thank you all
Statistical Fluctuation – No Pile Up – Counts = 1e10
Theoretical Spectrum Supposed to be perfectly known

ECHo-1k

Thierry Lassere + ECHo, in progress