Nuclear Spin Physics via Polarization Measurements

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Contents

Three nucleon force effects in few-nucleon systems
  • Clear signature of three nucleon forces and defects in spin-dependence
  • Comparison with chiral-EFT predictions
  • Isospin dependence

Spin-isospin responses for stable and unstable nuclei
  • Isospin dependence of spin-isospin responses and residual interactions
  • Spin-isospin incompressibility and neutron skin thickness

New spin-isospin mode and application to neutrino physics
  • Double Gamow-Teller transition $0\nu\beta\beta$ matrix element
  • Double Gamow-Teller resonance

Emphasis on recent experimental data from RIKEN/RIBF, RCNP, NSCL/MSU
  (high-precision polarization observables and spin-isospin excitations)
Three nucleon force effects in few-nucleon systems
3NF effects in finite nuclei

Ab Initio calculations for light nuclei

Green’s function Monte Carlo, no-core shell model, etc.

- 2NF: provide less binding energies
- 3NF: well reproduce the data (ex. $^4$He)

Different predictions for UIX and IL7 3NFs → What is different?

Many other observables (radii, densities, transitions, ...) also well described, Carlson, et al., RMP (2015)

Stefano Gandolfi (LANL) - stefano@lanl.gov

The EOS of neutron matter and neutron star structure 13 / 40

**Diagram:**

- $^4$He
- $^6$He
- $^6$Li
- $^7$Li
- $^8$Be
- $^9$Be
- $^{10}$B
- $^{12}$C

Argonne v18 with UIX or Illinois-7
GFMC Calculations 1 June 2011

**Graph:**

- Energy (MeV)

- Various nuclei with their energy levels and quantum numbers.
Isospin dependence of 3NF effects

UIX and IL7 3NF

\[ V_{ijk}^{\text{UIX}} = V_{ijk}^{2\pi, P} + V_{ijk}^{R} \]

\[ V_{ijk}^{\text{IL7}} = V_{ijk}^{2\pi, P} + V_{ijk}^{R} + V_{ijk}^{2\pi, S} + V_{ijk}^{3\pi} \]

- p-wave πN scattering term (Fujita-Miyazawa type)
- isospin-independent repulsive term
- s-wave πN scattering term (∼3-4%)
- 3π rings with Δ’s (∼10%)
  - different isospin dependence
  - more attraction for N>Z

General structure of 3NF

- 22 structure func./generators are needed under some invariances/symmetries

Need a systematic theoretical approach → chiral EFT


Chiral expansion of nuclear forces

Two-nucleon force

LO ($Q^0$)

NLO ($Q^2$)

$N^2$LO ($Q^3$)

$N^3$LO ($Q^4$)

Three-nucleon force

$2$ LECs in $3$NF at $N^2$LO
- B.E. of $^3$H
- c.s. minimum in Nd scattering

Four-nucleon force

Can chiral nuclear force at $N^2$LO (consistent 2N+3N forces) reproduce 3N scattering data?
3NF effects in p+d elastic scattering

Differential cross section at 70-250 MeV/nucleon
- Exp. data: RIKEN, RCNP, KVI
- Theor. calc: Faddeev calc. with chiEFT potential up to N^2LO
  - Red: NN potential only
  - Green: NN potential + 3NF

LEC, c_D, has been determined.

Parameter-free predictions

Theoretical calculations reproduce the exp. data up to 135 MeV/A w/o free parameter!
- Discrepancy at 250 MeV would be due to higher-order effects at higher energies
  → How about polarization observables?
3NF effects in polarization observables

\textbf{p+d polarization observables at 70 MeV/nucleon}
- Exp. data: RIKEN (70 MeV), RCNP (65 MeV)
- Theor. calc.: Faddeev calc. with chiEFT potential up to N^2LO
  - Red: NN potential only, Green: NN potential + 3NF

\textbf{Reasonable description within theor. uncertainties except for }T_{21}\text{ at backward angles}
- Need to go to higher chiral orders (N^4LO) to improve the theoretical accuracy
- }T_{21}\text{ might be sensitive to higher-order effects
Chiral expansion of 3NF

