Ordinary muon capture (OMC) studies by means of $\gamma$-spectroscopy

Joint Institute for Nuclear Research, DUBNA

D.R. Zinatulina

30.05.2017
MEDEX’17, Prague
Main goal:

\[
\left( T_{1/2}^{0}\right)^{-1} = \left( \frac{\langle m_v \rangle}{m_e} \right)^2 \times F_{0v} \times |NME_{0v}|^2
\]
Virtual transition (Left leg)

Virtual transition (Right leg)

$A, Z$

$A, Z+1$

$A, Z+2$

$\beta\beta$
$A, Z (p,n)$

Virtual transition (Left leg)

$A, Z$ to $A, Z+1$

Virtual transition (Right leg)

$A, Z+2$
The complications of OMC
<table>
<thead>
<tr>
<th>2β-decay</th>
<th>2β-experiments</th>
<th>OMC target</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>⁷⁶Ge</td>
<td>Gerda I/II, Majorana Demonstrator, LEGEND (R&amp;D)</td>
<td>⁷⁶Se</td>
<td>2004</td>
</tr>
<tr>
<td>⁴⁸Ca</td>
<td>TGV, NEMO3, Candles III</td>
<td>⁴⁸Ti</td>
<td>2002</td>
</tr>
<tr>
<td>¹⁰⁶Cd</td>
<td>TGV</td>
<td>¹⁰⁶Cd</td>
<td>2004</td>
</tr>
<tr>
<td>⁸²Se</td>
<td>NEMO3, SuperNEMO, Lucifer (R&amp;D)</td>
<td>⁸²Kr</td>
<td>2006</td>
</tr>
<tr>
<td>¹⁰⁰Mo</td>
<td>NEMO3, AMoRE (R&amp;D), LUMINEU (R&amp;D)</td>
<td>¹⁰⁰Ru</td>
<td>—</td>
</tr>
<tr>
<td>¹¹⁶Cd</td>
<td>NEMO3, Cobra</td>
<td>¹¹⁶Sn</td>
<td>2002</td>
</tr>
<tr>
<td>¹⁵⁰Nd</td>
<td>SuperNEMO, DCBA (R&amp;D)</td>
<td>¹⁵⁰Sm</td>
<td>2002, 2006</td>
</tr>
<tr>
<td>¹³⁶Xe</td>
<td>EXO200, nEXO (R&amp;D), Kamland-Zen, NEXT</td>
<td>¹³⁶Ba</td>
<td>—</td>
</tr>
<tr>
<td>¹³⁰Te</td>
<td>Cuore 0/Cuore, SNO+</td>
<td>¹³⁰Xe</td>
<td>—</td>
</tr>
</tbody>
</table>
Measurement set-up

\[ \mu_{\text{stop}} = \overline{C0} \land C1 \land C2 \land \overline{C3} \]

Number of \(\mu\)-stop = (8 – 25) \times 10^3 \text{ with } 20 – 30 \text{ MeV/c}
PSI, 2006

- Gas inlet
- Beam entrance
- Gas vessel (C3) covered with black paper
- PMT(C3)
- PMT(C1)
- PMC(C2)
Detector efficiencies and timing

- High $\gamma$'s from $^{35}$Cl(n,\(\gamma$), $^{56}$Fe(n,\(\gamma$), $^{28}$Si(n,\(\gamma$) and $\mu$X-rays from Au, Cd, Sm
- Timing deterioration due co-axial geometry of HPGe
- Time lag due to incomplete charge collection
What do we observe and what can we get from the data?:

• Correlated events which could be sorted by time or by energy:

  A. Sorted by energy: Total capture rates;
  
  B. Sorted by time from 20-50 ns: Cascade of muonic X-rays (prompt spectra) – normalization, identification, composition of around materials and target, enrichment by isotopic shifts;
  
  C. Sorted by time from 50-700 ns: Nuclear $\gamma$-rays following $\mu$-capture (delayed spectra) – partial capture rates, doppler shape of gamma lines can obtain angular correlation ($n, \nu$), energy of high excited GDR state;

• (Background) radiation not connected directly to muons (uncorrelated spectra)

  A. Yield of different isotopes from $\beta$-decay.
Time evolution (method)

H.O.U. Fynbo et. al., NPA724 (2003) 493

The fragment number (each fragment corresponds to 10 ns time period)
Muonic-X-rays

