Search for the neutrino mass scale

Cosmological bounds

Neutrinoless double $\beta$ decay

Direct neutrino mass determination

Summary
Absolute $\nu$ mass determination

Results of recent experiments: $\Theta_{23}$, $\Theta_{12}$, $\Delta m^2_{23}$, $\Delta m^2_{12}$

Motivation:
1) distinguish hierarchical and degenerate masses
2) check cosmological relevance ($\nu$ hot Dark Matter)
Absolute $\nu$ mass determination

Results of recent experiments: $\Theta_{23}, \Theta_{12}, \Delta m^2_{23}, \Delta m^2_{12}$

Motivation:
1) distinguish hierarchical and degenerate masses
2) check cosmological relevance ($\nu$ hot Dark Matter)

$\Rightarrow$ Cannot be resolved by oscillation experiments! Need absolute neutrino mass scale!
Search for the absolute neutrino mass scale

1) Cosmology
   very sensitive, but model dependent
Neutrino mass from cosmology

- WMAP
- Urknalltheorie: Neutrinodichte im Universum $n_e = 336 / \text{cm}^3$
- Messung der CMBR (Cosmic Microwave Background Radiation)
- Messung der Materie-Dichteverteilung
- LSS (Large Scale Structure)
- 2dF, SDSS, ...
- Modell-Entwicklung
- Neutrino mass from cosmology

Diagram:
- CMB
- LSS
- Current power spectrum $P(k)$
- Wavelength $\lambda$ [h$^{-1}$ Mpc]
- Wavenumber $k$ [h/Mpc]

- Cosmic Microwave Background
- SDSS galaxies
- Cluster abundance
- Weak lensing
- Lyman Alpha Forest

Tegmark & Zaldarriaga, astro-ph/0207047 + updates
Neutrino mass from cosmology

D.N. Spargel et al. (WMAP) (astro-ph/0302209)

\[ \sum m(\nu_i) < 0.7 \text{ eV} \]

WMAP+ACBAR+CBI+2dFGRS +Ly\(\alpha\) Daten
Neutrino mass from cosmology

D.N. Spargel et al. (WMAP) (astro-ph/0302209)
\[ \sum m(\nu_i) < 0.7 \text{ eV} \]

WMAP+ACBAR+CBI+2dFGRS +Ly\(\alpha\) Daten

S. Hannestad et al. (astro-ph/0303076)
\[ \sum m(\nu_i) < 1-2 \text{ eV} \]

same data, more conservative assumptions
Neutrino mass from cosmology

D.N. Spargel et al. (WMAP)  
(astro-ph/0302209)  
\[ \sum m(\nu_i) < 0.7 \text{ eV} \]

WMAP+ACBAR+CBI+2dFGRS +Ly\(\alpha\) Daten

S. Hannestad et al.  
(astro-ph/0303076)  
\[ \sum m(\nu_i) < 1\text{-}2 \text{ eV} \]

same data, more conservative assumptions

S.W. Allen et al.  
(astro-ph/0306386)  
\[ \sum m(\nu_i) \approx 0.64 \text{ eV} \]

WMAP+2dFGRS  
\(+f_{gas}+XLF\) (x-ray cluster data) data
Neutrino mass from cosmology

D.N. Spargel et al. (WMAP) 
(astro-ph/0302209) \( \Sigma m(\nu_i) < 0.7 \text{ eV} \)

**WMAP+ACBAR+CBI+2dFGRS +Ly\(\alpha\) Daten**

S. Hannestad et al. 
(astro-ph/0303076) \( \Sigma m(\nu_i) < 1-2 \text{ eV} \)

*same data, more conservative assumptions*

S.W. Allen et al. 
(astro-ph/0306386) \( \Sigma m(\nu_i) \approx 0.64 \text{ eV} \)