- $N^3\text{LO (}Q^4\text{)}$: parameter-free, but large $N^4\text{LO}$ contributions by $\Delta$ is expected
- $N^4\text{LO (}Q^5\text{)}$: new 10 LECs
  - Need high-precision $N$-$d$ scattering data in wide energy region → partial wave analysis

<table>
<thead>
<tr>
<th>NLO ($Q^2$)</th>
<th>$N^2\text{LO (}Q^3\text{)}$</th>
<th>$N^3\text{LO (}Q^4\text{)}$</th>
<th>$N^4\text{LO (}Q^5\text{)}$</th>
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<tbody>
<tr>
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<td>Ishitkawa, Robilotta '08 Bernard, EE; Krebs, Meißner '08,'11</td>
<td>Krebs, Gasparyan, EE '12</td>
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<td>Girlanda, Kievski, Viviani '11</td>
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</table>

Parameter-free!
3NF effects at higher energies

Comparison with data (RIKEN/IUCF) and predictions using chiral NN force (w/o 3NF)

- Faddeev calculations with NN potential only at \( N^4 \text{LO} \)

3NF effects are clearly needed and spin-dependent:
- At 70 MeV: Clear discrepancy for \( T_{21} \) and \( T_{22} \)
- At higher energies: Generally different at backward angles

\[ \begin{align*}
\text{3NF effects are clearly needed and spin-dependent:} \\
\text{• At 70 MeV: Clear discrepancy for } T_{21} \text{ and } T_{22} \\
\text{• At higher energies: Generally different at backward angles} \\
\text{• Limited to } T=1/2 \text{ for } N-d \rightarrow \text{Four nucleon system (p}^3\text{He, etc.) for } T=3/2 \text{ 3NF} \end{align*} \]
p$^+$$^3$He scattering and T=3/2 3NFs


Pisa Gr. succeeds in 4-body calc.

AV18 + UIX/IL 3NF

- Difference b/w UIX and IL predictions
- Importance of 3π-ring with $\Delta$ in IL-3NF

chiEFT (3NF@N^2LO)

- 3NF plays an important role, but is insufficient
- 3π-ring terms @ N^3LO would resolve the discrepancy

Now, it is interesting to study at higher energies for pol. observables with high accuracy!
New p-\(^3\)He \(A_y\) data at 70 MeV

courtesy of A. Watanabe and K. Sekiguchi

New \(^3\)He analyzing power exp./data for p-\(^3\)He by Tohoku group (Sekiguchi-Gr.)

**Side view**
- Pick-up Coil → Detect NMR signal
- Target Cell
- Main Coils → Static magnetic field (~1.2 mT)
- Drive Coils → RF field
- Beam axis
- Beam
- Target glass cell
- 150 mm
- Diode Laser
- Wavelength: 795 nm
- Power: 60 W

**Pol-\(^3\)He target**
- 3 atm (≈2 mg/cm\(^2\))
- ≈50% polarization

**Top view**
- Pol. \(^3\)He target
- Left Detectors (ΔE-E detector)
- Right Detectors (ΔE-E detector)
- 70-MeV p

**3NF effect at 70 MeV**
- ≈0.2

**3NF effect at 5 MeV**
- ≈0.05

**Preliminary**

**Experimental setup**
- \(\theta_{cm} \approx 40^\circ \sim 140^\circ\)

**Results of experiment**
- *A.
- Minimum and maximum angles.

**Calculations**
- Compared with the theoretical calculations including
- Large discrepancies at around
- Total momentum

**New p-\(^3\)He data**
- @ 70 MeV (new)
- @ 5 MeV

**3NF effect**
- Large and is useful for understanding \(T=3/2\) 3NFs.
Spin-isospin responses for stable and unstable nuclei
GT studies on stable nuclei and collectivity

Gamow-Teller → Most fundamental spin-isospin mode

- GTGR: collectivity by repulsive residual interaction
- Well described by Landau Migdal parameter $g'_{NN}$
- Nuclear astrophysics: weak processes in Type Ia, II SNe
- Deeper understanding of nuclear structures → nuclear ME in double beta decays

Landau-Migdal $g'_{NN}$ is the important key parameter and almost const. for stable nuclei
→ Extension to RI beam (isospin/density dependence?)
Overview of (p,n) studies for RI beam

