Introduction

Direct Neutrino Mass determination
- supernova tof measurements
- Rhenium $\beta$ decay and EC experiments
- Tritium $\beta$ decay experiments

The Karlsruhe Tritium Neutrino experiment KATRIN

Summary and Outlook
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 (Klapdor-Kleingrothaus et al.)?
First upper limit by EXO-200, GERDA is running

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**
    measure charged decay prod., $E^{-}$, $p$-conservation
    $\beta$-decay searches for $m(\nu_e)$
    - tritium $\beta$ spectrometers
    - $^{187}$Re, $^{163}$Ho bolometers
Comparison of the different approaches to the neutrino mass

Direct kinematic measurement: \[ m^2(\nu_e) = \sum |U_{ei}|^2 m^2(\nu_i) \] (incoherent)

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

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

problems with uncertainty of nuclear matrix elements

⇒ absolute scale/cosmological relevant neutrino mass in the lab by single $\beta$ decay
Neutrino mass from supernovae (time-of-flight)

Only one SN detected in ν`s: SN1987a

Simple dependence for sharp ν emission in time:

\[
\Delta t = \frac{L}{c} - \frac{L}{\beta_\nu} = L - \frac{L}{1 - \frac{m_\nu^2}{2E_\nu^2}}
\]

\[
\approx L - L \cdot \left(1 + \frac{m_\nu^2}{2E_\nu^2}\right) = -L \cdot \frac{m_\nu^2}{2E_\nu^2}
\]

with:

\[
m^2 = E^2 - p^2 = E^2(1 - \beta^2)
\]

\[
= E^2(1 + \beta)(1 - \beta) \approx 2E^2(1 - \beta)
\]

\[
\Rightarrow \beta = 1 - \frac{m^2}{2E^2}
\]
Neutrino mass from supernovae (time-of-flight)

Only one SN detected in $\nu$'s: SN1987a

No energy versus time dependence visible

→ only upper limit on neutrino mass

Results depends on underlying SN model, e.g.:

$m(\nu_e) < 5.7$ eV

T.J. Loredo et al., PRD65 (2002) 063002

$m(\nu_e) < 5.8$ eV

G. Pagliarolia, F. Rossi-Torresa and F. Vissani,

BUT
- galactic SN only about every 40 years
- not sensitive below 1eV (uncertainty of neutrino emission time spectrum)
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:

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

(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 $^3$H, ($^{187}$Re)

$\Rightarrow$ MAC-E-Filter

(or bolometer for $^{187}$Re)

E.W. Otten & C. Weinheimer
71 (2008) 086201
G. Drexlin, V. Hannen, S. Mertens,
C. Weinheimer
Adv. High Energy Physics, in press

Direct neutrino mass determination
Summary: $\beta$-spectrum incl. electronic final states + $\nu$ mixing

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 $\varepsilon_j = E_0 - V_j - E$

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

Final states of $T_2$ $\beta$-decay:

Including neutrino mixing

$$\frac{d^2 N}{dt \, dE} = A \cdot F(E, Z + 1) \cdot p \cdot (E + m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \left( \sum_i |U_{ci}|^2 \cdot \sqrt{\varepsilon_j^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i)) \right)$$

$\Rightarrow$ the different $m(\nu_i)$ are not important at present precision

$\Rightarrow$ "Electron neutrino mass"

$$m^2(\nu_e) := \sum_i |U_{ci}|^2 \cdot m^2(\nu_i)$$
Summary: $\beta$-spectrum incl. electronic final states + $\nu$ mixing

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 $\varepsilon_j = E_0 - V_j - E$

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

Final states of $\beta^-$ decay:

The electron spectrum coming out of a $\beta$-source is even more complicated due to inelastic scattering, backscattering. ...

