The neutrino mass scale: Where do we go?


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Introduction
Neutrino mass scale: Where do we stand
Neutrino mass from cosmology
Neutrino mass from neutrinoless double beta decay
Direct neutrino mass determination: \(^3\)H \(\beta\)-decay and \(^{163}\)Ho EC
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

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix} \cdot
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

with:

\[
0.37 < \sin^2(\theta_{23}) < 0.63 \quad \text{maximal!}
\]

\[
0.26 < \sin^2(\theta_{12}) < 0.36 \quad \text{large!}
\]

\[
0.018 < \sin^2(\theta_{13}) < 0.030 \quad 8.9^\circ
\]

\[
7.0 \times 10^{-5} \text{ eV}^2 < |\Delta m_{12}^2| < 8.2 \times 10^{-5} \text{ eV}^2
\]

\[
2.2 \times 10^{-3} \text{ eV}^2 < |\Delta m_{13}^2| < 2.6 \times 10^{-3} \text{ eV}^2
\]

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

additional sterile neutrinos?
Results of recent oscillation experiments:

$\Theta_{23}, \Theta_{12}, \Theta_{13}, \Delta m^2_{23}, \Delta m^2_{12}$

Non-zero neutrino masses go beyond the usual Yukawa coupling to the Higgs

$\rightarrow$ Beyond the Standard Model physics
1) **Cosmology**

very sensitive, but model dependent
compares power at different scales
current sensitivity: $\Sigma m(\nu) \approx 0.23$ eV
Neutrino mass from cosmology

measurement of CMBR
(Cosmic Microwave Background Radiation)

measurement of matter density distribution LSS
(Large Scale Structure)
by 2dF, SDSS, ...

compare to numeric. models including relic neutrino density
of 336 cm$^{-3}$

Planck Collaboration:
P. A. R. Ade et al., arXiv:1502.01589

Millenium simulation →
http://www.mpa-garching.mpg.de/galform/presse/
Neutrino mass from cosmology

Relies on \( \Lambda \)CDM model!

Is this fully correct, there are some discrepancies?

More than 95% of the energy distribution in the universe is not known (dark energy, dark matter)

\[
\sum m_\nu < 0.72 \text{ eV} \quad \text{Planck TT+lowP;}
\]
\[
\sum m_\nu < 0.21 \text{ eV} \quad \text{Planck TT+lowP+BAO;}
\]
\[
\sum m_\nu < 0.49 \text{ eV} \quad \text{Planck TT, TE, EE+lowP;}
\]
\[
\sum m_\nu < 0.17 \text{ eV} \quad \text{Planck TT, TE, EE+lowP+BAO.}
\]

\[
\left\{ \sum m_\nu < 0.23 \text{ eV} \right\} \quad 95\%, \text{ Planck TT+lowP+lensing+ext.}
\]

\( \Omega_\nu h^2 < 0.0025 \)

1) **Cosmology**
   very sensitive, but model dependent
   compares power at different scales
   current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV

2) **Search for $0\nu\beta\beta$**
   Sensitive to Majorana neutrinos
   First upper limits by EXO-200, KamLAND-Zen, GERDA
Results from GERDA phase 1

Very low background & high energy resolution:
18 kg enriched Ge detectors in LAr

\[ T_{1/2} > 2.1 \times 10^{25} \text{ yr (90\% C.L.)} \]
\[ T_{1/2} > 3.0 \times 10^{25} \text{ yr (90\% C.L.)} \] (using all $^{76}\text{Ge}$ experiments)
\[ m_{\beta\beta} < 0.2 - 0.4 \text{ eV} \] (using all $^{76}\text{Ge}$ experiments)

Former claim strongly disfavored

GERDA I
PRL 111 (2013)
122503
Three complementary ways to the absolute neutrino mass scale

1) Cosmology
   very sensitive, but model dependent
   compares power at different scales
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3) Direct neutrino mass determination:
   No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly
   * Time-of-flight measurements ($\nu$ from supernova) 
     SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV
   * Kinematics of weak decays / beta decays
     measure charged decay prod., E-, p-conservation
     $\beta$-decay searches for $m(\nu_e)$ - tritium, $^{187}$Re $\beta$-spectrum
     - $^{163}$Ho electron capture (EC)
Direct determination of $m(\nu_e)$ from $\beta$ decay

$\beta$ decay: $(A,Z) \rightarrow (A,Z+1)^{+} + e^- + \bar{\nu}_e$

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

phase space: $p_e \cdot E_e \cdot E_\nu \cdot p_\nu$

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

$m(\nu) < 2 \text{ eV} \ (\text{Mainz, Troitsk})$

Review:

