DF
Electron capture branching ratios for the odd-odd intermediate nuclei in ββ decay using TITAN

• Objectives:
  – experimental determination of nuclear matrix elements for 2νββ decay and 0νββ decay
  – test theory and improve theoretical prediction
  – expose deficiencies in theory
  – allow more reliable extraction of Majorana neutrino mass from 0νββ decay by using mostly experimental information

• Technique:
  – measurement of K-shell EC X-rays using radioactive ions (i.e. intermediate nuclei) trapped in an ion trap (EBIT)

• Advantages:
  – no backing material, i.e. no absorption
  – high-purity sample
  – background-free situation, i.e. precision and sensitivity
2νββ decay

allowed in SM and observed in many cases

\[
G_{(b^- b^-)}^{2n} = C G_F \frac{\sqrt{2}}{\alpha} \cos(Q_C) \frac{4}{137} F^{2n}_(-) \left| M_{(2n)}^{(DGT)} \right|^2 f(Q)
\]

\[
= G^{2n} (Q,Z) \left| M_{(2n)}^{(DGT)} \right|^2
\]

\[
M_{(2n)}^{(DGT)} = \hat{a}_m \left\{ \begin{array}{l}
\langle 0_{g.s.}^{(f)} | \hat{a}_k s_k t_k^- | 1^+_{m} \rangle \langle 1^+_{m} | \hat{a}_k s_k t_k^- | 0_{g.s.}^{(i)} \rangle \\
\frac{1}{2} Q_{bb} (0_{g.s.}^{(f)}) + E (1^+_{m}) - E_0
\end{array} \right\} + E_m \left( G T^+ \right) M_m \left( G T^- \right)
\]

accessible thru charge-exchange reactions in (n,p) and (p,n) direction (e.g. (d,\(^2\)He) or (\(^3\)He,t))
$\beta\beta$ decay

$0\nu\beta\beta$ decay

forbidden in MSM
lepton number violated
neutrino enters as virtual particle, $q\sim 0.5\text{fm}^{-1}$

mass of Majorana neutrino!!!

$G_{0n}^{0n}(b^- b^-) = G_{0n}^{0n}(Q,Z) \left| M_{DGT}^{(0n)} \frac{g_V}{g_A} M_{DF}^{(0n)} \right|^2 \left\langle m_{n_e} \right\rangle^2$

$G_{0n}^{0n}(b^- b^-) = G_{0n}^{0n}(Q,Z) \left| a_m \frac{\left\langle 0^{(f)}_{g.s.} \right| O^{(r, S, L)}_{st^-} \left\langle J^p_m \right| O^{(r, S, L)}_{st^-} \left\langle 0^{(i)}_{g.s.} \right\rangle}{\frac{1}{2} Q_{bb}(0^{(f)}_{g.s.}) + E(J^p_m) - E_0} \right|^2 \left\langle m_{n_e} \right\rangle^2 + \text{Fermi}$

nucl. matrix element

NOT accessible thru charge-exchange reactions
Theory claims:
1. both decay modes can be described with **ONE** parameter only, $g_{pp}$, which is the p-p part of the proton-neutron two-body interaction
2. $g_{pp}$ is fixed to the experimental $2\nu\beta\beta$ decay half life ($g_{pp} \sim 1$)
3. there are no intermediate cross checks with experiment
4. $2\nu\beta\beta$ decay is **sensitive** to $g_{pp}$, $0\nu\beta\beta$ decay is **insensitive** to $g_{pp}$
5. nuclear structure remains hidden
6. Theory: **trust us!!**
Recent critical assessment of the theoretical situation

1. gpp also enters into calculation of single $\beta$ decay
2. this allows to make (in few cases) precise predictions about EC-rates
3. in confronting with experiment, theory fails **BADLY** (if EC is known)

In case of single state dominance

$$M_{tot}^{(2n)} = \frac{M_{EC} M_{b-}}{\frac{1}{2} Q_{bb}(0_{g.s.}^{(f)}) + E_{g.s.}(1^+)} - E_0$$

EC = 1.4 $\varepsilon = 0.095\%$ $\log ft = 3.77$ theo

EC = 0.69 $\varepsilon = 0.023\%$ $\log ft = 4.39$ exp-1
Summarizing the theory

The use of $g_{pp}(\beta\beta) \sim 1.0$ reproduces the $2\nu\beta\beta$ decay half-life via a conspiracy of two errors: a much too large EC matrix element (too fast EC decay) is compensated by a much too small $\beta^-$ matrix element (too slow $\beta^-$ decay).

