New limits from the Milano neutrino mass experiment with thermal microcalorimeters

Monica Sisti
Infn - Sezione di Milano
on behalf of the Milano, Como and Trento groups

10th International Workshop on Low Temperature Detectors
Genova, July 7th - 11th 2003
Milano $\mu$-calorimeters for $^{187}$Re $\beta$ decay study

Neutrino mass measurement with arrays of 10 AgReO$_4$ $\mu$-calorimeters.

- lower pile-up
- higher statistics

**Absorbers**

AgReO$_4$ single crystals

$^{187}$Re fraction $\sim$0.32

$A_\beta \approx 5.4 \times 10^{-4}$ Hz/$\mu$g

Mass 250 $\sim$ 300 $\mu$g
Experimental set-up

Dilution refrigerator set-up for 10 detector experiment

- Inner vacuum chamber
- Mixing chamber 12mK
- Low noise bias network 12mK
- Detector holders 25mK
- Thermometer and heater for temperature stabilization at 25mK
- Signal leads
- X-ray fluorescence sources with shutter 2K
- Preamp front-end 120K(inside) 2K(outside)
- Liquid He 4K
- Liquid N shield 77K

Monica Sisti 10th International Workshop on Low Temperature Detectors, Geneva, July 7th - 11th 2009
X-ray fluorescence source for periodic calibration

- remotely controlled for continuous stability control
  - 1 cycle: 25 minutes open, 2 hours closed
- primary sources: $2 \times ^{55}\text{Fe} 5 \text{mCi}$
- roman lead to shield $^{55}\text{Fe}$ Inner-Bremsstrahlung
- fluorescence target:
  - $\text{Al } K_\alpha \rightarrow 1.5 \text{ keV}$
  - $\text{Cl } K_\alpha \rightarrow 2.6 \text{ keV}$
  - $\text{Ca } K_\alpha \rightarrow 3.7 \text{ keV}$
  - $\text{Ti } K_\alpha \rightarrow 4.5 \text{ keV}$
Measurement statistics and Detector performance

- Measurement started on June 21st 2002 and ended on April 29th 2003
  - 313 days of measurement (including daily service to cryostat, test calibrations, ...)
- Total acquired AgReO₄ mass: 2.174 mg \( \Rightarrow 187\text{Re} \) activity: 1.17 Hz
- Total statistics of β decay acquisition: 168 days \( \Rightarrow \) “beta acquisition efficiency”: 54%
  - 8751 hours×mg (AgReO₄)
  - \( 16.8 \times 10^6 \) \(^{187}\text{Re} \) decays
- Total effective measuring time: 210 days \( \Rightarrow \) “measurement efficiency”: 67%

<table>
<thead>
<tr>
<th></th>
<th>AgReO₄ mass [µg]</th>
<th>T_op [mK]</th>
<th>R_op [MΩ]</th>
<th>shutter ON [h]</th>
<th>shutter OFF [h]</th>
<th>Beta threshold [eV]</th>
<th>( \Delta E_{FWHM} ) baseline [eV]</th>
<th>( \Delta E_{FWHM} ) at 1.5 keV [eV]</th>
<th>( \Delta E_{FWHM} ) at 2.6 keV [eV]</th>
<th>( \tau_{rise} ) [µs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>272.0±3.0</td>
<td>104.0</td>
<td>1.3</td>
<td>996.7</td>
<td>4037.2</td>
<td>350</td>
<td>20.1</td>
<td>23.7</td>
<td>26.3</td>
<td>440</td>
</tr>
<tr>
<td>2</td>
<td>259.0±6.0</td>
<td>91.3</td>
<td>1.9</td>
<td>991.7</td>
<td>4069.2</td>
<td>350</td>
<td>19.4</td>
<td>23.2</td>
<td>26.6</td>
<td>340</td>
</tr>
<tr>
<td>3</td>
<td>280.3±6.5</td>
<td>104.0</td>
<td>1.3</td>
<td>1005.9</td>
<td>4105.2</td>
<td>350</td>
<td>25.8</td>
<td>28.7</td>
<td>30.5</td>
<td>670</td>
</tr>
<tr>
<td>4</td>
<td>227.7±3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>bad performances</td>
<td>375</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>249.7±2.0</td>
<td>107.1</td>
<td>1.2</td>
<td>966.3</td>
<td>3803.2</td>
<td>470</td>
<td>21.0</td>
<td>25.4</td>
<td>28.9</td>
<td>590</td>
</tr>
<tr>
<td>6</td>
<td>284.0±3.0</td>
<td>86.9</td>
<td>2.2</td>
<td>1006.7</td>
<td>4075.2</td>
<td>350</td>
<td>22.5</td>
<td>25.7</td>
<td>29.2</td>
<td>500</td>
</tr>
<tr>
<td>7</td>
<td>281.0±3.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>broken crystal</td>
<td>370</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>282.0±3.4</td>
<td>72.2</td>
<td>4.0</td>
<td>1013.9</td>
<td>4106.4</td>
<td>400</td>
<td>24.6</td>
<td>29.3</td>
<td>33.4</td>
<td>510</td>
</tr>
<tr>
<td>9</td>
<td>268.7±5.9</td>
<td>96.7</td>
<td>1.6</td>
<td>981.5</td>
<td>4017.1</td>
<td>400</td>
<td>18.4</td>
<td>21.3</td>
<td>24.9</td>
<td>430</td>
</tr>
<tr>
<td>10</td>
<td>278.3±1.5</td>
<td>101.3</td>
<td>1.4</td>
<td>981.9</td>
<td>3967.1</td>
<td>700</td>
<td>23.9</td>
<td>29.2</td>
<td>34.5</td>
<td>445</td>
</tr>
</tbody>
</table>

**Table:**

| TOT: | 7974.65 | 32180.7 |

**Array summed spectrum**

\( 21.9 \) 25.5 29.1
7975 hours detector with fluorescence source open
many extra peaks due to fluorescence of surrounding materials
Cl $K_\alpha$ nominal position ($E_{Cl K_\alpha} = 2.6217$ keV) missed by 0.5 eV
X-ray peaks have non-gaussian shape
Detector response function

- Are the response functions for X-rays and for $\beta$s from $^{187}\text{Re}$ decay the same?