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

$\Rightarrow$ Tritium $^3\text{H} \ (^{187}\text{Re}, \ ^{163}\text{Ho})$

$\Rightarrow$ MAC-E-Filter
(or bolometer for $^{187}\text{Re}, \ ^{163}\text{Ho}$)
Comparison of the different approaches to the neutrino mass

Direct kinematic measurement:  \( m^2(\nu_e) = \sum |U_{\nu_e i}|^2 m^2(\nu_i) \)  
\text{(incoherent)}

Neutrinoless double \( \beta \) decay:  \( m_{\beta\beta}(\nu) = |\sum |U_{\nu_e i}|^2 e^{i\alpha(i)} m(\nu_i)| \)  
\text{(coherent)}

if no other particle is exchanged (e.g. R-violating SUSY)

problems with uncertainty of nuclear matrix elements

\[ \Rightarrow \text{absolute scale/cosmological relevant neutrino mass in the lab by single} \ \beta \ \text{decay} \]
Future on neutrino mass results from cosmology

In addition to Planck CMB data (temperature + polarisation) use cosmic shear by weak gravitational lensing and galactic power specrum measured with EUCLID (VIS+NISP space-borne telescope by ESA)

"..Euclid will very likely provide a positive detection of neutrino mass .., the exact nature of the neutrino mass spectrum remains out of its reach .." J. Hamann S. Hannestad Y.Y.Y. Wong JCAP 11 (2012) 52, arXiv:1209.1043
Future on neutrino mass results from $0^\nu\beta\beta$ → sensitivity: $T_{1/2} > 10^{26}$ yr, $m_{\beta\beta} < 100$ meV

$$m_{\beta\beta} \sim (1/{\text{enrichment}})^{1/2} \cdot (\Delta E \cdot bg / M \cdot t)^{1/4}$$

⇒ mass → > 100 kg, high enrichment, very low background $bg$

2 ways to measure both $\beta$-electrons:

- semiconductor, cryogenic bolometer, liquid scintillator
- tracking calorimeter

source = detector

very sensitive gives more information on mechanism if observed

running: GERDA I/II, EXO-200, KamLAND-Zen
setting up: CUORE, SNO+, Majorana
planned: COBRA, Lucifer, AMORE, ...

finished: NEMO-3
setting up: SuperNEMO
planned: MOON
Future on neutrino mass results from $0^{\nu}\beta\beta$ → sensitivity: $T_{1/2} > 10^{26}$ yr, $m_{\beta\beta} < 100$ meV

GERDA II @LNGS starting in 2015: $^{76}$Ge, 38 kg better BEGe detectors lower bg rate due to active veto (WLF, PMT)

CUORE@LNGS under commissioning: $^{130}$Te, cooldown of cryostat to < 10 mK successful bg goal reached & demonstrated (CUORE-0) detector towers all mounted

Majorana demonstrator at DUSEL: $^{76}$Ge, similar goal as GERDA II

SuperNemo @Canfranc&LSM: demonstrator being built: $^{82}$Se, aim: $6 \times 10^{24}$ yr

Other experiments:
- $^{130}$Te: SNO+, $^{100}$Mo: AMORE, LUNIEU
- $^{136}$Xe: nEXO, NEXT, KamLAND-Zen
Future on neutrino mass results from $0_{\nu}\beta\beta$

$\rightarrow$ sensitivity: $T^{1/2} > 10^{26}$ yr, $m_{\beta\beta} < 100$ meV

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- Bg goal reached & demonstrated (CUORE-0) detector towers

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- Demonstrator being built:
  - $^{82}$Se, aim: $6 \times 10^{24}$

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- $^{100}$Mo: AMORE, LUNIEU
- $^{136}$Xe: nEXO, NEXT, KamLAND-Zen

Different methods to reach O(100) kg detectors with bg rate of $10^{-3}$ cnts/(kg year keV)
(or larger detectors with less energy resolution, but in addition: $2_{\nu}\beta\beta$ becomes unavoidable background)

$\rightarrow$ cover degenerated neutrino mass region & start attacking inverted hierarchy region

- Increase mass and lower bg:
  - Purer materials and surface event discrimination:
    - E.g. BEGe+PSA or dual read-out (light+heat)

But no way yet to become sensitive to normal hierarchy neutrino mass scenarios
Future on neutrino mass results from direct neutrino mass determination

Under setting up and commissioning:
- KATRIN experiment (tritium $\beta$-spectroscopy)