- **N=Z no isospin asymmetry**
- **Invariant mass spectroscopy**
  - $^{14}$Be: Y. Satou et al., PLB 697 (2011) 459
  - $^{8}$He: H. Sakai et al. @RIBF, $^{12}$Be: K. Yako et al. @RIBF
  - $^{11}$Li, $^{14}$Be: L. Stuhl et al. @RIBF (performed in this May)
  - $^{16}$C: S. Lipshutz et al. @NSCL

- **Missing mass spectroscopy**
  - **56Ni:** M. Sasano et al. @NSCL, PRC 86 (2012) 034324

- **132Sn:**
  - double-magic nuclei far from stability
  - Key nucleus for nuclear models in $A \sim 100$ region
  - performed @RIBF (spokesperson: M. Sasano & R. Zegers)

- **Isospin dependence**

- **Very neutron-rich system**
Why $^{132}\text{Sn}$?

$^{132}\text{Sn}$ is the doubly-magic nucleus between $^{90}\text{Zr}$ and $^{208}\text{Pb}$ (well studied nuclei)

**Benchmarking nucleus for nuclear models in medium heavy region**

- NR-RPA, R-RPA, R-TBA, NR-RPA+PVC, etc.

Long isotope chain (A=112→132)

- **Isospin-dependence of GTGR peak ($g'_{NN}$)**

- GTGR peak for $^{132}\text{Sn}$ might be deviate from the systematic trend.

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E. Litvinova et al., arXiv:1308.3183 [nucl-th].
Experimental setup at SAMURAI in RIKEN/RIBF

\[ ^{132}\text{Sn} \text{ 216 MeV/u} \]

Wide momentum acceptance $\sim 50\%$

$\rightarrow$ Measure $^{128-132}\text{Sb}$ simultaneously
(c.f. S800@NSCL $\sim 5\%$, SHARAQ@RIBF $\sim 2\%$)

Wide angle acceptance & low threshold

$\rightarrow$ Measure $\theta = 1^\circ \sim 12^\circ$ and $E_x \leq 30\text{ MeV}$
(GTGR is predominantly excited)

Experimental results

J. Yasuda, M. Sasano, R.G.T. Zegers et al., accepted for publication in PRL.

Experimental results and multipole decomposition analysis

- **GTR(ΔL=0) is observed/identified:**
  - \( E_x = 16.3 \pm 0.4 \text{(stat)} \pm 0.4 \text{(syst)} \), \( \Gamma = 4.7 \pm 0.8 \text{ MeV} \)
  - has a shoulder at \( E_x \approx 10 \text{ MeV} \)
- **SDR(ΔL=1) is also observed/identified:**
  - \( E_x \approx 25 \text{ MeV} \)

Extraction of GT strength \( B(GT) \)

Proportionality relation

\[
\sigma_{\Delta L=0}(q, \omega) = \hat{\sigma}_{GT} F(q, \omega) B(GT)
\]

- Unit cross section \((q,\omega)\) correction
- Systematic study at 200 MeV yields:
  \( \hat{\sigma}_{GT} = 2.7 \pm 0.5 \text{ mb/sr} \)
- Known \( B(GT) \) values yield:
  \( \hat{\sigma}_{GT} = 3.8 \pm 2.0 \text{ mb/sr} \)
B(GT) and Landau-Migdal parameter $g'_{NN}$

B(GT) distribution

$g'_{NN}$ is sensitive to GT peak and evaluated in RPA

- $g'_{NN} = 0.68 \pm 0.07$
- Consistent with 0.6 for $^{90}$Zr and 0.64 for $^{208}$Pb

$g'_{NN}$ is constant for isospin asymmetry $(N-Z)/A$ of 0.11($^{90}$Zr) to 0.24($^{132}$Sn)

Comparison with theoretical models

- Reasonably reproduce the GTR in $^{132}$Sn
- The shoulder structure depends on shell structure

Total strength of B(GT) up to 25 MeV (up to GTR)

$S_{GT}^- = 53 \pm 5$ (stat) $^{+11}_{-10}$ (syst)

- 56% of sum-rule value of $3(N-Z)=96$
- Consistent with the systematics in stable nuclei

- A future study for higher excitations is challenging
Gamow-Teller resonance for very neutron-rich nuclei, $^8$He and $^{12}$Be

- $^8$He: $(N-Z)/A = 0.50 \rightarrow \textit{Largest isospin asymmetry}$ (cf. 0.21 for $^{208}$Pb)
- $^{12}$Be: $(N-Z)/A = 0.33$

$^8$He and $^{12}$Be can be used to study \textit{isospin dependence} of residual interaction

- How to change (or NOT change) the repulsive spin-isospin interaction, $g'_{NN}$?
- How about the effects on Gamow-Teller resonance (collectivity)?