Including neutrino mixing

$$\frac{d^2 N}{dt \, dE} = A \cdot F(E, Z) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \left( \sum_i |U_{ci}|^2 \sqrt{\varepsilon_j^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i)) \right)$$

⇒ “Electron neutrino mass”

$$m^2(\nu_c) := \sum_i |U_{ci}|^2 \cdot m^2(\nu_i)$$

⇒ the different $m(\nu_i)$ are not important at present precision
Cryogenic bolometers, e.g. with $^{187}$Re

Measures temperature rise by $\beta$-decay in an absorber

→ all energy except that of the neutrino is measured

→ „single final state experiment“, no problems with inelastic scattering, backscattering, …

Disadvantage:

measure whole spectrum at once

→ pile-up problem

→ need many detector pixels
Cryogenic bolometers with $^{187}$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)
Uniquely forbidden $\beta$-decay of $^{187}$Re

$^{187}$Re $\rightarrow$ $^{187}$Os + e$^-$ + $\bar{\nu}_e$

$J^\pi = 5/2^+$ $\quad J^\pi = 1/2^-$

→ one of the out-going leptons has to carry away angular momentum $l=1$
→ long half-life of $4.3 \times 10^{10}$ a and new terms in $\beta$-spectrum

$$N(E) = \frac{G_F^2 \cdot \cos^2 \Theta_C}{2\pi^3} \cdot \left| M_{\text{nucl}} \right| \cdot (E_0 + m_e - \varepsilon) \cdot \sqrt{(E_0 + m_e - \varepsilon)^2 - m_e^2}$$

$$\sum_i U_{ei}^2 \cdot \frac{R_{\text{nucl}}^2}{3} \left( F_1(E, Z') \cdot \left( (E_0 + m_e - \varepsilon)^2 - m_e^2 \right) + F_0(E, Z') \cdot \left( \varepsilon^2 - m^2(\nu_i) \right) \right)$$

$$\varepsilon \cdot \sqrt{\varepsilon^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon - m(\nu_i)),$$

$E_{\nu} \quad p_{\nu}$

$E_e \quad p_e$

$E_{\nu} \quad p_{\nu}$

$\rho_e^2 \quad \rho_{\nu}^2$

Residual influence of electronic final states in the $\beta$-decay of $^{187}\text{Re}$

An electronic excitation takes away the energy $V_j$ with a probability $P_j$ from the available decay energy. Usually this energy $V_j$ is released soon electromagnetically by the excited atom and measured by the cryo-bolometer and added to the electron signal → no correction in 0th order necessary.

In 1st order the missing decay energy $V_j$ changes the phase space and energy-dependent correction factors appear:

$$
\begin{align*}
\hat{N}(E) &= \frac{G_F^2 \cos^2 \Theta_C}{2 \pi^3} \cdot |M_{\text{nucl}}|^2 \cdot \sum_{i,j} (E_0 + m_e - \epsilon) \cdot |U_{ei}^2| \cdot P_j \cdot \frac{R_{\text{nucl}}^2}{3} \\
&\quad \cdot \left( F_1(E, Z') \cdot \left( (E_0 + m_e - \epsilon)^2 - m_e^2 \right)^{3/2} \cdot \left( 1 - \frac{E_e}{p_e^2} V_j \right) \right) \\
&\quad + F_0(E, Z') \cdot \left( (E_0 + m_e - \epsilon)^2 - m_e^2 \right)^{1/2} \cdot \left( 1 - \frac{E_e}{p_e^2} V_j \right) \cdot (\epsilon^2 - m^2(\nu_i)) \\
&\quad \cdot \epsilon \cdot \sqrt{\epsilon^2 - m^2(\nu_i)} \cdot \Theta(\epsilon - m(\nu_i)).
\end{align*}
$$

from D. Drexlin, V. Hannen, S. Mertens, C. Weinheimer: „Direct Neutrino Mass Measurements“, Adv. in High Energy Physics, in press

$= 0.985$

for $E=2\text{keV}$

$V_j=20\text{eV}$
Cryogenic bolometers with $^{187}$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)
MARE neutrino mass project: $^{187}$Re beta decay with cryogenic bolometers