Future approaches and/or test experiments:
- Micro calorimeters to investigate EC of $^{163}$Ho: ECHo, HOLMES, NuMECS
- Project 8
- Time-of-flight with KATRIN
- PTOMELY?
The Karlsruhe Tritium Neutrino Experiment
KATRIN - overview

Sensitivity on $m(\nu_e)$: 2 eV $\rightarrow$ 200 meV
Molecular Windowless Gaseous Tritium Source WGTS

per mill stability source strength request:
\[ \frac{dN}{dt} \sim f_T \cdot N / \tau \sim n = f_T \cdot \rho \cdot V / R \cdot T \]
tritium fraction \( f_T \) & ideal gas law

WGTS: tub in long superconducting solenoids
\( \odot 9\text{cm}, \text{length: } 10\text{m}, T = 30\text{K} \)

Tritium recirculation (and purification)
\( p_{\text{inj}} = 0.003\text{ mbar}, q_{\text{inj}} = 4.7\text{Ci/s} \)

allows to measure with near to maximum count rate using
\[ \rho d = 5 \cdot 10^{17}/\text{cm}^2 \]
with small systematics

check column density by e-gun, \( T_2 \) purity by laser Raman
Commissioning of main spectrometer ($\Delta E = 0.93$ eV) and detector

- Transmission function measurement
- Time of flight measurement

TF with UV LED

$\sigma_E = 50$ meV

(single angular emittance)

$time-of-flight, \text{ see also N. Steinbrink et al., NJP 15 (2013) 113020}$
Radon induced background $^{219}$Rn from getter and artefical $^{220}$Rn source

→ radon-induced background is very efficiently eliminated by LN$_2$ baffles
→ residual non-radon background of about 600 mcps in winter 2015
→ optimal magnetic field settings: 477 mcps = reference background rate (SDS2)

SDS2b after baking to reach better understanding of residual background:
bg < 300 mcps reached (July 2015, preliminary)
KATRIN status & time line

- Windowless gaseous tritium source: mounting of parts delivery to KIT: August 2015
- Cryo-pumping section delivery to KIT: July 2015

- Commissioning of spectrometer & detector SDS IIb finished in August 2015
- Commissioning of tritium source & transport section: up to summer 2016
- Tritium data taking: start in 2016
- Sensitivity: 200 meV
Can KATRIN be largely improved?
Problems to be solved

1) The source is already opaque
   → need to increase size transversally
      magnetic flux tube conservation
      requests larger spectrometer too
      but a Ø100m spectrometer is not feasible

Possible ways out:

a) source inside detector (compare to \(0\nu\beta\beta\))
   using cryogenic bolometers (ECHo, HOLMES, ..)
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
Recent achievements by ECHo:

- new Q-value: 2.8 keV (independently by MMC & Penning trap, was 2.5 keV before!)
- new source production: chemical purification + mass separation → no $^{144}\text{Pm}$ or $^{166}\text{mHo}$
- very good energy resolution of this technology ($\Delta E_{\text{FWHM}} = 1.6$ eV at 6 keV)
- ultra-short response (pile-up!): risetime 90 ns
- 128 pixels: microwave SQUID multiplexing
- funding for ECHo-1k

![Diagram of ECHo setup](courage L. Gastaldo)
Prediction from test measurements:

\[ \Delta E_{\text{FWHM}} \approx 3 \text{ eV}, \tau_{\text{rise}} \approx 6 \mu\text{s}, \tau_{\text{decay}} \approx 130 \mu\text{s} \]

radiofrequency SQUID multiplexing

funding by ERC grant
courtesy A. Nucciotti
Prediction from test measurements:
\[ \Delta E_{\text{FWHM}} \approx 3 \text{ eV}, \quad \tau_{\text{rise}} \approx 6 \mu\text{s}, \quad \tau_{\text{decay}} \approx 130 \mu\text{s} \]


\[ ^{163}\text{Ho EC is investigated by 3 collaborations} \]

Cryo-calorimetric multipixel detectors are a very interesting technology
→ starts to become scalable

But many orders of magnitude to go for required statistics and background!

