荷電交換反応による二重ベータ崩壊核行列要素の研究

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0v double beta decay
- Majorana $\nu$ is emitted and absorbed.
- Nucleus is kicked by 50~100 MeV/c twice.

NME is important!
- analysis ... absolute mass / mass limit of $\nu$
- research planning ... which nucleus is the best candidate?
\[ M^{(0\nu)}_{GT} = \sum_{J^\pi} M^{(0\nu)}_{GT}(J^\pi) \]

\[ M^{(0\nu)}_{GT}(J^\pi) = \sum_{n\lambda} \langle 0^+_f || \sum_j [\sigma_j F_{\lambda}(r_j)] t_j^- || J^\pi n \rangle \]
\[ \times \langle J^\pi n || \sum_j [\sigma_j F_{\lambda}(r_j)] t_j^- || 0^+_i \rangle \]

Neutrino potential

- large uncertainty in GT(1+) component
- largest contribution from dipole (2-)

Intermediate states:
- g.s.
- other states of various \( J^\pi \).

Double Gamow-Teller
Double Spin-Dipole

\( (A,Z) \) \( \beta^+ \beta^- \) \( (A,Z+1) \)

\( (A,Z+2) \)

\( J^\pi \) of intermediate state

\[
\begin{array}{c}
g_{pp} = 0.89 \\
g_{pp} = 0.96 \\
g_{pp} = 1.00 \\
g_{pp} = 1.05
\end{array}
\]
Several Methods...

- Ab-initio (more correlations)
- Coupled cluster Calculation
- RPA + (n-n/p-p pair)
- No-core shell model
- Shell model
- Renormalization of transition operator
  - Holt and Engel, arXiv:1304.4202
  - Engel and Hagen, PRC79,064317(2009)
- (Light nuclei)
- Non-perturbative Higher order corr.
  - G. Hagen et al. (ORNL+Oslo...)
- Large-basis calculations

... the first convergence may appear for the $^{48}$Ca case
Correlations or model spaces?

For example, comparing SM w/ QRPA

- Each has uncertainty of ~ 30%
- SM predictions … 20-50% smaller than QRPA.
- Concerns…

SM : limited model space
QRPA : sufficient correlation?

Menendez, PRL100(2008)052503

FIG. 3 (color online). The neutrinoless double beta decay NME’s; comparison of ISM and QRPA calculations. Tu07; QRPA results from Ref. [20], Jy07; QRPA results from Ref. [21]. ISM $s \leq 4$ and ISM; present work. The ISM results have uncertainties in the 20% range (see text).

…Guides from Experiments are necessary.
Experimental attempts to guide the calculation

1. Static properties: particle occupation / vacancy
2. Single transitions
   - Single beta decay
   - GT transitions
   - Other transitions
3. Double transitions
   - $2
\nu\beta\beta$ decay ($M^{2\nu}$)
   - Double GT resonance?
GT strength distributions... comparison with shell model

Shell model ...
with quenched operator
Spectra agree qualitatively up to ...
(p,n) : \( E_x = 15 \text{ MeV} \)
(n,p) : \( 8 \text{ MeV} \)
Strengths beyond ...
... underestimated.

Necessity of larger model space? Correlations?, …
Constraint of double transition (in addition to $M^{2\nu}$)
... Double GT resonance

Sum rule:

$$\Sigma B(\text{DoubleGT}) = 6(N-Z)(N-Z-1)$$

= 336 for $^{48}\text{Ca}$

Only 0.02 is going to g.s. of $^{48}\text{Ti}$
10 days of experiment was fully approved at RCNP BPAC, Mar2014

Search for
Double Gamow-Teller Giant Resonances in $^{48}$Ti
via
the Heavy-Ion Double Charge Exchange
$^{48}$Ca($^{12}$C, $^{12}$Be($0^+_2$)) Reaction

Motonobu Takaki (CNS, University of Tokyo)
&
Tomohiro Uesaka (RIKEN Nishina Center)
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.

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

- \(\tau(^{12}\text{Be}(0^+_{2})) = 330\) ns \(\gg\) TOF \~ 150 ns
- \(~70\%\) of the \(^{12}\text{Be}(0^+_{2})\) state can survive until reaching the GR F.P.

... Effective in Double GT excitation.

\((^{12}\text{C},^{12}\text{Be})\) reaction = Double GT probe

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

Exp by Takaki

Exp by Takaki

\(0p_{1/2}\)

\(0p_{3/2}\)

\(0s_{1/2}\)

(proton)

(neutron)

\((^{12}\text{C},^{12}\text{Be})\) reaction = Double GT probe

... Effective in Double GT excitation.

Delaye\(\gamma\) tagging enables clear event identification.

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\(\text{two 511 keV }\gamma\)-ray in back to back
Exp by Takaki

Experimental setup

Target

- $^{48}\text{Ca}:10 \text{ mg/cm}^2$
- $\text{H}_2^{18}\text{O}:20 \text{ mg/cm}^2$

Plastic + 16 NaI(Tl) → identify back-to-back 511 keV photon

$^{12}\text{Be}$ beam (100 MeV/u, 30 pnA)
Test Experiment

$^{18}$O($^{12}$C,$^{12}$Be$\gamma$)$^{18}$Ne(gnd)

Decay time constant: $395^{+173}_{-92}$ ns
$\Leftrightarrow$ 331 ns in literature

BG due to particle mis-identification

with $\gamma$-tag $\times 10$

w/o $\gamma$-tag

Counts (A.U.)

Excitation Energy

Nal(Tl)
17kHz

511keV

12Be

511keV
<table>
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<tr>
<th>item</th>
<th>Exp</th>
<th>Theory</th>
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<tr>
<td>static</td>
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<td>△</td>
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<tr>
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<td>○</td>
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<tr>
<td>single transition Beta decay</td>
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<td>○</td>
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<tr>
<td>B(GT) dist. at Low Ex</td>
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<td>△</td>
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<td>High Ex</td>
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<tr>
<td>Double SD</td>
<td>×</td>
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Occupation No. を良く記述するよう理論計算のインプットを調整
-> QRPA と Shell model との M^{2v} 予言値 がほぼ一致

... 新たな実験データは計算信頼度の向上に役立っている。
Summary

- \( 0^\nu \) nuclear matrix element \( M^{0\nu} \) is necessary to deduce the majorana \( \nu \) mass from the \( 0^\nu \) half life.
- Prediction of \( M^{0\nu} \) depends on the models of nuclear structure → Guiding data are needed.

- \( B(GT) \) distributions in the \( ^{48}\text{Ca}(p,n)^{48}\text{Sc} / ^{48}\text{Ti}(n,p)^{48}\text{Sc} \)
  - \( B(GT; \beta^+) \) is underestimated
    ... correlations/model space is not enough.
- Search for double GT resonance in \( ^{48}\text{Ca}({}^{12}\text{C},{}^{12}\text{Be}) \) reaction ...
  ... main component of the double GT transition is studied.