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 $10^6$ events in 4 years $\rightarrow$ ~ 4 eV sensitivity

MARE-1 @ Genova
- R&D effort for Re single crystals on transition edge sensors (TES)
  $\rightarrow$ improve rise time to ~ $\mu$s and energy resolution to few eV
- large arrays ($\approx 10^3$ 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 ≠ spectrometer
MAC-E-Filter

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

\[ \Theta_{\text{max}} \text{ (degree)} \]

\[ 0.4 \quad 0.35 \quad 0.3 \quad 0.25 \quad 0.2 \quad 0.15 \quad 0.1 \quad 0.05 \]

\[ 0.5 \quad 1 \quad 1.5 \]

\[ E-U \text{ (eV)} \]

⇒ sharp integrating transmission function without tails

Magnetic Adiabatic Collimation + Electrostatic Filter
The Mainz Neutrino Mass Experiment
Phase 2: 1997-2001

After all critical systematics measured by own experiment (atomic physics, surface and solid state physics: inelastic scattering, self-charging, neighbour excitation):

$$m^2(\nu) = -0.6 \pm 2.2 \pm 2.1 \text{ eV}^2 \Rightarrow m(\nu) < 2.3 \text{ eV (95\% C.L.)}$$

**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)

$m_\beta < 2.05\text{ eV}, 95\% \text{ CL}$
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:
  \[ \frac{A_{\text{spectrometer}}}{A_{\text{source}}} = \frac{B_{\text{source}}}{B_{\text{spectrometer}}} = \frac{E}{\Delta E} = \frac{20000}{1} \]

KATRIN Design Report
Scientific Report FZKA 7090)

windowless gaseous molecular tritium source
WGTS: tub in long superconducting solenoids
\( \varnothing \ 9\text{cm}, \text{length:} \ 10\text{m}, \ T = 30 \text{ K} \)

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
Very successful cool-down and stability tests of the WGTS demonstrator

arrival of WGTS demonstrator at KIT: April 2010

cooling concept of WGTS: pressurized 2-phase Ne

S. Grohmann, Cryogenics 49, No. 8 (2009) 413

Currently: tests of sc magnets, constructing of WGTS out of demonstrator

per mill stability request:
\[ \frac{dN}{dt} \sim n = \frac{pV}{RT} \]

Ideal gas law
Successful magnet tests of WGTS at Saclay

WGTS – magnet tests at CEA

- **Test objectives:** (KIT-CEA agreement)
  - demonstrate viability of
    - new magnet safety concept
      (energy dump to external resistor)
    - driven mode operation
      (power supplies remain attached)
    - magnetic forces during quench

**SEHT** = buried vertical cryostat (depth: 8 m)

**irfusaclay**
Tritium loops at Tritium Laboratory Karlsruhe

tritium source: loop system

- $10^{-4}$ stability of loop system achieved for $p_{in}$ in test set-up
Transport and differential & cryo pumping sections

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping with Argon snow at LHe temperatures (successfully tested with the TRAP experiment)

\[ T_2 \text{-injection 1.8 mbar l/s (STP)} = 1.7 \times 10^{11} \text{ Bq/s} = 40 \text{ g/d} \]

\[ \approx 10^{-7} \text{ mbar l/s} \]

\[ < 2.5 \ 10^{-14} \text{ mbar l/s} \]

⇒ adiabatic electron guiding & \( T_2 \) reduction factor of \( \sim 10^{14} \)

FT-ICR Penning traps to measure ions from WGTS
Currently:
Problem of a broken diode of the safety system of a superconducting coil

First gas flow reduction measurements with Ar:
S. Lukic et al., Vacuum 86 (2012) 1126

FT-ICR Penning traps:

