Various aspects and results on beta decay, DBD, COBRA and LFV

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Contents

- Highly forbidden beta decays
- Double EC captures
- Various double beta decays
- Status of the COBRA experiment
- Charged lepton number violation
- Summary
Highly forbidden beta decays have different energy spectra, a lot of operators

3-fold forbidden: $^{180m}\text{Ta}$, ....

4-fold forbidden non-unique: $^{50}\text{V},^{113}\text{Cd},^{115}\text{In}$

5-fold forbidden: $^{96}\text{Zr},^{48}\text{Ca}$ (in the range of double beta decay)
Ta-180m

Natures rarest “stable” isotope, only nucleus present in nature in an isomeric state

M. Hult et al., Appl. Rad. Isot. 67, 918921 (2009)

New measurement:
- Sandwich Ge-detector at HADES
- Almost twice as much statistics
- Lower intrinsic background
- Improved statistical analysis
- Combining all data sets

Example:

> 5.8 x10^{16} yrs

The case of V-50

The search for V-50 has a long history...started 1955

\[ T_{1/2} > 1.7 \times 10^{18} \text{ yrs} \]

\[ T_{1/2} = 2.29 \pm 0.25 \times 10^{17} \text{ years} \]

Measurement at PTB Braunschweig (ASSE)
The case of V-50

What about beta- branch?

Theoretical prediction (shell model) for beta- branch: \[ T_{1/2} \approx 2 \times 10^{19} \text{ yrs} \]

M. Haaranen, P. Srivastava, J. Suhonen, K. Zuber, PRC 90, 044314 (2014)

New measurement ongoing at LNGS: M. Laubenstein, S. Nagomy, K. Zuber in preparation
The case of $^{113}$Cd

4-fold forbidden non-unique beta decay ($1/2^+ \rightarrow 9/2^+$)

COBRA experiment (CdZnTe detectors)

Q-value:

$$322 \pm 0.3\text{(stat.)} \pm 0.9\text{(sys.)} \text{ keV}$$


AME 2012 value: 322.6 ± 0.8 keV

Penning trap value: 323.89 (27) keV


Half-life:

$$T_{1/2} = 8.00 \pm 0.11\text{(stat.)} \pm 0.24\text{(sys.)} \times 10^{15} \text{ years}$$


Double EC and DBD

Both modes can occur with/without neutrinos
Also transitions into excited states possible

There are 35 double beta (and ECEC) emitters out of which are 6 double positron emitters

\[
(T_{1/2}^{0\nu})^{-1} = G_{A}^{4} | M_{0\nu} |^2 \left( \frac{\langle m_{ee} \rangle}{m_{e}} \right)^2
\]

Depending on Q-value competing with double positron and EC/positron decay
Excited state transitions

First excited $0^+$ states have only been seen in Mo-100 and Nd-150

GERDA phase I: First (and only) multi-detector analysis in GERDA

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$n_k$</th>
<th>$m_k$</th>
<th>$\epsilon_k$ (%)</th>
<th>Frequentist 90% C.I. $T_{1/2}$ [$10^{23}$ yr]</th>
<th>Bayesian 90% C.I. $T_{1/2}$ [$10^{23}$ yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_g.s. - 2^+_1$</td>
<td>2</td>
<td>10</td>
<td>0.389</td>
<td>&gt; 1.6</td>
<td>&gt; 1.3</td>
</tr>
<tr>
<td>$0^+_g.s. - 0^+_1$</td>
<td>5</td>
<td>34</td>
<td>0.919</td>
<td>&gt; 3.7</td>
<td>&gt; 2.7</td>
</tr>
<tr>
<td>$0^+_g.s. - 2^+_2$ branch 1</td>
<td>6</td>
<td>29</td>
<td>0.594</td>
<td>&gt; 1.7</td>
<td>&gt; 1.4</td>
</tr>
<tr>
<td>$0^+_g.s. - 2^+_2$ branch 2</td>
<td>0</td>
<td>2</td>
<td>0.092</td>
<td>&gt; 0.74</td>
<td>&gt; 0.49</td>
</tr>
<tr>
<td>$0^+_g.s. - 2^+_2$ combined</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>&gt; 2.3</td>
<td>&gt; 1.8</td>
</tr>
</tbody>
</table>