**WMAP+2dFGRS +\( f_{\text{gas}} \) +XLF (x-ray cluster data) data**

J. Beacom et al. astro-ph/0404585: no upper limit on \( \Sigma m(\nu_i) \) from cosmology

*neutrino annihilate into light or massless scalars*
Conclusions:
- neutrinos: hot Dark Matter
- important for
  - evolution of universe
  - interpretation of LSS + CMB
    (correlations with other cosmological parameters)
- important quantity: \( \Sigma m(v_i) \)
- model dependent limits:
  \( \Sigma m(v_i) < 0.7 - 2.2 \text{ eV} \) or
  \( \Sigma m(v_i) > 0 \)

need laboratory experiment on absolute neutrino mass
Search for the absolute neutrino mass scale

1) Cosmology
   very sensitive, but model dependent
Search for the absolute neutrino mass scale

1) Cosmology
   very sensitive, but model dependent

2) Search for $0\nu\beta\beta$
   very sensitive, but needs $\nu$ to be of Majorana-type
   sensitive to coherent sum: $m_{ee}(\nu) = |\sum |U_{ei}|^2 e^{i\alpha(i)} m(\nu_i)|$
   ⇒ partial cancelation possible
NEMO3 in the Frejus tunnel

Start of data taking: February 2003

① 20 sectors: foils with $\beta\beta$ emitters

$^{100}$Mo (7.2kg), $^{82}$Se (1kg),
$^{116}$Cd (0.4kg), $^{130}$Te (0.6kg)

② tracking in magnetic field

6180 Geiger cells

③ calorimeter: plastic scintillators

First results on $2\nu\beta\beta$ of $^{100}$Mo

Expected sensitivity on $0\nu\beta\beta$:

$^{100}$Mo: $m_{ee} < 0.1 - 0.4$ eV

$^{82}$Se: $m_{ee} < 0.6 - 1.2$ eV
Cuoricino in Gran Sasso

41 kg TeO$_2$ cryo detectors

data taking since April 2003

\[ T_{1/2} > 5.5 \cdot 10^{23} \text{ a} \]

\[ \Rightarrow m_{ee} < 0.37 - 1.9 \text{ eV (90\% C.L.)} \]  

(PLB584 (2004) 584)

expected in 3 years: \( m_{ee} < 0.25 - 0.60 \text{ eV} \)
Evidence for $0\nu\beta\beta$ at Heidelberg Moscow Exp.?  

Klapdor-Kleingrothaus et al., MPLA 37 (2001) 2409  
(s.also comments: hep-ex/0202018, hep-ph/0205228, hep-ph/0205293)

Nearly same data as earlier (54kgy: 8/1990 - 5/2000)  
but now assumptions of peaks in [2000,2080] keV:  
\[ \Rightarrow \text{background level is lower} \]  
fit only [2032,2046] keV with background and peak  
\[ \Rightarrow \text{peak at } 0\nu\beta\beta \text{ signal position (2039 keV)} \]

\[ \Rightarrow T_{1/2}^{0\nu} = (0.8 -18.3) \times 10^{25} \text{ y} \]
\[ \Rightarrow m_{ee} = (0.11 - 0.56) \text{ eV} \]
\[ \Rightarrow m(\nu_e) = (0.05 - 3.4) \text{ eV} \]
\[ \Rightarrow \text{(fast) degenerierte } \nu \text{ ?} \]  
(jeweils 95 % C.L.)

Peak search  
Hd Moscow

Peak search  
UCBS  
(non-enriched Ge)  
all peaks except signal?
Evidence for $0\nu\beta\beta$ at Heidelberg Moscow Exp.?