Also interesting:

- Halo/skin/cluster effects
- Deformation effects (ex. ellipsoid ratio = 2:1 for $^{12}$Be)

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**First (p,n) measurements in inverse kinematics at RIBF**

courtesy of Y. Kanada-Enkyo
Systematics for stable nuclei

Gamow-Teller ($\Delta S=1$) and IAS ($\Delta S=0$) peak difference is given by

$$E_{GT} - E_{IAS} = \Delta E_{ls} + \text{const.} \left( \frac{g'_{NN}}{f'} \right) \frac{(N-Z)}{A}$$

- $\Delta E_{ls}$: energy spacing between spin-orbit partners
- Energy difference would be proportional to isospin asymmetry: $(N-Z)/A$
- Exp. data: Zr, Nb, Mo, Sn, Tm, Pb
- Almost proportional to $(N-Z)/A$
  - Support constancy of $g'_{NN}$
  - Slightly modified by $\Delta E_{ls}$


Bohr and Mottelson, Nuclear Structure.

Existing data for stable nuclei support the constancy of $g'_{NN}=0.6 \pm 0.1$ up to $(N-Z)/A=0.21$

→ How about very neutron-rich nuclei for $^{12}$Be and $^{8}$He with $(N-Z)/A=0.33$ and 0.50
Gamow-Teller resonances have been successfully observed for $^8$He and $^{12}$Be.

$^8$He($p,n$) at 200 MeV/A

$^{12}$Be($p,n$) at 200 MeV/A

$E_{GT} - E_{IAS} = -2.5 \pm 0.5$ MeV

$E_{GT} - E_{IAS} = -1.2 \pm 0.5$ MeV


courtesy of K. Yako
Collectivity in $(N-Z)/A > 0.21$; Very neutron-rich nuclei

Data are consistent with predictions employing $g'_{NN}=0.6\pm0.1$
→ Suggests the constancy of residual interaction for up to $(N-Z)/A=0.5$ (very neutron-rich)
Isovector (IV) spin-monopole (IVSM) response

Spin-isospin ($\Delta S = \Delta T = 1$) modes with $\Delta L = 0$

- Gamow-Teller
  \[0 \hbar \omega\]
  \[GT^\pm(\mu) = \sum_k t_\pm(k) \sigma_\mu(k)\]

- IV spin monopole (IVSM)
  \[0 \hbar \omega + 2 \hbar \omega\]
  \[IVSM^\pm(\mu) = \sum_k t_\pm(k) \sigma_\mu(k) r(k)^2\]

Energy centroid $E$ and width $\Gamma$ of IVSMR

- Isovector spin-incompressibility
- Effective interaction in spin-isospin channel: Landau-Migdal parameter $g'_{NN}$

**Sum-rule (model-independent)**

\[S_- - S_+ = 3(N \left< r^4 \right>_n - Z \left< r^4 \right>_p)\]

- Neutron skin thickness:
  \[\delta_{np} \equiv \sqrt{\left< r^2 \right>_n} - \sqrt{\left< r^2 \right>_p}\]
  \[\approx \frac{\sqrt{3/5}}{\sqrt{4/3/7}} \left(4\left< r^4 \right>_n - 4\left< r^4 \right>_p\right)\]

Sensitive to neutron skin by 4th power for $r$

IVSM and sum-rule give constraint on neutron matter equation of state (EOS)
IVSM probed by HI charge-exchange

Surface absorption in HI charge-exchange enhances monopole cross section

Transition densities of monopole resonances have a node near nuclear surface

Heavy-ion probes get absorbed at around nuclear surface
→ No cancellation b/w the inner and outer portions

Heavy-ion charge-exchange: \((^{12}N, ^{12}C), (t, ^{3}He)\)

