Perspectives of direct searches of neutrino mass
with
very low energy beta spectroscopy of Re-187

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Three ways for measuring $m_\nu$

- $\beta$ decay: $m_i^2 \neq 0$ can affect spectrum endpoint. 
  Sensitive to the “effective electron neutrino mass”:

$$m_\beta = \left[ c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \right]^{\frac{1}{2}}$$

- $0\nu2\beta$ decay: Can occur if $m_i^2 \neq 0$ and $\nu=\bar{\nu}$. Sensitive to the “effective Majorana mass” (and phases):

$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

- Cosmology: $m_i^2 \neq 0$ can affect large scale structures in (standard) cosmology constrained by CMB+other data. Sensitive to:

$$\Sigma = m_1 + m_2 + m_3$$
The searches via a $\beta$ decay

- $(A,Z) \rightarrow (A,Z+1) + e^- + \nu$  (+ $Q$)

- $dN(\varepsilon) = G^2 \ F(Z,\varepsilon) \ |M|^2 \ S(\varepsilon) \ p \ \varepsilon \ (\varepsilon-\varepsilon_0)^2 \ d\varepsilon$

\[ \downarrow \]

$\varepsilon \rightarrow \varepsilon_0$

\[ dN(\varepsilon) = A \ (\varepsilon-\varepsilon_0)^2 \ d\varepsilon \]

- $dN(\varepsilon) = A \ (\varepsilon-\varepsilon_0)^2 \ [1 - m_\nu c^4 / (\varepsilon-\varepsilon_0)^2]^{1/2} \ d\varepsilon$

$\Rightarrow \varepsilon_{\text{max}} = \varepsilon_0 - m_\nu c^2$

$\Rightarrow \text{deficit} \ \propto [ m_\nu c^2 / \varepsilon_0 ]^3$
1st method: beta impulse spectroscopy

Mainz
ν group
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 ($\approx 130$ ML), area 2cm$^2$
- Thickness determination by ellipsometry
Systematic unknown effects affect the shape at the end-point: in particular the so called “final states effect”
2nd method: calorimetric beta spectoscopy

Advantages:
- Measurement of whole energy of the decay
  \[ E_i = \varepsilon_i + \Delta_i \]
  \[ \Rightarrow dN(E) = A \sum_i w_i (E_i - E_0)^2 \, dE \]
- No model dependent corrections for atomic and molecular final states.
- No correction for nuclear recoil energy and for electron energy losses, ...

Disadvantages:
- Beta Source inside the detector
  \[ \Rightarrow \] all spectrum must be acquired: but interesting area proportional to \[ [m_c^2 / E_0]^3 \]
  \[ \Rightarrow \text{Re}^{187}: \text{lowest } Q \sim 2.5 \text{ keV}. \]
  \[ \Rightarrow \text{Re}^{187}: [m_c^2 / E_0]^3 \sim 1/400 \text{ of } H^3 \]
Few Historical hints

- 1985 - First conceptual proposal of determining neutrino mass by using $^{187}$Re (S. Vitale)
- Re-187 properties relatively unknown
- Only two measurements in 1965 and 1967

Decay of Rhenium-187

R. L. Brodzinski and D. C. Conway
Department of Chemistry, Purdue University, Lafayette, Indiana
(Received 21 September 1964; revised manuscript received 23 February 1965)

The end-point energy for $^{187}$Re has been determined to be $2.62 \pm 0.09$ keV by use of (CaH)$_2$ReH$_8$ vapor in a proportional-counter spectrometer. The $^{187}$Re half-life determined from the proportional-counting experiments is $(6.4 \pm 0.3) \times 10^9$ years. This is identified as the upper half-life for decay to continuum states only. When this is combined with the total half-life of $(6.1 \pm 0.2) \times 10^9$ year obtained from $^{187}$Re/$^{188}$Os ratios in geologically dated minerals, the ratio of bound-state to continuum-state decays is found to be $0.5 \pm 0.3$. 

\begin{align*}
E_0 &= 2.6 \text{ keV} \\
E_0^* &= 2.7 \text{ keV}
\end{align*}
Cryogenic microcalorimeter for β decay

**Absorber**
- Re single crystal (99.99% purity)
- Typical dim. 500x500x500 μm
- Surfaces cleaned to optical level
- Annealed at 1300°C in UHV
- 63% of 187-Re

**Thermistor**
- Ge-NTD (#19) 50x100x240 μm with 3000Å Au pads

**Electrical & Heat link**
- Al -1% Si wires
- 15 μm diam., 1 mm length

**Thermal contact**
- High purity epoxy (spec. for optical appl.)

**ΔE FWHM=2.35ζ(kT²C) ¹/²**
Re properties

- Re metallic superconductor
  - HCP lattice
  - $T_c = 1.69$ K
  - $\rho = 21$ g/cm$^3$
  - T(Debye)= 460 K
  - M.P.=3000 K
  - Z=75
  - A=185(37%), 187(63%)
  - $\tau(1/2)$ Re-187=4x10$^{10}$ y

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- Specific heat seems contains a small contribution of normal electrons (about 1/1000) measured exciting with ionizing particles.

