Double Gamow-Teller transitions and its relation to neutrinoless $\beta\beta$ decay

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Outline

• Large scale shell model calculations of neutrinoless double beta decay nuclear matrix element ($0\nu\beta\beta$ NME) of $^{48}$Ca

• Double Gamow Teller Resonance and its relation to $0\nu\beta\beta$ NME of $^{48}$Ca

• Relation between double Gamow Teller transition and $0\nu\beta\beta$ NME, systematic study
Nuclear Matrix Element (NME) of neutrinoless double-beta decay

Majorana particle or not? neutrinoless double beta decay

lepton number violation (beyond the standard model)

Theoretical prediction on the $0\nu\beta\beta$ NME varies depending on theoretical models.

$[T_{1/2}^{0\nu}]^{-1} = G_{1}^{0\nu} |M_{0\nu}|^2 \left( \frac{<m_{\beta\beta}>}{m_e} \right)^2$

Half life (exp.) | NME | effective neutrino mass

SM calc. for nuclear matrix element (NME) of $^{48}{\text{Ca}}$ $0\nu\beta\beta$ decay

$2\nu\beta\beta$ decay
$^{48}{\text{Ca}} \rightarrow ^{48}{\text{Ti}} + 2e^- + 2\bar{\nu}_e$

$0\nu\beta\beta$ decay
$^{48}{\text{Ca}} \rightarrow ^{48}{\text{Ti}} + 2e^-$

Half life (exp.)
NME
Effective neutrino mass

Large scale shell model calculation including 2hw excitation from sd shell with closure approximation

Why does the NME increases by extending the model space?

decompose this sum

\[ M_{0\nu} = \sum_{J} \langle 0_f^+ | \sum_{i,j,k,l} M_{ij,kl}^{J} \left[ (\hat{a}_{i}^+ \hat{a}_{j}^+)^{J} (\hat{a}_{k} \hat{a}_{l})^{J} \right]^0 | 0_i^+ \rangle \]

pairing

⇒ Talk by T. Otsuka, tomorrow
$0\nu\beta\beta$-decay NME and double Gamow-Teller (DGT) transition

- $0\nu\beta\beta$-decay nuclear matrix element (NME) with closure approximation

$$M^{0\nu} = M_{GT}^{0\nu} - \left( \frac{g_V}{g_A} \right)^2 M_F^{0\nu} + M_T^{0\nu}$$

$$\mathcal{O}_{GT} = \tau_1\tau_2 (\sigma_1 \cdot \sigma_2) H_{GT}(r, E_\kappa),$$

$$\mathcal{O}_F = \tau_1\tau_2 H_F(r, E_\kappa),$$

$$\mathcal{O}_T = \tau_1\tau_2 S_{12} H_T(r, E_\kappa),$$

$$H_\alpha(r, E_\kappa) = \frac{2R}{\pi} \int_0^\infty \frac{f_\alpha(qr) h_\alpha(q^2)q \, dq}{q + E_\kappa - (E_i + E_f)/2}$$

N.B. GT-type NME is dominant

- DGT transition

$$\mathcal{O}^\pm = [\sigma t^\pm \otimes \sigma t^\pm]^{(\lambda)} \quad \lambda = 0, 2$$
Double Gamow-Teller transition

• DGT transition probability

\[ B(DGT; \lambda) = \frac{1}{2J_i + 1} \langle J_f \parallel [\sigma t^- \otimes \sigma t^-]^{(\lambda)} \parallel J_i \rangle^2 \]


• DGTR itself attracts attention as an exotic collective motion

• In the first half of this talk, focus on \(^{48}\text{Ca}\)
  – one of \(\beta\beta\) decay nuclei with large Q value
  – shell model calc. is a suitable theoretical method
  – DGT resonance (DGTR) was/will be measured experimentally

  Takaki at RCNP/Osaka, plan: RIBF/RIKEN, INFN/Catania
By studying the stronger DGT transitions experimentally (…), theoretically, one may be able to “calibrate” the calculations of 2β-decay nuclear elements.