Klapdor-Kleingrothaus et al., MPLA 37 (2001) 2409
(s.also comments: hep-ex/0202018, hep-ph/0205228, hep-ph/0205293)

Nearly same data as earlier (54kgy: 8/1990 - 5/2000)
but now assumptions of peaks in [2000,2080] keV:
⇒ background level is lower
fit only [2032,2046] keV with background and peak
⇒ peak at $0\nu\beta\beta$ signal position (2039 keV)

New, data up to 2003: 72 kgy,
with new data selection, new calibration
Klapdor-Kleingrothaus et al., PL B586 (2004) 198

⇒ Peak at 2038.1(5) keV (expected: 2039.006(50) keV)
Multi-Gauss. Fit: 4.2σ significance for $0\nu\beta\beta$,
$T_{1/2}^{0\nu} = (0.34-20.3) \times 10^{25}$ y
⇒ $m_{ee} = 0.1-0.9$ eV (99.7% C.L., incl. uncertainty of $M_{\text{nucl}}$)
Neutrinoless double $\beta$ decay and $m_\nu$

Observable: $\langle m_\nu \rangle = \langle m_{ee} \rangle = | \sum |U_{ei}|^2 e^{i\phi(i)} m(\nu_i)|$

Uncertainty: phases $e^{i\phi(i)} = \pm 1$, mixing $U_{13} < 13^\circ$, matrix element $\Delta M_{\text{Kem}}/M_{\text{Kem}} = \pm 2$

$\Rightarrow$ factor of 10 uncertainty for $\sum m(\nu_i)$

Neutrinoless double $\beta$ decay and $m_\nu$

Observable: $<m_\nu> = <m_{ee}> = | \Sigma |U_{ei}|^2 e^{i\phi(i)} m(\nu_i)|$

Uncertainty: phases $e^{i\phi(i)}=\pm 1$, mixing $\Theta_{13}<13^\circ$, matrix element $\Delta M_{\text{Kern}}/M_{\text{Kern}}=\pm 2$

$\Rightarrow$ factor of 10 uncertainty for $\Sigma m(\nu_i)$

Neutrinoless double $\beta$ decay and $m_\nu$

Observable: $<m_\nu> = <m_{ee}> = |\sum |U_{ei}|^2 e^{i\phi(i)} m(\nu_i)|$

Normal hierarchy

Inverted hierarchy

Uncertainty: phases $e^{i\phi(i)}=\pm 1$, mixing $U(\Theta_{13} < 13^\circ)$, matrix element $\Delta M_{\text{Kem}}/M_{\text{Kem}} = \pm 2$

$\Rightarrow$ factor of 10 uncertainty for $\sum m(\nu_i)$

Future 0νββ projects

\[ m_{ee} \sim \left(\frac{1}{\text{enrichment}}\right)^{1/2} \cdot (\Delta E \cdot \text{bg/M} \cdot \text{t})^{1/4} \]

⇒ mass ≈ 1t, high enrichment, very low background

- GENIUS/New \(^{86}\text{Ge}\) ββ exp. at Gran Sasso
  \(^{76}\text{Ge}, 1\text{t}, 86\%\) enriched
cryo liquid active shielding, GTF started

- Majorana
  \(^{76}\text{Ge}, 0.5\text{t}, 86\%\) enriched
segmented HPGe diodes with PSA
prototype under development

- MOON (Japan, USA, Rußland)
  \(^{100}\text{Mo}, 3.3\text{t}, 85\%\) enriched
foils between tracking detectors and calorimeters

- EXO
  \(^{136}\text{Xe}, 10\text{t}, 75\%\) enriched
TPC, optical detection of barium ions

- CUORE
  \(^{130}\text{Te}, 760\text{ kg}, 34\%\) natural or enriched
TeO\(_2\) cryo detectors

- many more proposals
e.g. Cobra

These experiment expect large background improvements
expected sensitivity on \(m_{ee}\): 10 - 100 meV
Search for the absolute neutrino mass scale

1) Cosmology
   very sensitive, but model dependent

2) Search for $0\nu\beta\beta$
   very sensitive, but needs $\nu$ to be of Majorana-type
   sensitive to coherent sum: $m_{ee}(\nu) = |\sum |U_{ei}|^2 e^{i\alpha(i)} m(\nu_i)|$
   $\Rightarrow$ partial cancelation possible
Search for the absolute neutrino mass scale