- Very small electron escape depth $L$ (Ex: $L < 100$ Å @ 1.6 keV) ⇒ negligible corrections for energy escape

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- $\sim 1$ pJ / mg K
- $\sim 100$ fJ / mg K
First steps

- 1992 (660 eV FWHM)
- 1996 (30 eV FWHM)

Energy Threshold = 50 eV

Detection of $^{187}$Re beta decay with a cryogenic microcalorimeter. Preliminary results

E. Cosulich, G. Gallinaro, F. Gatti and S. Vitale
INFN - Sezione di Genova, Università di Genova, via Dodecaneso 31, 16146 Genova, Italy

Received 13 July 1992

COUNTS/keV

ENERGY (eV)

$^{187}$Re $\beta$-spectrum
First pilot experiment (‘99)
End point = (2470 ± 1 stat ± 4 sys) eV
Half life = (4.12 ± 0.02 stat ± 0.11 sys) \times 10^{10} \text{y}

F. Gatti, Nucl Phys B.

Improvement of the present limits on massive neutrino admixture
But something unexplained

- The residuals of the beta spectra fit with the theoretical function show correlation well beyond the admitted statistical fluctuation.
- This has been found to be caused by a physical effect.
Why the Beta Spectrum Oscillates

- \( E(\beta) \gg E(\text{Fermi}) \Rightarrow \) beta electrons interacts with atomic cores.
- \( k^2 = 2m(E(\beta) - V)/\hbar^2 \), \( V \sim -15 \text{ eV} \),
  \( \lambda(100) \sim 0.2\text{A}, \lambda(1000) \sim 0.04\text{A} \)
  \( a = 2.76\text{A}, c = 4.45\text{ A}, c/a = 1.61\text{A} (1.63 \text{ A}) \).
- Self interference of outgoing and reflected waves from atomic shells:
  \( \Rightarrow (\text{backscattering amplitude}) \times (\text{self-interference amplitude on Re nucleus from each atomic shell}) \times (\text{number of atoms of shell}) \)
- Thermal motion energy: \( T \rightarrow 0 \sim \exp(2k^2/M\Theta_D) \)
- \( \beta \) wave attenuation ("range"): \( \exp(-\gamma R), \gamma(\varepsilon) \sim 3-20 \text{ A} \)
- First hypothesis: S.E.Koonin in 91(Nature 354,486), never observed.

\[
\chi(T_e) = \sum_i \frac{N_i |f_i(\pi)|}{kR_i^2} \sin(2kR_i + \phi_i + 2\delta_0) e^{-\gamma R_i} e^{-2\sigma_i^2 k^2}
\]
Fine Structure of the Beta Decay

F. Gatti et. Al., NATURE, VOL 397, 14, Jan, 1999
The BEFS spectroscopy could be a new appealing tool for studying hydrogen-charged materials that have received new interest in the last years because of the researches of efficient fuel hydrogen stockage.

Indeed, the atomic sites of the hydrogen could be efficiently investigated by BEFS spectroscopy experiments using the tritium b-isotope as a probe. Actually this information is hardly achievable by the EXAFS spectroscopy, because of the low electron binding energy practically preventing the recording of an EXAFS signal and the tiny cross section of H for a photoelectron of hundreds of eV coming in general to a negligible EXAFS signal.
A second generation experiment for neutrino mass search

- New technology for sensor we have been developed in the last years allow to perform an experiment with about 1 eV/c² sensitivity.

- The result of Mainz & Troitszk can be reproduced with a different methodology and hopefully improved.
A 300 Re detectors experiment

Tokyo, August 4th, 2005

Flavio Gatti
Next Generation Experiment
(proposal MARE) down to 0.1 eV\textsuperscript{7c^2}

Sensitivity at 90% c.l. [eV]

- (2.5, 2, 5)
- (5.0, 5, 20)
- (5.0, 1, 10)
- (2.5, 1, 10)

10,000 detectors deployed per year

Measurement live time [y]