Discrepancies of 1 – 2 orders of magnitude are possible

The loose end:
EC rats are badly known, or not known at all
$^{116}$Cd $2\nu\beta\beta$ decay

$$
\begin{array}{c|c|c|c}
\text{B(GT)}^- & \text{B(GT)}^+ & M_{DGT}^m & \Sigma M_{DGT} \\
0.032 & 0.256 & 0.025 & 0.025 \\
0.12 & 0.11 & 0.020 & 0.045 \\
0.17 & 0.07 & 0.013 & 0.058 \\
\end{array}
$$

Matrix element from counting experiment:
$$\Sigma M_{DGT} = 0.064 \pm 0.007$$

$^{116}$Cd($^{3}\text{He},t$)$^{116}$In

$^{116}$Sn($d,^2\text{He}$)$^{116}$In

$^{3}\text{He}^+$ g.s. 1.0 2.2

$E^{3}\text{He} = 450$ MeV
$\Delta E = 300$ keV

$\Theta_t = [0 \ldots 2^\circ]$

$^{116}$Sn($d,^2\text{He}$)$^{116}$In

$\Theta_{c.m.} = [0 \ldots 2^\circ]$

$E_d = 183$ MeV
$\Delta E = 120$ keV
Single state dominance and its oddities

the conjecture

the oddity

- $Q_{\beta^-\beta^-} = 2802$ keV

<table>
<thead>
<tr>
<th>Case</th>
<th>$B(GT^-)$</th>
<th>$B(GT^+)$</th>
<th>$M(DGT)$</th>
<th>$T^{(2\nu)}_{1/2}$ [10$^{19}$ y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct</td>
<td>$-$</td>
<td>$-$</td>
<td>0.064</td>
<td>3.3</td>
</tr>
<tr>
<td>$(^3\text{He},t)/\beta^-$</td>
<td>0.032</td>
<td>0.256</td>
<td>0.025</td>
<td>22</td>
</tr>
<tr>
<td>EC/ $\beta^-$</td>
<td>0.47</td>
<td>0.256</td>
<td>0.09</td>
<td>1.5</td>
</tr>
<tr>
<td>theory</td>
<td>1.165</td>
<td>0.065</td>
<td>0.07</td>
<td>2.4</td>
</tr>
<tr>
<td>$(^3\text{He},t)/(d,^2\text{He})$</td>
<td>0.322$^*$</td>
<td>0.436$^*$</td>
<td>0.058</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Experiment for EC using EBIT

holding 7 ports for X-ray detectors
Electrons from β-decay (10^6 times more intense than EC) are guided away to the exit of the trap and can be used for monitoring by a channeltron.
presently investigated at Jyväskylä using „tape-station“ technique

Important to show how our technique can compete

11 shifts /10% measurement (*****)

easy measurement and used for proof of principle

will be used for initial tests

1 hour!! /10% measurement (*****)

**Diagram:**
- **100 Tc**
  - $Q_{EC} = 0.168$
  - $\varepsilon^+ = 0.002\%$
  - $t = 15.8\ s$
- **100 Mo**
- **100 Ru**
- **110 Ag**
  - $Q_{EC} = 0.892$
  - $\varepsilon = 0.3\%$ (from 1965)
  - $t = 24.6\ s$
- **110 Pd**
- **110 Cd**
measurements of EC branch from 1956 (log ft= 4.85)
2+ excited state at 558 keV can be reached

2 hour!! /10% measurement

Important measurements also because of the present conflicting experimental values.

1 – 13 shifts depending on value of $\varepsilon$
If \( \log ft(\text{EC}) = \log ft(\beta^-) \approx 8.4 \),

\( \varepsilon \approx 10^{-8} - 10^{-9} \)

Can be used a standard for calibration

Branching has been measured with high precision (0.8%)

20 shifts for 5% measurement
The most important case!!!

Experimental log ft (β⁻) = 9.7
Experimental log ft (EC) ~ 9.1

Theoretical log ft (β⁻) = 8.7
Theoretical log ft (EC) = 8.8

ε = 0.01%
ε = 0.02%

Estimated measuring time: 20,000 to 40,000 hours (because of long half-life!)
The most important case!!!

$\exp \log ft (\beta^-) = 9.7$  $\text{theo. } \log ft (\beta^-) = 8.7$

$\exp \log ft (\text{EC}) \sim 9.1$  $\text{theo. } \log ft(\text{EC}) = 8.8$

$\epsilon = 0.01\%$  $\epsilon = 0.02\%$

$\Sigma B(GT^+) \sim 0.36$

$M(\beta^-) = 0.38 (\text{exp})$

$M(\beta^-) = 0.09 (\text{theo})$
• Improvements:
  
  • Increase solid angle by **factor 2.25**
  • Increase load from $10^5$ to $5 \times 10^6$ **factor 50**

• **Beam time 200 – 400 hours**
  (25 – 50 shifts at 10%)
Presently requested beam time

- 2 x 6 shifts for tests and commissioning
  - storage capacity
  - storage times
  - isobar separation
  - capabilities of measuring absolute values
  - evaluating backgrounds

Investments

- 7 high resolution X-ray detectors
  - to be applied for at German DFG