Lighter-ion probes scan throughout target
→ Cancellation b/w the inner and outer portions

Light-ion charge-exchange: \((p,n), (n,p)\)

New data for IVSM by \((^{12}N, ^{12}C)\) and \((t, ^{3}He)\) on \(^{90}Zr\) at RIKEN/RIBF with SHARAQ
Experimental results

\[ \beta^-: \text{ } ^{90}\text{Zr}(^{12}\text{N}, \text{ }^{12}\text{C}) \]

- (p,n): GTR at \( E_x \approx 10 \text{ MeV} \) only
  \( \rightarrow \) insensitive to IVSM
- \( ^{12}\text{N},^{12}\text{C} \): GTR and IVSM at \( E_x \approx 25 \text{ MeV} \)
  \( \rightarrow \) sensitive to IVSM

\( \rightarrow \) Powerful new tool for IVSM

\[ \beta^+: \text{ } ^{90}\text{Zr}(t, ^{3}\text{He}) \]

- Significant enhancement \( E_x \approx 20 \text{ MeV} \) by IVSM compared with (p,n) data
- Consistent with HF-RPA (blue)

\( \rightarrow \) Clearest identification of \( \beta^+\)-IVSM

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\[ \text{\( ^{90}\text{Zr}(^{12}\text{N},^{12}\text{C}) \) @175 MeV/u} \]

\[ \text{\( ^{90}\text{Zr}(p,n) \) @200 MeV} \]

---


**Sum-rule and neutron skin thickness**

\[ \beta^-: {}^{90}\text{Zr}(^{12}\text{N}, {}^{12}\text{C}) \]

\[ d^2\sigma / d\Omega dE_x (\text{mb sr}^{-1} \text{MeV}^{-1}) \]

\[ 0^\circ - 1^\circ \]

\[ {}^{90}\text{Zr}(^{12}\text{N}, {}^{12}\text{C}) \] @175 MeV/u

\[ {}^{90}\text{Zr}(p, n) \] @200 MeV

\[ d^2\sigma / d\Omega dE_x (\text{mb sr}^{-1} \text{MeV}^{-1}) \]

\[ 0^\circ - 1^\circ \]

\[ \Delta L = 0 \]

\[ \Delta L = 1 \]

\[ \Delta L = 2 \]

\[ \Delta L = 3 \]

\[ \beta^+: {}^{90}\text{Zr}(t, {}^3\text{He}) \]

\[ d^2\sigma / d\Omega dE_x (\text{arb. unit}) \]

\[ E_x ({}^{90}\text{Nb}) \text{ (MeV)} \]

\[ 0^\circ - 1^\circ \]

\[ \Delta L = 0 \]

\[ \Delta L = 1 \]

\[ \Delta L = 2 \]

\[ \Delta L = 3 \]

\[ 0^\circ - 1^\circ \]

\[ 2^\circ - 3^\circ \]

\[ 4^\circ - 5^\circ \]

\[ 6^\circ - 7^\circ \]

\[ 8^\circ - 9^\circ \]

\[ 10^\circ - 11^\circ \]

\[ \text{Data} \]

\[ \text{Difference} \]

\[ S^- = (25 \pm 6) \times 10^3 \text{ fm}^4 \]

\[ S^+ = (16 \pm 6) \times 10^3 \text{ fm}^4 \]

\[ S^- - S^+ = 9 \pm 9 \times 10^3 \text{ fm}^4 \]

\[ S^- - S^+ = 3(N\langle r^4 \rangle_n - Z\langle r^4 \rangle_p) \Rightarrow \delta_{np} = 0.10 \pm 0.16 \text{ fm} \]

**Method**

<table>
<thead>
<tr>
<th>Method</th>
<th>( \delta_{np} ) (fm)</th>
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</thead>
<tbody>
<tr>
<td>p elastic</td>
<td>0.09 \pm 0.07</td>
</tr>
<tr>
<td>p-bar X-ray</td>
<td>0.09 \pm 0.02</td>
</tr>
<tr>
<td>SDR</td>
<td>0.07 \pm 0.04</td>
</tr>
</tbody>
</table>

\[ S^- = (25 \pm 6) \times 10^3 \text{ fm}^4 \]

\[ S^+ = (16 \pm 6) \times 10^3 \text{ fm}^4 \]

\[ S^- - S^+ = 9 \pm 9 \times 10^3 \text{ fm}^4 \]

\[ S^- - S^+ = 3(N\langle r^4 \rangle_n - Z\langle r^4 \rangle_p) \Rightarrow \delta_{np} = 0.10 \pm 0.16 \text{ fm} \]
New spin-isospin mode and application to neutrino physics
0νββ decay and double charge exchange