N. Auerbach, L. Zamick and D.C. Zheng

“smearing” the Fermi surface. The matrix element, however, still remains very small and accounts for only a $10^{-4}$ to $10^{-3}$ fraction of the total DGT sum rule [13]. A precise calculation of such hindered transitions is, of course, very difficult and is inherently a subject of large percent uncertainties. At the present there is no direct way to “calibrate” such complicated nuclear structure calculations involving miniature fractions of the two-body DGT transitions. By studying the stronger DGT transitions and, in particular, the giant DGT states experimentally and as we do here, theoretically, one may be able to “calibrate” the calculations of 2β-decay nuclear elements.
Both sides of the Gamow-Teller transitions are also useful for the “calibration” of the $\beta\beta$-decay nuclear elements. However only absolute values can be measured experimentally. (relative phase unknown)

Red symbol : exp.
Blue line: shell-model calc.

Y. Iwata et al., JPS Conf. Proc. 6, 030057 (2015)
Double Gamow-Teller Resonance in $^{48}$Ca
by shell-model calculations
Lanczos strength function smeared out by Lorentzian $\Gamma = 1$ MeV

focus on GXPF1B and $pf$ shell hereafter
Dependence of isoscalar pairing

We artificially add the isoscalar pairing interaction

\[ H' = H + G^{10} P^{J=1, T=0} \]

The NME is sensitive to the J=1 proton-neutron matrix element, or isoscalar pairing
Isoscalar pairing dependence: $0\nu\beta\beta$ decay NME and DGT

The NME is sensitive to the J=1 proton-neutron matrix element, or isoscalar pairing
DGTR width vs NME

\[
\sigma = \sqrt{\sum_{f} (E_f - E_c)^2 B(DGT2, f) / \sum_{f} B(DGT2, f)}
\]

\[
E_c = \sum_{f} E_f B(DGT2, f) / \sum_{f} B(DGT2, f).
\]

N. B. width is independent of quenching factor.
DGTR and Isovector pairing

\[ H' = H + G^{01} P_{J=0, T=1} \]

\[ E_c = \sum_f E_f B(DGT2, f) / \sum_f B(DGT2, f). \]

DGTR centroid energy vs. NME

\[ E_c (\text{MeV}) \]
DGT transition between the ground states

See the relation between DGT(\(\lambda = 0\)) and \(0_{\nu\beta\beta}\) NME (initial and final states are common)
DGT($\lambda = 0$) transition vs. $0\nu\beta\beta$ decay NME

Ca, Ti, Cr isotopes
(N=22, 24, ..., 36)

SM: KB3G, GXPF1B, SDPFMU-DB interactions

filled symbol: SM w/ seniority-zero approximation

EDF: $^{48}$Ca Gogny+GCM
Rodriguez et al., PLB719 174 (2013)
DGT transition vs 0vbb decay NME

$^{74-82}$Ge, $^{74,76}$Se, $^{124-132}$Sn, $^{128-130}$Te, $^{134,136}$Xe

SM: shell model
GCN2850, jj44b, JUN45, GCN5082, QX

EDF: Gogny+GCM
Rodriguez et al., PLB719 174 (2013)

QRPA: AV18+G-matrix
F. Simkovic et al., PRC83, 015502 (2011).
DGT and $0\nu\beta\beta$ NMEs: distance and momentum dependences: $^{48}\text{Ca}$

\[ M = \int C(r_{ab}) dr_{ab} \quad \text{internucleon distance} \]

\[ M = \int C(|q|) d|q| \quad \text{momentum transfer} \]
DGT and $0\nu\beta\beta$ NMEs: distance and momentum dependences: $^{136}\text{Xe}$
Why linear correlation between DGT and $0_{\nu}\beta\beta$ NMEs?

- Similar dependence in distance dependence, contrary to momentum dependence
- Intermediate and long-range parts show cancellation, resulting small contribution to the NME. The short-range character dominates

- factorization: short-distance details decouple from long-distance dynamics
NO cancellation
⇒ small M(DGT)

F. Simkovic et al., PRC 83 015502 (2012)
Summary

• Using the shell-model calculations, double Gamow-Teller Resonance of $^{48}$Ca and its relation to $0\nu\beta\beta$ NME is studied.
  – DGTR is correlated to the $0\nu\beta\beta$ NME via isovector and isoscalar pairing correlations.

• DGT and $0\nu\beta\beta$ NMEs show clear linear correlation. They are dominated by the short-range character.

• The HIDCX reaction may be useful to “calibrate” theoretical studies of $0\nu\beta\beta$ NME. Challenges remain: reaction theory of HIDCX, …