Reaction studies of Double Gamow-Teller transitions in $\beta\beta$-decay nuclei

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Starting point

Experimental information on nuclear double Gamow-Teller/double spin-dipole responses is seriously limited.

**Lifetimes of $2\nu\beta\beta$ nuclei**
- limited to low lying states (mostly ground states) for $\sim 10$ species.

**Single Gamow-Teller/spin-dipole responses**
- rich data, constraints to structure models.
  Relationship to double GT/SD responses is not direct.
Existing data: lifetimes of $2\nu\beta\beta$ decay nuclei

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}^{2\nu}$ (y)</th>
<th>References</th>
<th>$M_{GT}^{2\nu}$ (MeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>$(4.2 \pm 1.2) \times 10^{19}$</td>
<td>(55, 56)</td>
<td>0.05</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>$(1.3 \pm 0.1) \times 10^{21}$</td>
<td>(57–59)</td>
<td>0.15</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>$(9.2 \pm 1.0) \times 10^{19}$</td>
<td>(60, 61)</td>
<td>0.10</td>
</tr>
<tr>
<td>$^{96}\text{Zr}^\dagger$</td>
<td>$(1.4^{+3.5}_{-0.5}) \times 10^{19}$</td>
<td>(62–64)</td>
<td>0.12</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>$(8.0 \pm 0.6) \times 10^{18}$</td>
<td>(65–70), (71)$^\dagger$</td>
<td>0.22</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>$(3.2 \pm 0.3) \times 10^{19}$</td>
<td>(72–74)</td>
<td>0.12</td>
</tr>
<tr>
<td>$^{128}\text{Te}^b$</td>
<td>$(7.2 \pm 0.3) \times 10^{24}$</td>
<td>(75, 76)</td>
<td>0.025</td>
</tr>
<tr>
<td>$^{130}\text{Te}^c$</td>
<td>$(2.7 \pm 0.1) \times 10^{21}$</td>
<td>(75)</td>
<td>0.017</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>$&gt;8.1 \times 10^{20}$ (90% CL)</td>
<td>(77)</td>
<td>$&lt;0.03$</td>
</tr>
<tr>
<td>$^{150}\text{Nd}^\dagger$</td>
<td>$7.0^{+11.8}_{-0.3} \times 10^{18}$</td>
<td>(68, 78)</td>
<td>0.07</td>
</tr>
<tr>
<td>$^{238}\text{U}^d$</td>
<td>$(2.0 \pm 0.6) \times 10^{21}$</td>
<td>(79)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

< 10$^{-3}$ of sum rule values

>99.9%: unobserved

Elliot & Vogel (2002)
Reaction studies of nuclear weak responses

Charge exchange reaction: driven by STRONG interaction
($p, n$), ($^3\text{He}, t$), ($d, ^2\text{He}$) . . .

$^A(Z-1)$ $^A(Z-1)$

$^A Z$ $^A Z$

$\nu$ $\pi^+$

$W^+$

Proportionality

Our understanding of GT responses

Gamow-Teller giant resonances → quenching tensor force effects $g_{\text{NN}}$, $g_{\text{NA}}$

accessed with charge exchange reactions
Our understanding of GT² responses

Gamow-Teller giant resonances
→ quenching tensor force effects $g_{NN}$, $g_{N\Delta}$

Double GT Giant resonances
(exhausts a major part of sum-rule strength)

(0.01–0.1% of the sum-rule strength)

Accessed with charge exchange reactions

β-decay

Ground state of the parent nucleus

$E_x$ in daughter nucleus

$E_x$ in grand-daughter nucleus

Accessed with double charge exchange reactions
Double Gamow-Teller Giant Resonances

Gamow-Teller resonance built on a Gamow-Teller resonance exhausts a major part of the $(GT)^2$ strength ↔ $2\nu\beta\beta$ decay


$B(GT^2) \sim 100$

$B(GT^2) \sim 0.1$
Reaction studies of DGT responses will open

- Extension of DGT studies to wider range of excitation energies (no Q-value restriction) any nuclei (not limited to $\beta\beta$ nuclei)
- Quenching of the $\text{GT}^2$ strength
- Nature of DGTGR

Is the DGTGR a simple superposition of single GT?

- Momentum-transfer dependence of $\beta\beta$-decay ME

Double GT Giant resonances (exhausts a major part of sum-rule strength)

(0.01–0.1% of the sum-rule strength)

Accessed with double charge exchange reactions

$E_x$ in grand-daughter nucleus

Accessed with charge exchange reactions

$\beta\beta$-decay
Which double charge-exchange reaction should be used?
Previous attempts to observe DGTR: \((\pi^+, \pi^-)\)

\((\pi^+, \pi^-) @ 292 \text{ MeV LAMPF}\)

S. Mordechai et al., PRL 60, 408 (1988).

Double IAS & Double GDR

Double GT

\((\pi^+, \pi^-)\) populates spin-flip states only weakly
Previous attempts to observe DGTR: \((^{18}\text{O},^{18}\text{Ne})\)

\((\pi^+,\pi^-) \@ 292 \text{ MeV LAMPF}\)

populates spin-flip states only weakly

S. Mordechai et al., PRL 60, 408 (1988).

\((^{18}\text{O},^{18}\text{Ne}) \@ 76\text{MeV/A MSU, GANIL}\)


\((^{18}\text{O},^{18}\text{Ne})\) induces \(\beta^+\beta^+\) transitions

\(\beta^+\) is \(\times 10\) weaker than \(\beta^-\)
due to Pauli blocking
Previous attempts to observe DGTR: \((^{11}\text{B},^{11}\text{Li})\)

\((\pi^+\pi^-) @ 292\text{ MeV LAMPF}\)
- populates spin-flip states only weakly
- S. Mordechai et al., PRL 60, 408 (1988).