Normalization: Number of Incoming muons ~ sum of KX-lines
The information from the $\mu$X-ray spectra catalogue is important! (It helps us to identify $\gamma$-lines, background, and gives correct selection of the targets and construction materials for different experiments with muons.)
Total μX-ray spectrum of Cd
Extraction of the partial rates

\[ \lambda_{(i)} = \frac{\sum I_{\downarrow} - \sum I_{\downarrow}}{\varepsilon \sum I(nK)} \]

detailed balance

\[ \lambda_{cap} = \lambda_{total} - Q \lambda_{decay} \quad Q \rightarrow \text{Huff-factor} \]

\[ \lambda_{(i)}[\%] = \frac{\lambda_{(i)}}{\lambda_{cap}} \]
Angular correlations with $\nu$ in OMC (Doppler shape of $\gamma$-lines)
Uncorrelated spectrum measured with $^{76}\text{Se}$ target
Yield of different isotopes from $\beta$-decay

\[
\begin{align*}
(A, Z) + \mu^- & \rightarrow (A, Z - 1) + \nu \\
(A, Z) + \mu^- & \rightarrow (A - 1, Z - 1) + \frac{1}{0}n + \nu \\
(A, Z) + \mu^- & \rightarrow (A - 2, Z - 1) + \frac{1}{2}n + \nu \\
(A, Z) + \mu^- & \rightarrow (A - 1, Z - 2) + \frac{1}{1}p + \nu
\end{align*}
\]
Target: $^{48}\text{Ti}$

Enrichment: 95.8%
Composition: $\text{TiO}_2$ powder
Quantity: 1.0 g
Total $\mu$-capture rates on $^{48}$Ti

$^{48}$Ti($\mu^-$,v1n)$^{47}$Sc($3^-_2$,807.8)
$\gamma_{807.8}$

$^{48}$Ti($\mu^-$,v1n)$^{47}$Sc($3^-_2$,767.1)
$\gamma_{767.1}$

$^{48}$Ti($\mu^-$,v1n)$^{48}$Sc($3^+_2$,622.6)
$\gamma_{370.3}$

$^{48}$Ti($\mu^-$,v1n)$^{47}$Sc($3^-_2$,1297.1)
$\gamma_{1297.1}$

272 ns isomer

Half-life: 361.1 ns
i.e., $\lambda_{cap} = 2.32 \mu s^{-1}$
Partial rates results of the $^{48}\text{Sc}$

$\sum \Lambda_{\text{par}}(\%) = 8.40 (157)$

$\Lambda_{\text{par}}$ % of $\Lambda_{\text{cap}}$ | $\Lambda_{\text{par}}$ relative
--- | --- | ---
<3 |  | 
1+ | 0.14 (8) | 
1+ | 0.45 (24) | 0.396 | 0.102
2+ | 1.175 (717) | 
1+ | 0.53 (29) | 0.466 | 0.128
1, 2, 3 | 
2+ | 0.47 (33) | 
4+, 5+ | 0.19 (8) | 
1+, 2- | 0.19 (6) | 0.167 | 0.001
1, 2- | 1.064 (628) | 0.936 | 0.007
1+ | 0.52 (23) | 0.46 | 0.05
2+ | 0.71 (42) | 
3+ | 0.55 (32) | 
3- | 0.11 (6) | 
2- | 1.136 (707) | 1.000 | 1.000
2+ | 1.185 (677) | 1.043 | 0.011
3+ | 
4+ | 
5+ | 
6+ | 

$^{48}\text{Sc}$

$\beta^-$

$^{48}\text{Ti}$

J. Suhonen
Targets: $^{76}\text{Se}$, $\text{nat}\text{Se}$

$^{76}\text{Se}$
- Enrichment: 92.4%
- Composition: Se granules
- Quantity: 5.0 g

$\text{nat}\text{Se}$
- Composition: Se granules
- Quantity: 5.0 g
Total $\mu$-capture rates on Se isotopes

Half-life: 148.48 ns
i.e., $\lambda_{\text{cap}} = 6.3 \, \mu s^{-1}$
Partial rates results of the $^{76}$As

$\beta^-\Lambda y(\%) = 13.65(255)$

$\Lambda_{par}$, % of $\Lambda_{cap}$

$\sum \Lambda_{par} (\%) = 11.99 (105)$
Targets: $^{106}\text{Cd}$, $^{\text{nat}}\text{Cd}$

$^{106}\text{Cd}$
- Enrichment: 63.0%
- Composition: Cd metal foil
- Quantity: 5.0 g

$^{\text{nat}}\text{Cd}$
- Composition: Cd metal foil
- Quantity: 5.0 g
Total $\mu$-capture rates on Cd isotopes