Ion test source:
S. Lukic et al., Rev. Scient. Instr. 82 (2011) 013303

gas inlet \approx 3 \times 10^{17} 
molecules/s

outgoing gas flow \approx 3 \times 10^{12} 
molecules/s
A new warm-bore Differential Pumping Section is being built

DPS – new layout

- implementation of new DPS design:
  - electron transport: 5 stand-alone recondenser-type magnets (excellent experience of US groups with this type for detector section)
  - differential pumping: 5 pump ports with beam tube @ RT (re-use TMPs)

elements tilted by 20°
CPS: cryogenic pumping section

- cryosorption of $T_2$ by Ar frost
- magnetic guiding field $B = 5.6$ T
- specification finished
- estimated delivery 2010

TRAP: TRitium Argon frost Pump

F. Eichelhardt et al., Fusion Science and Technology 54 (2008) 615
Electromagnetic design: magnetic fields

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

Requirements

- detection of $\beta$-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 (148 pixels)
  → record azimuthal and radial profile of the flux tube
  → investigate systematic effects
  → compensate field inhomogeneities
KATRIN detector has been commissioned at KIT
As smaller $m(\nu)$ as smaller the region of interest below endpoint $E_0$ → quantum mechanical thresholds help a lot!

A few contributions with $\Delta m^2_{\nu} \leq 0.007 \text{ eV}^2$ each:

1. inelastic scatterings of $\beta$´s inside WGTS
   - dedicated e-gun measurements, unfolding of response fct.

2. fluctuations of WGTS column density (required < 0.1%)
   - rear detector, Laser-Raman spectroscopy, $T=30K$ stabilisation, e-gun measurements

3. WGTS charging due to remaining ions (MC: $\varphi < 20\text{mV}$)
   - monocrystaline rear plate short-cuts potential differences

4. final state distribution
   - reliable quantum chem. calculations

5. transmission function
   - detailed simulations, angular-selective e-gun measurements

6. HV stability of retarding potential on $\sim3\text{ppm}$ level required
   - precision HV divider (with PTB), monitor spectrometer beamline
Measurement of tritium concentration by laser Raman spectroscopy

R.J. Lewis et al.,
M. Sturm et al,

$\text{H}_2 / \text{HD} / \text{T}_2 / \text{DT} / \text{HT} = 0.820 / 0.083 / 0.003 / 0.005 / 0.085$
Tritium source systematics

tritium source systematics – a review

- near-time monitoring tools & quasi 3-D source model
  - extensive sensor instrumentation & control/monitoring systems ✓
  - successful large-scale test experiments (WGTS demo, LARA, loops) ✓
  - improved source modelling: quasi-3D model of gas flow ✓

M. Babutzka et al.,
Monitoring of the operating parameters of the KATRIN Windowless Gaseous Tritium Source

M. Hötzel et al.,
Accurate computation of the integrated tritium β-spectrum near the endpoint energy for KATRIN to be subm. to New J. of Phys.
A new pulsed angular-defined UV LED photoelectron source

Idea:
fast non-adiabatic acceleration
with adjustable non-parallel E and B fields

Angle at
electron source: 0°
pinch magnet: 0°

Resolution: 5 eV
angle: 12 deg

Normalized intensity vs. voltage

Preliminary

K. Valerius et al., NJP 11 (2009) 063018
K. Valerius et al., JINST 6 (2011) P01002
K. Hugenberg,
Prog. Part. Nucl. Phys. 64 (2010) 288
Stability of retarding potential / energy calibration: ppm at 18.6 kV

- Measure HV by precision HV divider
- Lock retarding HV by measuring energetically well-defined electron line with monitor spectrometer

- condensed $^{83m}$Kr: Münster/Mainz
- evaporated and implanted $^{83}$Rb/$^{83m}$Kr: Rez/Mainz/Münster/Karlsruhe
- $^{83}$Rb production: Bonn, Rez