\((^{18}\text{O},^{18}\text{Ne}) @ 76\text{MeV/A MSU, GANIL}\)
- \(\beta^+ \times 10\) weaker than \(\beta^-\) due to Pauli blocking

\((^{11}\text{B},^{11}\text{Li}) @ 69\text{MeV/A RCNP}\)
- Lightest projectile
- Small overlap in projectile?
What does “good” double exchange reaction mean

Large production yield
- Large cross section
- Large luminosity
  (high-intensity beam)

Clear event identification

\[(\pi^+, \pi^-) \ (^{18}\text{O}, ^{18}\text{Ne}) \ (^{11}\text{B}, ^{11}\text{Li})\]

<table>
<thead>
<tr>
<th>Large cross section</th>
<th>Large luminosity</th>
<th>Clear event identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\times)</td>
<td>(\times)</td>
<td>(\triangle)</td>
</tr>
<tr>
<td>(\times)</td>
<td>(\bigcirc)</td>
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<td>(\times)</td>
<td>(\bigcirc)</td>
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<tr>
<td>(\times)</td>
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</tbody>
</table>
New idea to use \((^{12}\text{C}, ^{12}\text{Be})\) reaction

&

First experimental results on \(^{48}\text{Ca}\)
New Idea: \( (^{12}\text{C}, ^{12}\text{Be}(0^+_2)) \) Reaction

\( ^{12}\text{C}(\text{gnd}) \rightarrow ^{12}\text{Be}(0^+_2) \) transition is strong.

\( B(\text{GT}^2) \sim 0.3 \)

\( ^{12}\text{C}(^{18}\text{O}, ^{18}\text{Ne}) \) experiment → Matsubara, Takaki, TU et al., Few-Body Syst. 54, 1433 (2013).

• This is because all of the initial \( ^{12}\text{C}(0^+_\text{g.s.}) \), intermediate \( ^{12}\text{B}(1^+_\text{g.s.}) \) and final \( ^{12}\text{Be}(0^+_2) \) state are dominated by 0\( \hbar \omega \) configuration.

• Delayed-\( \gamma \) tagging enables clear event identification.

\( \tau( ^{12}\text{Be}(0^+_2)) = 331 \text{ ns} \)

\( \Rightarrow \) TOF \( \sim 150 \text{ ns} \) (Grand Raiden)

• \( \sim 70\% \) of the \( ^{12}\text{Be}(0^+_2) \) state can survive and reach the focal plane.

These two characteristics make this reaction specially effective in DGTR studies.

Large cross section & high-intensity beam

Clear event identification

two 511 keV \( \gamma \)-ray in back to back
Experiment @ Grand Raiden (RCNP)  

Active stopper (plastic) + NaI scintillators

2×511 keV γ-ray in back-to-back

Target $^{48}$Ca:10 mg/cm$^2$

$^{12}$C beam (100 MeV/u, 16 pnA)

$\tau = 331$ ns

$\tau = 362.96 \pm 33.31$ ns
DCX Spectrum and comparison with \((\pi^+,\pi^-)\)

\[ \sigma \tau^2 \]

\[^{48}\text{Ca}(^{12}\text{C},^{12}\text{Be}(0^+))\]
\[ \theta_{\text{lab}}=0^\circ \]

Takaki, TU et al.

\[ \tau^2 \]

M. Kaletka et al., PLB 199, 336 (1987)

DIAS

No apparent structure
“Double Gamow-Teller” Spectrum in $^{48}$Ti

$^{48}\text{Ca}(^{12}\text{C},^{12}\text{Be}(0^+_2))$ @0deg:
Takaki, TU et al.

Definitely there is something.
Usefulness of $(^{12}\text{C},^{12}\text{Be}\gamma)$ is proved.
But limited statistics prevent us from drawing final conclusion.
(near) Future Plan
Future experiment @RI Beam Factory, RIKEN

High intensity $^{12}\text{C}$ beam ($<1\mu\text{A}$)
High efficiency $\gamma$-ray array (DALI2)
\[ \rightarrow \times 500 \text{ statistics!} \]
Liq. Hydrogen to stop $^{12}\text{Be}$
\[ \rightarrow \text{ background free} \]

Higher statistics data
Momentum transfer dependences
Data for $^{48}\text{Ca}$, $^{76}\text{Ge}$, $^{116}\text{Cd}$ etc. etc.
Summary

Reaction study with heavy-ion double charge exchange reactions can extend our reach to double GT/SD states to a wider range of excitation energy to a variety of nuclei. One flagship is observation of DGT giant resonances. 

$^{12}\text{C}, ^{12}\text{Be}\gamma$ can be a good probe to investigate the DGT states. Results from the first RCNP experiment indicate existence of DGT giant resonances in $^{48}\text{Ti}$. ★ Reliable reaction theory for the double charge exchange should be established for quantitative discussions.
Collaborators


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