Electron Capture branching ratio measurements at TITAN-TRIUMF

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Outline

• Neutrino experiments and the neutrino mass

• Double beta decay experiments and their theoretical description

• Electron Capture Branching Ratio measurements (EC-BR) with the EBIT
Neutrino experiments and the neutrino mass

Neutrino oscillation

- Indicate a neutrino mass [1]
- Determination of mixing angle $\theta_{ij}$
- Indicate mass hierarchy
- Determination of $\delta m^2$

Tritium decay

- Endpoint energy of $^3$H decay
- Effective mass for degenerated neutrinos:

$$m^2 = \sum_j \left| U^*_{ej} \right|^2 m_j^2$$


SNO, picture taken from http://www.oit.on.ca

KATRIN, picture taken from http://students.washington.edu
Double $\beta$ decay

Worldwide topic

Standard model

$2\nu$ double $\beta$ - decay

$n + n \rightarrow 2\, p + 2\, \beta^- + 2\, \bar{\nu}_e$

Half life $> 10^{17}$ years ($^{76}$Ge)

Dirac - Neutrino

New physics

$0\nu$ double $\beta$ - decay

$n + n \rightarrow 2\, p + 2\, \beta^- + 0\, \bar{\nu}_e$

Lepton number violation

Half life $> 1.9 \times 10^{25}$ years [2] ($^{76}$Ge)!!!

Majorana - Neutrino

Double $\beta$ decay

Worldwide topic

Standard model

$2\nu$ double $\beta$ - decay

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$\textbf{Dirac - Neutrino}$

New physics

$0\nu$ double $\beta$ - decay

$n + n \rightarrow 2\; p + 2\; \beta^- + 0\; \bar{\nu}_e$

Lepton number violation

If observed:

\[
\langle m_{\nu_e} \rangle = \left( F_N T_{1/2}^{0\nu} \right)^{1/2} \; eV
\]

Majorana Neutrino

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\[ \Gamma^{2\nu}_{(\beta^- \beta^-)} = \frac{C}{8\pi^7} \left( \frac{G_F}{\sqrt{2}} \cos(\Theta_C) \right)^4 \mathcal{F}^2(-) \left| M^{(2\nu)}_{\text{DGT}} \right|^2 f(Q) \]
\[ = G^{2\nu}(Q,Z) \left| M^{(2\nu)}_{\text{DGT}} \right|^2 \]

Primakoff-Rosen approximation [4]

\[ M^{(2\nu)}_{\text{DGT}} = \sum_m \langle 0_{g.s.} | \sum_k \sigma_k \tau_k^- | 1^+_m \rangle \langle 1^+_m | \sum_k \sigma_k \tau_k^- | 0_{g.s.} \rangle \]
\[ = \sum_m \frac{M_m (GT^+)}{E_m} M_m (GT^-) \]

accessible thru charge-exchange reactions in (n,p) and (p,n) direction (e.g. (d,^2\text{He}) or (^3\text{He},t)) as well thru EC-BR

$\Gamma_{0\nu}^{\beta^{-}\beta^{-}} = G_{0\nu}^{\beta^{-}\beta^{-}} (Q,Z) \left| M_{DGT}^{(0\nu)} - \frac{g_{V}}{g_{A}} M_{DF}^{(0\nu)} \right|^{2} \left\langle m_{\nu_{e}} \right\rangle^{2}$

$\Gamma_{0\nu}^{\beta^{-}\beta^{-}} = G_{0\nu}^{\beta^{-}\beta^{-}} \sum_{m} \frac{\left\langle 0_{g.s}^{(f)} \right\rangle \left| \mathcal{O}_{\sigma \tau}^{-(r, S, L)} \right| \left\langle J_{m}^{\pi} \right\rangle \left\langle J_{m}^{\pi} \right\rangle \left| \mathcal{O}_{\sigma \tau}^{-(r, S, L)} \right| 0_{g.s.}^{(i)} }{ \sqrt{2} Q_{\beta\beta}^{(0_{g.s.})} + E(J_{m}^{\pi}) - E_{0} }$ + Fermi $\left\langle m_{\nu_{e}} \right\rangle^{2}$

nucl. matrix element

NOT accessible thru charge-exchange reactions

Forbidden in Standard Model
lepton number violated
neutrino enters as virtual particle

Theoretical description

• Description of double $\beta$ decay nuclei with the **proton-neutron Quasiparticle Random Phase Approximation (pn-QRPA)**

• Adjustable particle-particle parameter $g_{pp}$ in pn-QRPA for all **single** and **double** $\beta$ decay calculations (The many-particle Hamiltonian is a function of $g_{pp}$)

• Extrapolation of calculated matrix elements to $2\nu\beta\beta$ half life provides $g_{pp}$ ($g_{pp} \sim 1$)

• $2\nu\beta\beta$ decay is **sensitive** to $g_{pp}$, $0\nu\beta\beta$ decay is **insensitive** to $g_{pp}$

• Cross check of $g_{pp}$ with single $\beta^-$ and EC decays
Recent critical assessment of the theoretical situation

1. \( g_{pp} \) 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:**

\[
M^{(2\nu)}_{\text{tot}} \approx \frac{M_{EC} M_{\beta^-}}{\frac{1}{2} Q_{\beta\beta} \left( 0 \left\langle f \right| g, s, \right) + E_{g.s.} (1^+) - E_0}
\]

- \( M_{EC} = 1.4 \) \( \varepsilon = 0.095\% \) \( \text{theory [5]} \)
- \( M_{EC} = 0.69 \) \( \varepsilon = (0.0227 \pm 0.0063)\% \) \( \text{exp 1 [6]} \)
- \( M_{EC} = 0.18 \) \( \varepsilon = (0.0019 \pm 0.003)\% \) \( \text{exp 2 [7]} \)

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Determination of $M_{EC}$

\[ M^{(2\nu)}_{tot} \approx \frac{M_{EC} M_{\beta_-}}{\frac{1}{2} Q_{\beta\beta}(0_{g.s.}) + E_{g.s.}(1^+) - E_0} \]

The use of $g_{pp}(\beta\beta) \sim 1.0$ reproduces the $2\nu\beta\beta$ decay half-life but not the single EC and $\beta^-$ decay.