- $^{83}$Rb
- $^{83m}$Kr

EC: $T_{1/2} = 86.2$ d

$T_{1/2} = 1.83$ h
$\alpha = 2011$
$E = 32,1517(5)$ keV

$T_{1/2} = 154.4$ ns
$\alpha = 17$
$E = 8.4$ keV

D. Venos et al., Appl. Rad. Iso. 63 (2005) 323
M. Rasulbaev et al., Appl. Rad. Iso. 66 (2008) 1838
M. Sležák et al., EPJ A48 (2012) 12
Example of KATRIN simulation & fit (last 25eV below endpoint, reference):

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

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

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
KATRIN´s sensitivity

Example of KATRIN simulation & fit (last 25eV below endpoint, reference):

⇒ 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:

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

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
Influence of a 4th sterile neutrino near the endpoint $E_0$

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)

e.g.

$m(\nu_4) = 2$ eV

$\sin^2(\theta) = 0.3$

e.g.

$m(\nu_{123}) \approx 0$ eV

$\cos^2(\theta) = 0.7$

Remark: Neutrinoless double $\beta$ decay: $m_{\beta\beta}(\nu) = | \sum U_{ei}^2 | \frac{n_a + n_s}{2} e^{i \alpha(i)} m(\nu_i)$ (coherent)

measures only „one number“ → cannot distinguish sterile neutrinos if $U_{ei}$ is small
Sterile neutrino limits from the Mainz Neutrino Mass Experiment

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

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*

Sensitivity on sterile neutrinos of up-coming direct neutrino mass experiments

KATRIN

\[ \Delta m^2 (eV^2) \]

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

\[ \rightarrow \text{KATRIN can check full parameter space of reactor anomaly!} \]

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

MARE II

\[ m_\nu [eV] \]

\[ \text{excluded } \sin^2(\theta) \text{ (90\% CL)} \]

\[ N_{ev} = 10^{14}, \Delta E = 1.5 \text{ eV, } f_{pp} = 10^{-6} \]
\[ N_{ev} = 10^{13}, \Delta E = 5 \text{ eV, } f_{pp} = 10^{-5} \]
\[ N_{ev} = 10^{12}, \Delta E = 30 \text{ eV, } f_{pp} = 10^{-4} \]

\[ \rightarrow \text{Need certainly a new strategy!} \]

A. Nucciotti, Meudon Workshop, June 2011
Some ideas to study

1) Extrapolate systematics by model fitting
   use atomic „sum rules“

2) Reduce background from spectrum above kink
   by non-integrating TOF mdus
   („gated-filter“ is fine)

3) Low column density source

Extrapolate downwards and check for additional keV sterile neutrino

How precise can we become?

e.g. $m_{\text{sterile}} = 2$ keV

$\sin^2(\theta) = 0.025$

(unrealistically high for Warm Dark Matter)
Outlook - Project 8: Measure coherent cyclotron radiation of tritium $\beta$ electrons

B. Monreal and J. Formaggio, PRD 80:051301, 2009

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

General idea:

- Source = KATRIN tritium source technology:
  - uniform B field
  - low pressure T$_2$ gas

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

A lot of R&D necessary and has just started
- Is it really possible?
- What are the systematic uncertainties?
Different ways for a direct neutrino mass measurement
- time-of-flight measurements $\rightarrow$ SNe
- cryogenic bolometers investigating $^{187}\text{Re}$ $\beta$-decay ($\rightarrow$ MARE)
- cryogenic bolometers investigating $^{163}\text{Ho}$ EC ($\rightarrow$ MARE, ECHO)
- tritium $\beta$-decay using MAC-E-Filter ($\rightarrow$ KATRIN)
- detection of synchrotron radiation ($\rightarrow$ Projekt 8)
- …

KATRIN is using a complex but established method:
$\rightarrow$ sensitivity: 2 eV $\rightarrow$ 200 meV

Cryobolometers seem to have a large potential but need large arrays $\rightarrow$ multiplexing what are the systematics?

Are the alternative methods feasible?