Direct Determination of Neutrino Mass with KATRIN

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- Motivation/Methods
- Previous $\beta$-decay exp.
- KATRIN
- Conclusions
Current Theory

- Neutrino flavors a mix of three mass eigenstates
- Know the relative mass scale
- What is the absolute mass scale?
- What is the order of masses?
Neutrino Masses and Schemes

"normal" mass hierarchy $m_1 < m_2 < m_3$

quasi-degenerate

tritium experiments

Super-Kamiokande

hierarchical

first task: decide $\nu$ mass scenario
second task: Determine the $\nu$ role as hot dark matter and impact on cosmology
**Measurement Methods**

**Flavor change/oscillation:**
- Solar, atmospheric, reactor, supernova $\nu$’s
- ex. SNO, SuperK, KamLand

**$0\nu\beta\beta$-decay $\rightarrow \langle m_\nu \rangle$:**
- ex. Heidelberg-Moscow, Cuoricino
- Majorana particle

**Cosmology $\rightarrow \Sigma m_\nu$:**
- CMBR + LSS
- Model dependent
- ex. WMAP, 2dF, SDSS
Tritium provides:
- “simple” structure
- Low endpoint energy
- Moderate half-life (12.3 years)
- Super allowed transition
- Availability

But also . . .
μ calorimeters for $^{187}$Re β decay

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

$E_0 = 2.46$ keV

neutrino mass measurement with array of 10 AgReO$_4$ crystals
→ lower pile up
→ higher statistics

MIBETA experiment
(Milano, Como, Trento)


$m_\nu < 15$eV

$T_{op} \sim 70$-100mK
Tritium Beta Decay Lessons

- Los Alamos -- first to use $T_2$ gas
- Mainz & Troitsk -- used MAC-E spectrometer, improved systematics
Adiabatic magnetic guiding of $\beta_L$ along field lines in stray B-field of s.c. solenoids:

$B_{\text{max}} = 6 \, \text{T}$

$B_{\text{min}} = 3 \times 10^{-4} \, \text{T}$

Energy analysis by static retarding E-field with varying strength:

High pass filter with integral $\beta$ transmission for $E \geq qU$
## Previous Beta Decay Results

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<th>Methodology</th>
<th>Result</th>
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<td>ITEP</td>
<td>$T_2$ in complex molecule</td>
<td>$m_\nu$ 17-40 eV</td>
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<td>magn. spectrometer (Tret'yakov)</td>
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<td>Los Alamos</td>
<td>gaseous $T_2$ - source</td>
<td>&lt; 9.3 eV</td>
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<td>$T_2$ - source impl. on carrier</td>
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<td>Troitsk (1994-today)</td>
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<td>electrostat. spectrometer</td>
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<td>Mainz (1994-today)</td>
<td>frozen $T_2$ - source</td>
<td>&lt; 2.2 eV</td>
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<tr>
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<td>electrostat. spectrometer</td>
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</table>

![Graph showing experimental results](image)
Results from MAINZ

- frozen $T_2$ on graphite
- $T=1.86K$
- $A=2cm^2$
- 20mCi activity
- spectr.: $l=2m$, $\varnothing=0.9m$
- $\Delta E=4.8eV$

1994-2001 improvements in systematics:
- roughening of $T_2$ film
- inelastic scattering
- self charging of $T_2$ film
Goal: Improvement of 10x

• Strong source
  – $5 \times 10^{17}$ molecules/cm$^2$ column density
• High source purity
  – 95%
• Long term stability
• Excellent energy resolution
  – $\Delta E < 1$ eV
• Low Background rate
  – $< 10$ mHz total in endpoint region

KATRIN Task:
Investigate Tritium endpoint with sub-eV precision!!

KATRIN Aim:
Improvement of $m_\nu$ by x 10 ($2 \text{eV} \rightarrow 0.2 \text{eV}$)
Experimental Set-up

Rear System: Monitor source parameters
Source: Provide the required tritium column density
Transp. & Pump. system: Transport the electrons, adiabatically and reduce the tritium density significantly
Pre-spectrometer: Rejection of low energetic electrons and adiabatic guiding of electrons
Main-spectrometer: Rejection of electrons below endpoint and adiabatic guiding of electrons
Detector: Count electrons and measure their energy
TLK (part of FZK) is the only lab worldwide with a closed tritium cycle
- Built to demonstrate the fuel cycle for fusion (ITER)
- Provides all the necessary infrastructure for processing
- Licensed amount of 40 g, current inventory 25 g
Windowless Gaseous Tritium Source (WGTS)
- Tritium injection in the middle at 3x10⁻³ mbar
- Target column density: 5x10¹⁷ molecules/cm²
- Rear system monitors the source strength and purity
- Contained within TLK
Transport Section:
- Beam tube sections, L= 1 m, d=75 mm
- Differential Pumping Section (DPS)
- Total reduction in tritium by factor of $10^{11}$
- Cryogenic Pumping Section (CPS)
- Cryotrapping at 4.2 K by charcoal or Argon frost
Pre-Spectrometer

Parameters:
• Length: 3.4 m (flange to flange)
• Diameter: 1.7 m
• Vacuum: < $10^{-11}$ mbar
• Material: Stainless steel
• Magnets: 4.5 T

Status:
• Vacuum $7\cdot 10^{-11}$ mbar (without getter)
• Outgassing $7\cdot 10^{-14}$ mbar l/s cm$^2$
• Measurements scheduled for Fall 2005
**Requirements of main spectrometer:**

- Length (from flange to flange): about 24 m.
- Inner Diameter (cylindrical part): 9.80 m.
- Wall outgassing rate < $10^{-12}$ (mbar·l/s·cm²).
- Ultimate pressure < $10^{-11}$ mbar.
- Temperatures between $-20 \degree C$ and $350 \degree C$.
- Voltage of 18.6 kV with 1 ppm accuracy

Electromagnetic design determines the vessel shape.
How To Travel 350 km in Style!
Detector

Requirements for detector:
• Background: < 1 mHz
• Post acceleration option
• Segmented detection
• Sensitive to e⁻ < 100 keV
• Energy res. < 600 eV

Status:
• Design phase
• Discussions with manufacturers

Prespectrometer detector
Backgrounds

- Backgrounds near detector from natural radioactivity, muons, neutrons
- Minimize by material selection and active/passive shielding
- Post acceleration
- Background from spectrometer -- position resolution of detector

Monte Carlo of detector backgrounds
Challenges

• Vacuum of $10^{-11}$ mbar in the main spectrometer of over 1000 m$^3$
• Measuring tritium density to 0.1% precision
• Maintaining gradient of $10^{11}$ from WGTS to main spectrometer to avoid contamination
• Detector background of < 1 mHz
• Heating and cooling the set-up safely to reach vacuum
KATRIN Sensitivity

- Improved over original design (7 m diameter main spectrometer, source luminosity)
- Reduction in background
- Only shows statistical uncertainty
Status

- Pre-Spectrometer tests scheduled for Fall
- Most major components are ordered (main spectrometer, pumping sections, magnets, WGTS)
- Ground-breaking for building was Sept. 5
- German funding is in place
- Plan to submit a US proposal for the detector section to DOE in Fall ‘05
- On schedule for data collection beginning in 2009
Conclusions

• KATRIN can measure neutrino mass directly via kinematics of beta decay -- model independent
• Improvement of order of magnitude over previous best
• Goal of $m_\nu < 0.2$ eV (90% C.L.) achievable
• Technical challenges are in hand
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