Quest for detection of 0νββ decay

• lepton-number violation/Majorana type
• absolute neutrino mass

Large diff. in matrix element calc: factor=2-3

• How can experiments guide 0νββ decay?

Double charge-exchange (DCX)

• resemble 0νββ decay

Operators: 0νββ vs. Double GT by DCX

\[ \hat{\mathcal{O}}_{\text{GT}}^{0\nu} = \sum_{i<j} V_{\text{GT}} \sigma_i \sigma_j \tau_i^- \tau_j^- \]

\[ \hat{\mathcal{O}}_{\text{DCX}}^{0\nu} = \sum_{i<j} [\sigma_i \tau_i^- \times \sigma_j \tau_j^-]_0 \]

Difference: ν-potential V

Linear corr. b/w 0νββ and DGT matrix elements → DCX \((^{18}\text{O},^{18}\text{Ne})\) could provide \(M^{0\nu\beta\beta}\)
HI double charge exchange (DCX) reaction I

$^{40}$Ca($^{18}$O,$^{18}$Ne)$^{40}$Ar at 270 MeV at INFN-LNS

Observe $^{40}$Ca(0$^+$)$\rightarrow^{40}$Ar(0$^+$) with $\sigma$(0$^\circ$) = 11 $\mu$b/sr

$\Delta L=0$ transition with

- Double Gamow-Teller (DGT)
- Double Fermi (DF)

Nuclear matrix element

$$\sigma(0^\circ) = \sigma_{\text{DGT}} + \sigma_{\text{F}}$$

$B(\text{DGT}) : B(\text{DF}) = \sum B(\text{GT}^-)B(\text{GT}^+) : \sum B(\text{F}^-)B(\text{F}^+)$

$$M_{\text{DGT}} = \sqrt{B(\text{DGT})} = 0.22$$

$$M_{\text{DF}} = \sqrt{B(\text{DF})} = 0.24$$

$$M^{0\nu\beta\beta}(^{40}\text{Ca}) \simeq M_{\text{DGT}} + \left(\frac{g_V}{g_A}\right)^2 M_{\text{DF}} = 0.37 \pm 0.18$$

Consistent w/ theor. prediction of 2.28

Pauli blocking collection

$$M^{0\nu\beta\beta}(^{48}\text{Ca}) = 2.6 \pm 1.3$$


Double GT (DGT) resonance by double charge exchange

2νββ decay matrix element: \( M^{2\nu} \)
- Exhaust only less than 0.1% of sum-rule
- Similar to delay of single β-decay (missing strength)
  - Missing strength → GT resonance (GTR)
  - Observed by single charge exchange, \((p,n)\) etc.

Missing strength would be found as Double GTR
- DGT: new spin-isospin mode predicted 30y ago
- Excited by double charge exchange (DCX)

DCX reaction
\((\pi^+,\pi^-)\)
- Successfully observe Double IAS
- Populates Spin-flip states (DGT) only weakly

New idea/probe: \(^{12}\text{C},^{12}\text{Be}[0^+_{\text{g.s.}}]\) at RCNP/RIBF
- Large projectile transition
- Clear identification by γ-tagging