Discrepancies of 1 – 2 orders of magnitude are possible

The loose end: EC rates are badly known, or not known at all

$Q_{EC} = 0.168$
$\epsilon = (1.8 \pm 0.9) \times 10^{-3} \%$ [8]

$Q_{\beta} = 3.202$

**TITAN Facility**

**TRIUMF Ion Trap for Atomic and Nuclear science**

- **Penning trap for high precision mass measurements**
- **Electron Beam Ion Trap (EBIT) for charge breeding**
- **Radio-Frequency Quadrupole (RFQ) cools and bunches ISAC beams**
- **Wien filter: \( q/m \) selection**

- Short-lived isotopes from an Isotope Separator and Accelerator (ISAC)
- Penning trap to cool HCl from EBIT (under design)
The EBIT - Schematic

Cryogen-free superconducting coils

Working parameters:
- Max. e-beam energy: ~70 keV
- Max. e-beam current: 500 mA \textbf{(up to 5 A)}
- Max. magnetic field strength: 6 T
- Current density (center): $10^4 \text{ - } 10^5 \text{ A/cm}^2$

Electron gun
- Einzel lenses
- Trap
- Electron collector
- Retractable e-gun
- Dip

Magnetic-field distrib. Taken from M. Froese

~460 mm
~235 mm
~60 kV
0 to ~10 kV
Up to ~60 kV

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The EBIT - Schematic

Cryogen-free superconducting coils

Einzel lenses

Trap

1/7 X-ray detector

Beta detector

EC-BR measurements

Magnetic-field distrib.
Taken from M. Froese

Dip

~284 mm

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Setup ECBR measurements

- Ion injection of $10^5 - 10^6$ ions trapped
- Storage and detection
- Penning trap
- X-ray detector
- 6 T magnet
- Beta detector (PIPS)
- Trap electrodes

**TITAN Electron Capture Branching Ratio:**
- New approach: spatial separation of X-ray and $\beta^-$ detection
- Seven X-ray detectors around segmented trap
- 2.1% solid angle for X-ray detection after EC
- No electron background at X-ray detectors due to strong magnetic field (6T)
- Long holding times in vacuum of $P < 10^{-11}$ mbar
### Branching Ratio Measurements

#### CANDIDATES FOR BRANCHING RATIO MEASUREMENTS

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Parent</th>
<th>Branching Ratio</th>
<th>Half-Life</th>
<th>Alpha Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>$^{100}$Tc</td>
<td>1+ → 0+</td>
<td>15.8 s</td>
<td>17.5 keV</td>
</tr>
<tr>
<td>$^{110}$Pd</td>
<td>$^{110}$Ag</td>
<td>1+ → 0+</td>
<td>24.6 s</td>
<td>21.2 keV</td>
</tr>
<tr>
<td>$^{114}$Cd</td>
<td>$^{114}$In</td>
<td>1+ → 0+</td>
<td>71.9 s</td>
<td>25.3 keV</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$^{116}$In</td>
<td>1+ → 0+</td>
<td>14.1 s</td>
<td>25.3 keV</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$^{82m}$Br</td>
<td>2- → 0+</td>
<td>6.1 min</td>
<td>11.2 keV</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>$^{128}$I</td>
<td>1+ → 0+</td>
<td>25.0 min</td>
<td>27.5 keV</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$^{76}$As</td>
<td>2- → 0+</td>
<td>26.2 h</td>
<td>9.9 keV</td>
</tr>
</tbody>
</table>

10$^5$ ions in trap with one half-life measurement cycle:
- solid angle: 2.1%
- detection efficiency: 30%

5.7 x 10$^{-3}$ EC counts/cycle

100 EC counts → 17636 EBIT fills → 74h

88h proposed for $^{100}$Tc
Simulations

3 MeV electrons

Loss through magnetic bottle for $\theta > 79$deg:

\[
\left( \frac{v_{||}}{v_{\perp}} \right)_{\text{crit}} = \sqrt{\frac{B_{\text{max}}}{B_{\text{min}}}} - 1
\]

Loss through wall collisions

$\rightarrow$ Rotating wall cooling or side-band cooling
β - detector

Passivated Implanted Planar Silicon detector

$^{9}$Li

Data: Li912531k3_B
Model: ExpDec1
Equation: $y = A_1 \exp(-t/t_1) + y_0$

$T_{1/2} = 178.3$ ms  $T_{1/2 \text{ (PIPS)}} = 217.3(16.6)$ ms

$Q = 13.6$ MeV

$1130$ counts

$2.1 \times 10^6$ counts

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Summary

- There are discrepancies in the description of $2\nu\beta\beta$ within the pn-QRPA
- $M_{EC}$ and $M_\beta$ for single decays do not agree with those extrapolated from $2\nu\beta\beta$ decay
- TITAN EBIT offers a novel approach for EC-BR measurements
  - Long storage times
  - Low background at X-ray detector

...for the future

- TITAN EBIT will be connected to the TITAN beam line (EBIT was commissioned in August 2006).
- First EC branching ratio measurements with the EBIT by the end of this year
People/Collaborations


U. of Manitoba
McGill U.
Muenster U.
MPI-K
GANIL

U. of Calgary
U. of Windsor
Colorado School of Mines
UBC
TU München