1) Cosmology
   very sensitive, but model dependent

2) Search for $0\nu\beta\beta$
   very sensitive, but needs $\nu$ to be of Majorana-type
   sensitive to coherent sum: $m_{ee}(\nu) = | \sum |U_{ei}|^2 e^{i\alpha(i)} m(\nu_i)|$
   $\Rightarrow$ partial cancelation possible

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) $\Rightarrow m(\nu_e) < 23$ eV (PDG 2002)
   - **Kinematics of weak decays**
     measure charged decay products, use energy/momentum conservation $\Rightarrow m^2(\nu)$
     $\beta$-decay searches for $m(\nu_e)$
     - tritium $\beta$ decay spectrometers
     - $^{187}$Re bolometers
Direct Determination of $m(\nu_e)$

Neutrino mass determination requires:

- Very high energy resolution
- Very high luminosity

$\Rightarrow$ MAC-E-Filter

Super allowed

$E_0 = 18.6 \text{ keV}$

$t_{1/2} = 12.3 \text{ a}$

Tritium $\beta$ decay:

$^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \nu_e$

Average neutrino mass

$m_\nu = 0 \text{ eV}$

$m_\nu = 1 \text{ eV}$

$\text{const. offset} \sim m^2(\nu_e)$

$(\Sigma_i |U_{ei}|^2 m_i^2)$

Need:

- Very high energy resolution
- Very high luminosity
- Very low background

$\Rightarrow$ MAC-E-Filter

(or bolometer for $^{187}\text{Re}$)
$\beta$ decay compared to $0\nu\beta\beta$

- $\beta$ decay yields:
  \[ m^2(\nu_e) := \Sigma |U^{2}_{ei}| \cdot m^2(\nu_i) \], which determines very precisely $\Sigma m(\nu_i)$
- $0\nu\beta\beta$ experiments might be more sensitive, but they cannot determine $\Sigma m(\nu_i)$ so well
- $m(\nu_e)$ and $m_{ee}$ are complementary observables
Cryo bolometer experiments with $^{187}\text{Re}$

Multiple purpose, scalable new detector technology

basic idea: $\beta$ emitting crystal = cryodetector

$\Rightarrow$ single final state: detection of total energy except $\nu$

Choice of $\beta$ emitter: $^{187}\text{Re}$: $E_0 = 2.5$ keV ($t_{1/2} = 5 \times 10^{10}$ y)

MANU2 (F. Gatti et al., Genua)
- Re metallic crystal (1.5 mg)
- BEFS observed (F. Gatti et al., Nature 397 (1999) 137)
- sensitivity:
  - future: eV resolution by s.c. transition sensors.
    (now typically: $\Delta E = 30$ eV)

MiBeta (E. Fiorini et al., Mailand, Como)
- $\text{AgReO}_4$ (10 * 250 - 350 mg)
- Final result of MiBeta after 1 year data taking with 10 detectors:
  (M. Sisti et al., NIMA520 (2004) 125)
  $m_\nu^2 = -112 \pm 207 \pm 90$ eV$^2 \Rightarrow m_\nu < 15$ eV (90% CL)

$\beta$ environmental fine structure (BEFS) seen

Future: sensitivity 1 - 10 eV expected need: better resolution + large arrays
The Mainz Neutrino Mass Experiment 1997-2001

Mainzer ν-Gruppe 2001:

J. Bonn
B. Bornschein*
L. Bornschein*
B. Flatt
Ch. Kraus
B. Müller**
E.W. Otten
J.P. Schall
Th. Thümmler**
Ch. Weinheimer**

* → FZ Karlsruhe
** → Univ. Bonn

- $T_2$ film at 1.86 K
- quench-condensed on graphite (HOPG)
- 45 nm thick ($\approx$130ML), area 2cm$^2$
- thickness determination by ellipsometry
Final Mainz result