Half-life: 72.97 ns
i.e., $\lambda_{\text{cap}} = 13.28 \, \mu s^{-1}$
Partial rates results of the $^{106}\text{Ag}$

$\beta^-:\Lambda_{y,1+}(\%) = 22.85(806)$

$\sum \Lambda_{par,1+}(\%) = 12.36 (201)$
Target: $^{12}\text{C}$

Year: 2006
Composition: $\text{C}_4\text{H}_{10}$ (gas)
Quantity: 1.0 l (1 atm.)
The figure shows experimental spectra for the $^{12}$B nucleus, comparing the Co-60, K-40, B-12, TI-208, and B-11 isotopes. The data is displayed in three categories: uncorrected (Uncorr.), prompt, and delayed. The spectra are plotted against energy, $E_\gamma$, in keV.
Comparison of fitted spectral lines and doublets with optimal values of parameters vs experimental results

\[ \chi^2 / n = 0.69 \]
\[ dE1 = 2.6 \text{ keV} \]
\[ dE2 = 0.2 \text{ keV} \]
\[ a2(\gamma_1) = 0.0 \]
\[ a2(\gamma_2) = +0.1 \]
\[ 0.75 \gamma_1 + 0.25 \gamma_2 \]

| \( E_\gamma, \text{ keV} \) | | \( E_\gamma, \text{ keV} \) |
|-----------------------------|-----------------------------|
| \( \tau, \text{ fs} \) | \( \tau, \text{ fs} \) |
| 1667.54 | 1670.14(20) |
| \( \tau < 70 \text{ fs} \) | \( \tau < 19 \text{ fs} \) |
| 1673.52 | 1673.8(5) |
| \( \tau < 50 \text{ fs} \) | \( \tau < 6 \text{ fs} \) |
Level scheme of the $^{12}$B bound states

- 2723 keV, 0+,
- 2623.3 keV, < 19 fs, 1-,
- 1673.9 keV, < 6 fs, 2-,
- 953.14 keV, 260 fs, 2+,
- 0 keV, 1+,

$^{12}$B

$\beta^-$

$^{12}$C

<table>
<thead>
<tr>
<th>Level</th>
<th>Scheme</th>
<th>Roesch et. al. (10$^3$ c$^{-1}$)</th>
<th>Giffon et. al. (10$^3$ c$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0+</td>
<td></td>
<td>0.62 (6)</td>
<td>1.08 (13)</td>
</tr>
<tr>
<td>1-</td>
<td></td>
<td>0.38 (10)</td>
<td></td>
</tr>
<tr>
<td>2-</td>
<td></td>
<td>0.08 (4)</td>
<td>0.06 (20)</td>
</tr>
<tr>
<td>2+</td>
<td></td>
<td>0.72 (4)</td>
<td>0.27 (10)</td>
</tr>
</tbody>
</table>

$\Lambda_{par} 10^3$ c$^{-1}$

- 2622.8 keV, 6% 1670.20 keV, 80%
- 949.4 keV, 14%
- 1673.8(5) keV, 96.8%
- 720.6 keV, 3.2%
- 953.1 keV

Giffon et. al. (10$^3$ c$^{-1}$)
Conclusion and further plans:

- OMC can provide important information about the high-q component of the weak nuclear response, i.e. it is relevant for the neutrinoless double beta decay (here in particular the 2- and 1+ states)

- $^{48}$Ti, $^{76}$Se, $^{106}$Cd and $^{12}$C (and $^{82}$Kr, $^{150}$Sm) have been studied in $\mu$-capture by our group
  
  A. Total capture rates were measured;
  B. Normalization to $\mu$X-rays (total intensity of the $\mu$X(Z)-ray $K$-series gives the number of muons stopped exactly in the target with specific Z), identification were done (as a result – by product – muxrays.jinr.ru for around 75 elements)
  C. Partial capture rates were extracted, as for $^{12}$B the correct values of energies and levels life-times were found by fit with $\chi^2$ function;
  D. Yield of $^{76}$Se and $^{106}$Cd from $\beta$-decay have been measured.

- All results about $\mu$-capture experiments with different isotopes ($^{48}$Ti, $^{76}$Se, $^{106}$Cd, $^{150}$Sm and $^{82}$Kr) are in preparation.

- Collaborative work with J.Suhonen (compare results more precisely)
- Join to H. Ejiri’s group for further $\mu$-capture experiments.
Thank you for your attention!

The road to wisdom is quite simple...