M. Agostini et al.,
Excited state transitions

More measurements:

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$\gamma$-energies</th>
<th>HL limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0/2\nu\beta\beta$ decays into excited states</td>
<td>&quot;Our&quot; measurements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{110}$Pd</td>
<td>815.3 / 657.8 keV</td>
<td>$4.0 \cdot 10^{21}$ yrs (90% CI)</td>
<td>arXiv:1606.06616 [nucl-ex], accepted</td>
</tr>
<tr>
<td>$^{102}$Pd</td>
<td>468.6 / 475.1 keV</td>
<td>$8.8 \cdot 10^{18}$ yrs (90% CI)</td>
<td>arXiv:1606.06616 [nucl-ex], accepted</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>760.5 / 818.5 keV</td>
<td>$6.9 \cdot 10^{23}$ yrs (90% CL)</td>
<td>Phys. Rev. C 93 035501 (2016)</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>1257.5 / 536.1 keV</td>
<td>$1.3 \cdot 10^{23}$ yrs (90% CL)</td>
<td>Phys. Rev. C 85 045503 (2012)</td>
</tr>
</tbody>
</table>


More half-life limits exist but almost always below $10^{20}$ years
Double EC and DPD

Theory prediction lacking for neutrinoless double EC:

- Internal bremsstrahlungs gamma (monoenergetic)
- Pair production in nuclear field
- Internal conversion


(GERDA and „our“ measurements)

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$\gamma$-energies</th>
<th>HL limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{36}$Ar</td>
<td>429.9 keV</td>
<td>$3.6 \cdot 10^{21}$ yrs (90% CL)</td>
<td>arXiv:1605.01756 [nucl-ex]</td>
</tr>
<tr>
<td>$^{58}$Ni</td>
<td>1918.3 keV</td>
<td>$2.1 \cdot 10^{21}$ yrs (90% CL)</td>
<td>J. Phys. G: Nucl. Part. Phys. 43 065201 (2016)</td>
</tr>
</tbody>
</table>

Again more measurements exist
Double EC

Suggestion: Use LXe dark matter detectors for search ($^{124,126}$Xe)


Xenon-collab: $T > 6.5 \times 10^{20}$ years, ($^{124}$Xe) Phys. Rev. C 95, 024605 (2017)
XMASS-collab.: $T > 4.7 \times 10^{21}$ years ($^{124}$Xe)
       $T > 4.3 \times 10^{21}$ years ($^{126}$Xe), Phys. Lett. B 759, 64 (2016)
Russian collab.: $T > 2.1 \times 10^{21}$ years ($^{124}$Xe), Phys. Part. Nucl. 48, 38 (2017)

More to come - more data, larger detectors like DARWIN and others
Use large amount of CdZnTe Semiconductor Detectors

- Allows for searches of Te-130, Te-128, Zn-70, Cd-114, **Cd-116** (two electrons)
- Allows for searches of Zn-64, **Cd-106**, Cd-108, Te-120 (positron/EC)

COBRA

Operation at LNGS – deep underground

Outer shielding
- 1400 m rock coverage (3700 m.w.e.)
- 7 cm boron-loaded polyethylene
- EMI box against electromagnetic interference
- Radon shield and dry N₂-flushing
COBRA

On-site detector layer assembly at LNGS

- Inner shielding
  - 5 cm of low level alpha lead (A<3 Bq/kg) and 15 cm standard lead (total 2.3 t)
  - nest: 5 cm thick electro-formed copper
  - setup completed in Nov. ’13

Publication: J. Ebert et al., The COBRA demonstrator at the LNGS underground laboratory, NIM A (2016), 10.1016/j.nima.2015.10.079
Identified background features

- $^{113}$Cd $\beta$-decay
- $^{116}$Cd $0\nu\beta$-decay ROI
- $^{40}$K
- $^{190}$Pt
- $^{210}$Po