Improvement of S/Bg by factor 10

(analysed: \(\Sigma t = 20\) weeks)

Stable background: HF pulses on electrode inbetween single measurements of 20s


\[
m^2(\nu) = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2 \quad \Rightarrow \quad m(\nu) < 2.2 \text{ eV} \quad (95\% \text{ C.L.})
\]


Neighbour excitation amplitude from own tritium \(\beta\) spectrum

\[
m^2(\nu) = -0.7 \pm 2.2 \pm 2.1 \text{ eV}^2 \quad \Rightarrow \quad m(\nu) < 2.3 \text{ eV} \quad (95\% \text{ C.L.})
\]

C. Kraus, EPS HEP03, Aachen, July 2003

final publication will come soon: C. Kraus et al.
The Karlsruhe Tritium Neutrino experiment KATRIN

(Letter of Intent: hep-ex/0109033)

Physics Aim:

Sensitivity on neutrino mass scale: \( m(\nu) \ll 1 \text{eV} \)

- higher energy resolution: \( \Delta E \approx 1 \text{eV} \)
  since \( E/\Delta E \sim A_{\text{spectrometer}} \)
  \( \Rightarrow \) larger spectrometer

- relevant region below endpoint becomes smaller
  even less count rate \( dN/dt \sim A_{\text{spectrometer}} \)
  \( \Rightarrow \) larger spectrometer

\( \varnothing 10 \text{m} \)

new, since 12/2002
Molecular tritium sources

Standard source:

Windowless Gaseous Tritium Source (WGTS): ∅ 9 cm, length: 10 m, T = 30 K
allows to measure with near to maximum count rate using
\[ \rho d = 5 \cdot 10^{17} / \text{cm}^2 \]
with small systematics

QCTS: ∅ 8 cm, T=1.6 K, d = 35 nm
presently limited by self-charging

Alternative Source:

Quench Condensed Tritium Source (QCTS):

[Diagram showing the source components and the reaction process]

\[ \text{IN}_2 \rightarrow \text{IHe} \]

\[ \text{asymptotic maximum} = 0.5 \times \rho_d \text{free} \]

max. starting angle
45° 60° 80°

KATRIN working point
\[ \theta_{\text{max}} = 51° \]
\[ \rho_d = 5 \times 10^{17} \]

[Graph showing the column density vs. \( \rho_d \)]
Main spectrometer

- Energy resolution: \( \Delta E = 0.93 \text{ eV} \)
- high luminosity: 
  \[ L = A_{\text{Seff}} \frac{\Delta \Omega}{4\pi} = A_{\text{analyse}} \frac{\Delta E}{2E} = 20 \text{ cm}^2 \]
- Ultrahigh vacuum requirements (Background) \( p < 10^{-11} \text{ mbar} \)
- „simple“ construction: vacuum vessel at HV = electrode + „massless“ screening electrode
- industry study

Pre spectrometer:

- Transmission of electron with highest energy only 
  \( (10^{-7} \text{ part in last } 100 \text{ eV}) \)
  \( \Rightarrow \) Reduction of scattering probability in main spectrometer
  \( \Rightarrow \) Reduction of background
- only moderate energy resolution required: 
  \( \Delta E = 50 \text{ eV} \)
- Test of new ideas (XHV, shape of electrodes, avoid and remove of trapped particles, ... )
- Design optimisation '01 - '03
- Tritium purity by tritium laboratory (>95%)
- 2× stronger gaseous source
  (Ø=75mm → Ø=90mm)
  Requires Ø=10m spectrometer
- Optimised measuring point distribution (~5 eV below E₀)
- Active background reduction by inner electrode system, low background detector
  (needs further detailed tests)
Systematic uncertainties
As smaller $m(\nu)$
as smaller the region of interest below endpoint $E_0$

⇒ Excited electronic final states does not play a role ($\Delta E_{\text{exc}} > 27 \text{ eV}$)