Systematics and show stoppers on the way?
→ We should stay tuned!
Can KATRIN be largely improved? Problems to be solved

1) The source is already opaque
   → need to increase size transversally magnetic flux tube conservation
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Possible ways out:

a) source inside detector (compare to 0νββ)
   using cryogenic bolometers (ECHo, HOLMES, ..)

b) hand-over energy information of β electron
   to other particle (radio photon),
   which can escape tritium source (Project 8)
Project 8's goal: Measure coherent cyclotron radiation of tritium $\beta$ electrons

General idea:

- Source = KATRIN tritium source technology:
  - uniform B field + low pressure $T_2$ gas

  $\beta$ electron radiates coherent cyclotron radiation

  $$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and carries the information of the $\beta$-electron energy

B. Monreal and J. Formaggio, PRD 80 (2009) 051301
Project 8's phase 1: detection single electrons from $^{83m}$Kr


courtesy J. Formaggio, RGH Robertson
Project 8's phase 1: Detection single electrons from $^{83}\text{mKr}$

First detection of single electrons successfull but still a lot of R&D necessary
- Is a large scale experiment possible ?
- What are the systematic uncertainties & other limitations?

courtesy J. Formaggio, RGH Robertson
Can KATRIN be largely improved?

Problems to be solved

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b) hand-over energy information of β electron
   to other particle (radio photon),
   which can escape tritium source (Project 8)

c) make better use of the electrons
   → time-of-flight spectroscopy
Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer

Electrons are strongly retarded in the main spectrometer → time-of-flight depends strongly on surplus energy w.r.t. retarding potential
Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer

Time-of-flight spectrum corresponds to a full energy spectrum
→ sensitive to the neutrino mass
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 already all the information

$\rightarrow$ Factor 5 improvement in $m^2_\nu$ w.r.t. standard KATRIN in ideal case!

N. Steinbrink et al.
NJP 15 (2013) 113020

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

$E_1 = 18574.999622 \pm 0.001032 \text{ eV}$
$m^2_\nu = -0.004046 \pm 0.000096 (\text{eV})^2$
$\chi^2/\text{d.o.f.} = 1836.45/1655.000000$
How to realize time-of-flight spectroscopy @KATRIN

N. Steinbrink et al., NJP 15 (2013) 113020

Advantage: measure $\beta$-spectrum by time-of-flight at one (a few) retarding potential(s)

Stop: Can measure time-of-arrival with KATRIN detector with $\Delta t = 50$ ns $\rightarrow$ ok

Start: $e^-$-tagger: Need to determine time-of-passing-by of $e^-$ before main spectrometer without disturbing energy and momentum by more than 10 meV:

$\rightarrow$ factor 5 in $\Delta m(\nu)^2_{stat}$ under ideal conditions

added value: significant background reduction!

One implementation: reduce pre spectrometer length & add a Project 8-type tagger within a long solenoid or another type of electron tagger

or: Use pre spectrometer as a „gated-filter“ by switching fast the retarding voltage $\rightarrow$ as sensitive on $m(\nu)$ as standard KATRIN!
Can KATRIN be largely improved?
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Possible ways out:

a) source inside detector (compare to $0\nu\beta\beta$)
   using cryogenic bolometers (ECHo, HOLMES, ..)

b) hand-over energy information of $\beta$ electron
   to other particle (radio photon),
   which can escape tritium source (Project 8)

c) make better use of the electrons
   → time-of-flight spectroscopy

2) Resolution is limited to $\sigma = 0.34$ eV
   when using molecular tritium by the
   excitation of ro-vibrational states in the final state
   → use atomic tritium
Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

Supported by: The Simons Foundation

PPPL (May 2015)
Goals for 2015: Tritium-loaded Graphene Surface from SRNL
0.15eV@100eV TES Energy Resolution from Goddard/ANL
Integrated Graphene / TES into 1% MAC-E Filter to Measure Spectrum
New Forefront for Calorimeter-based Methods @ Tritium Endpoint

But to get enough statistics requires a special trick
to overcome Lionville's magnetic flux conservation

Will this really work?

arXiv:1307.4738
Conclusions

Search for the neutrino mass scale & pattern: Beyond the SM physics

Threefold way to the neutrino mass scale:

- **Cosmology:**
  CMB, LSS, cosmic shear (EUCLID, by gravitational waves):
  detection of neutrino mass expected, but no details of spectrum
  dependent on cosmological model

- **Neutrinoless double beta decay:**
  Several experiments close start for $T_{1/2} > 10^{26}$ yr and $m(\nu) < 100$ meV
  GERDA II, MAJORANA, CUORE, ..
  larger mass, lower background (sophisticated methods)
  lepton flavour violation required and tested

- **Direct neutrino mass measurements:**
  KATRIN is close to start ($m(\nu) < 200$ meV)
  significant R&D on $^{163}$Ho micro calorimeters (ECHo, HOLMES, ..)
  new ideas like Project 8, ..

THANK YOU FOR YOUR ATTENTION!