- $\lambda(6 \text{ keV}) \approx 3 \mu\text{m}$
- Absorber dimension $\approx 300 \mu\text{m}$

**Ti K$_{\alpha}$ line**: $E = 4.511 \text{ keV}$

- Energy resolution depends on energy

$\Delta E_{\text{FWHM}} = 28.5 \text{ eV}$

at $E = 2.466 \text{ keV}$

($^{187}\text{Re} \beta$ end-point)
\( ^{187}\text{Re} \beta \text{ spectrum - summed Kurie plot} \)

- \( 6.2 \times 10^6 ^{187}\text{Re} \) decays collected above 700 eV
- Fit with the function: 
  \[
  F = (f_{\text{th}} + f_{\text{pup}} + f_{\text{bck}}) \otimes f_{\text{det}}
  \]
  under various assumptions for:
  - \( f_{\text{det}} \): constant/energy dependent FWHM, single/double gaussian response
  - \( f_{\text{bck}} \): constant/linear background spectrum below \( \beta \) spectrum
  - \( f_{\text{th}} \): Buhring theoretical spectrum/Buhring parametrizations

8751 hours\( \times \)mg (\( \text{AgReO}_4 \))

- \( f_{\text{th}} \rightarrow \) theoretical spectrum
- \( f_{\text{pup}} = f_{\text{th}} \otimes f_{\text{th}} \rightarrow \) pile-up spectrum
- \( f_{\text{bck}} \rightarrow \) background spectrum
- \( f_{\text{det}} \rightarrow \) detector response function

Free fit parameters:
- \( \beta \) end-point
- \( m^2 \)
- \( \beta \) spectrum normalization
- pile-up spectrum normalization
- background level
$Q = 2465.3 \pm 0.5_{\text{stat}} \pm 1.6_{\text{sys}} \text{ eV}$

Fitting interval: 0.9 ÷ 4 keV

Most precise value for $^{187}\text{Re}$

$Q$ value is stable with respect to fitting interval

good description by fit function $F$

evaluation of systematics in different energy intervals
is in progress ...
\( \tau_{1/2} = 43.2 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}} \text{ Gy} \)

- From distribution of time intervals \( \Delta t \) between \(^{187}\text{Re} \) \( \beta \) decays
- Statistical error mainly from uncertainties in the masses
- Systematic error mainly from uncertainties in the pile-up discrimination
- Most precise published value; especially relevant for geochronology

\[ N(\Delta t) = A e^{-r \Delta t} \]

- \( r \equiv \beta \) decay rate
- \( r \propto 1 / \tau_{1/2} \)
Neutrino mass

$m_{\nu}^2 = -112 \pm 20^{\text{stat}} \pm 90^{\text{sys}} \text{ eV}^2$

$m_{\nu} < 1.5 \text{ eV (90 \% C.L.)}$

Fitting interval: $0.9 \div 4 \text{ keV}$

- gaussian response function with $\Delta E_{\text{FWHM}} = 28.5 \text{ eV}$
- free constant backg.: $7 \times 10^{-3} \text{ c/keV/h}$
  $\diamond S/N (Q-30 \text{ eV} \div Q) \sim 12$
- free pile-up fraction $f_{\text{pile-up}}: 1.9 \times 10^{-4}$
  $\diamond \chi^2/\text{d.o.f.} = 0.905$

evaluation of systematics in different energy intervals
is in progress ...
Beta Environmental Fine Structure (BEFS)

- Theoretical prediction for $\Delta E_{\text{FWHM}} = 30\text{eV}$
- Experimental data:
  - threshold: 470 eV
  - statistics: $32157 \text{h} \times \text{det}$ (added old meas.)

\[ \Rightarrow \text{analysis still in progress} ... \]
Outlook and Future

- High statistic measurement of $^{187}\text{Re}$ spectrum run uninterruptedly for more than 10 months with big reproducibility

- A preliminary limit $m_\nu < 15$ eV (90% C.L.) has been set on the electron antineutrino mass

- A measurement for the “internal” calibration of the detectors to investigate the energy response function is foreseen this fall

- A new Milano calorimetric neutrino mass search has been proposed with improved sensitivity on $m_\nu \Rightarrow$ goal: $m_\nu \sim 2-3$ eV before KATRIN experiment starts

- R&D phase will start soon!
“Internal” calibration of AgReO$_4$ detectors

- Escape peaks allow internal calibration
  - $\lambda(6 \text{ keV}) \approx 3 \mu$m
  - $\lambda(70 \text{ keV}) \approx 400 \mu$m
- Escape peaks following incident X-rays are intrinsically broad $\Rightarrow$ seen in previous high statistic measurement with Pb-Re K-K escapes
  - $\Gamma_{\text{escape KK}} = \Gamma_{\text{PbK}} + \Gamma_{\text{ReK}} \approx 60.2 \text{ eV} + 42.1 \text{ eV} = 102 \text{ eV}$

Internal calibration with $^{44}$Ti
  - $\gamma$ rays @ 78.4 keV
  - no intrinsic broadening

Re K-edge @ 71.7 keV

$\gamma$-X escape peaks have only
ReK intrinsic width (~42 eV)