⇒ Inelastic scattering in $T_2$ is small
  ($\Delta E_{\text{inel.}} > 12 \text{ eV} \Rightarrow$ largest interval 25eV: 2%)

⇒ One well-defined final state
  (similar to cryo detectors)

Is only true, since MAC-E-Filter response function has no tails

Still systematic uncertainties:
inelastic scattering, column density
retarding high voltage
tritium purity
potential in windowless gaseous tritium source
......
Systematic uncertainties

KATRIN's sensitivity (since June 2003):

- higher T2 purity
- larger statistics
- optimized measurement point distribution
- smaller systematic uncertainties

$\Rightarrow$ sensitivity on $m(\nu_e)$

$\approx 0.20 \, \text{eV/c}^2$

(about equal contribution from stat. and syst. uncertainties)

(90% C.L. upper limit for $m(\nu_e) = 0$)

$m(\nu_e) = 0.30 \, \text{eV}$ observable with $3\sigma$

$m(\nu_e) = 0.35 \, \text{eV}$ observable with $5\sigma$

...
Status and schedule of Katrin

2001  Presentation at Bad Liebenzell Workshop
       Foundation of KATRIN collaboration
       Letter of Intent (hep-ex/0109033)
       First, but significant funds by BMBF, FZ Karlsruhe

2002  Very positive report of International Review Panel

2003  Background investigations at Mainz
       Setup of pre spectrometer at FZK

2004  Reviewing, design report

2004 - 2008  Setup of major KATRIN components:
              WGTS, transport system, main spectrometer, detector

2008  Commissioning at start of data taking
Status of hardware components

October/November 2003

status s.c. magnets:
10/03: 2 'cryogenfree' magnets
11/03: quench tests

status main spectrometer:
04/03: X-VAT Workshop
11/03: industrial study

status detector:
10/03: 8x8 Si-PIN diode array prototype tests

status pre-spectrometer:
1.10.03: 
10/03-05/04
delivery on-site vacuum tests
06/04-12/04
emagnet tests, background studies

DPS2-F

Differential pumping section:
07/03: specification
until 10/03: tender
11/03: order
11/03: test T₂ extinction @ 4K (TLK)
Setup of pre spectrometer at FZ Karlsruhe
Electric screening by „massless“ wire electrode

Secondary electrons from wall/electrode by cosmic rays, environmental radioactivity, ...
wire electrode on slightly more negative potential

First realisation: Mainz III

Mainz V (2004-)

KATRIN pre spectrometer

New record! April 04

Gitterspannungsabhängigkeit
B=5.1T

count rate [mHz]

detector background rate 1.6mHz
total background rate: 2.8mHz

PhD thesis: B. Flatt/Mz
Neutrino masses from astrophysics and cosmology:

- **now:** $\sum m(\nu_i) < 0.7 - 2.2$ eV oder $\sum m(\nu_i) > 0$ (WMAP, 2dF/SDDS, ...)
- **in 5-10 years:** $\Delta \sum m(\nu_i) \approx 0.1$ eV ? (Planck, SDSS)
- **but always model-dependent**

$0\nu\beta\beta$:  
- very sensitive, but dependent on phases, mixing, $M_{\text{nucl}}$
- Nemo3, Cuoricino started, signal from Hd-Moscow at $m_{ee} = 0.4$ eV ?

$\beta$ endpoint spectrum: only model independent method:  
- Cryogenic detectors with Rhenium: fascinating new approach, how far do they go?  
- Mainz finished: $m(\nu_e) < 2.3$ eV (95% C.L.)  
- **KATRIN:** A large tritium $\beta$ neutrino mass experiment with sub-eV sensitivity  
  $m(\nu_e) < 0.2$ eV or $m(\nu_e) > 0$ eV (for $m(\nu_e) \geq 0.30$ eV @ 3$\sigma$)  
  $\Rightarrow$ key experiment w.r.t. absolute neutrino mass scale

**Summary**