- Mostly contaminations on lateral surfaces
- Double-energy events of $^{190}$Pt
- Near-anode reconstruction distortions

Counts [cts/kg/keV/yr] vs. energy [keV]

Results: PRC
# Obtained limits

<table>
<thead>
<tr>
<th>isotope</th>
<th>COBRA‘09</th>
<th>COBRA‘13</th>
<th>COBRA‘15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{114}$Cd</td>
<td>$2.0 \times 10^{20}$</td>
<td>$1.06 \times 10^{21}$</td>
<td>$2.27 \times 10^{21}$</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>$1.7 \times 10^{20}$</td>
<td>$1.44 \times 10^{21}$</td>
<td>$2.39 \times 10^{21}$</td>
</tr>
<tr>
<td>$^{70}$Zn</td>
<td>$2.2 \times 10^{17}$</td>
<td>$2.57 \times 10^{18}$</td>
<td>$6.12 \times 10^{18}$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$5.9 \times 10^{20}$</td>
<td>$3.88 \times 10^{21}$</td>
<td>$8.85 \times 10^{21}$</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$9.4 \times 10^{19}$</td>
<td>$9.19 \times 10^{20}$</td>
<td>$1.52 \times 10^{21}$</td>
</tr>
</tbody>
</table>

The next stage – COBRA XDEM

- switch to larger crystals (2.0 x 2.0 x 1.5) cm³ (36 g per detector)
  - higher detection efficiency
  - reduces surface contribution due to smaller surface-to-volume ratio
- concentrate on quad-CPG approach – hybrid of CPG and pixel detector
  - improve detector yield, reduce costs
  - possibility of sub-grid vetoing
  - detection of in-plane MSEs
- design and build detector module consisting of 9 x 6 cm³ CZTs

Status: 9 detectors ordered (doubles mass), 4 have arrived, installation autumn 2017
A REAL large scale experiment

A real time low-energy solar neutrino and Supernova experiment?

Threshold energy: 464 keV

$^7$Be contribution g.s. alone: 227 SNU

$\tau = 14$ s

$^{116}\text{Cd}$

$^{116}\text{In}$

$^{116}\text{Sn}$


$(^3\text{He},t)$ Beamtime at RCNP last year
Charged lepton flavour violation (CLFV)

DBD limits have improved by about a factor 10 in 15 years (optimistic)

If you want to have fun: Factor 10000 in 7 years

Focus: Coherent muon - electron conversion on nuclei (coherent = via ground state)
CLFV

\[ R = \frac{\Gamma(\mu-e \text{ conversion})}{\Gamma(\mu \text{ capture})} \]

Aim: \( R \) about \( 10^{-17} \)
(My) Questions

- What fraction int muon-electron conversion is mediated via excited states (GDR)?

- This would be most interesting for Aluminum (COMET, Mu2e)

- How does this depend on the element, i.e. target?

- Could there be spin dependent and spin independent reactions like in dark matter?  

- Could/Should there be something like 2 neutrino mu- e+ decay?
Total lepton number violation

- Neutrino-less double beta decay
  \[ T_{1/2} \approx 10^{25-26} \text{ yrs} \]

- \( \mu^- \rightarrow e^+ \) conversion on nuclei \((^{32}\text{S})\)

- Neutrino-less double muon decay of the pion
  \[ K^+ \rightarrow \pi^- \mu^+ \mu^+ \quad (< 8.6 \times 10^{-11}) \]

In general: BSM physics

Summary

• Measurement of half-lives of long living nuclides is still interesting as some values are not as good as they look at first glance

• The EC-branch half-life of V-50 has been measured

• A new value for Ta-180m half-live is given

• Spectral shape searches in highly forbidden beta decay sounds interesting for learning about quenching of $g_A$

• Various new limits on excited states searches in double beta decay and in radiative double EC have been obtained

• Resonance enhancement for double EC into excited state seems to be realised in Gd-152, but still worse than neutrino mass searches in double beta decay

• Big progress expected in the next years in charged lepton number violation processes