Promising DGTR data

<table>
<thead>
<tr>
<th>Decay</th>
<th>( M^{2\nu} ) (MeV(^{-1}))</th>
<th>( T_{1/2}^{2\nu} ) (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{48}\text{Ca} \rightarrow ^{48}\text{Ti} )</td>
<td>( 0.047 \pm 0.003 )</td>
<td>( 4.4 \times 10^{19} )</td>
</tr>
<tr>
<td>(^{76}\text{Ge} \rightarrow ^{76}\text{Se} )</td>
<td>( 0.140 \pm 0.005 )</td>
<td>( 1.5 \times 10^{21} )</td>
</tr>
<tr>
<td>(^{82}\text{Se} \rightarrow ^{82}\text{Kr} )</td>
<td>( 0.098 \pm 0.004 )</td>
<td>( 9.2 \times 10^{19} )</td>
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<tr>
<td>(^{96}\text{Zr} \rightarrow ^{96}\text{Mo} )</td>
<td>( 0.096 \pm 0.004 )</td>
<td>( &lt; 0.1% ) of sum-rule</td>
</tr>
<tr>
<td>(^{100}\text{Mo} \rightarrow ^{100}\text{Ru} )</td>
<td>( 0.246 \pm 0.007 )</td>
<td>( 1.9 \times 10^{24} )</td>
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<tr>
<td>(^{116}\text{Cd} \rightarrow ^{116}\text{Sn} )</td>
<td>( 0.136 \pm 0.005 )</td>
<td>( 6.8 \times 10^{20} )</td>
</tr>
<tr>
<td>(^{128}\text{Te} \rightarrow ^{128}\text{Xe} )</td>
<td>( 0.049 \pm 0.006 )</td>
<td>( 2.1 \times 10^{21} )</td>
</tr>
<tr>
<td>(^{130}\text{Te} \rightarrow ^{130}\text{Xe} )</td>
<td>( 0.034 \pm 0.003 )</td>
<td>( 8.2 \times 10^{18} )</td>
</tr>
<tr>
<td>(^{136}\text{Xe} \rightarrow ^{136}\text{Ba} )</td>
<td>( 0.019 \pm 0.002 )</td>
<td>( 2.0 \times 10^{18} )</td>
</tr>
<tr>
<td>(^{150}\text{Nd} \rightarrow ^{150}\text{Sm} )</td>
<td>( 0.063 \pm 0.003 )</td>
<td>( 2.0 \times 10^{18} )</td>
</tr>
</tbody>
</table>
HI double charge exchange (DCX) reaction II

$^{48}\text{Ca}(^{12}\text{C},^{12}\text{Be}[0^+])$ at 100 MeV/A at RCNP

Identify $^{12}\text{Be}(0^+)$ with $\gamma$-ray tagging

Clearly observed “forward-peaking” two peaks

- $E_x \approx 17$ MeV; relatively narrow peak
  - Single GT resonance (one-phonon)
- $E_x \approx 27$ MeV; broad beak
  - Double GT resonance (“two-phonon”)
DGT and its relation to 0νββ decay

Theoretical prediction of DGT of $^{48}\text{Ca}$

Shell-model predictions with GXPF1B int.

- Double peaks → consistent with exp. data
- Double GT resonance at $E_x \approx 26$ MeV
  - Consistent with exp. result of $\approx 27$ MeV

Theoretical prediction b/w $E_x$ and $M^{0\nu\beta\beta}$

- DGT dist. → sensitive to paring corr.: $G^{(01)}$
- $M^{0\nu\beta\beta}$ → sensitive to $G^{(01)}$

Present data: $G^{(01)} \approx 0$ → useful for $M^{0\nu\beta\beta}$


[Diagram showing the relationship between $E_x$, $M^{0\nu\beta\beta}$, and $G^{(01)}$.]

Courtesy of M. Takaki
Summary and Outlook

Three nucleon force effects in few nucleon systems

Data is accumulating → 3NF effects are clear

3NFs at N^2LO are insufficient especially for spin-isospin dependence (pol. obs.)

• Push the chiral expansion to N^4LO
• More N-d scattering data for phase-shift analysis and p-^3He data for T=3/2 3NFs

Spin-isospin responses for stable and unstable nuclei

Observe Gamow-Teller resonances for ^8He&^12Be (n-rich) and ^132Sn (double magic)

Constancy of g’_{NN} in wide nuclear chart region with A≈8–208 and (N-Z)/A≈0.1–0.5

• Further investigations for the total strength and higher multipole modes such as SD IVSM → clearly observed by HI charge-exchange

Double charge-exchange/Gamow-Teller and neutrino-related physics

DCX reaction → constraint on M^{0\nu\beta\beta}; the double beta-decay nuclear matrix element

Candidate of Double GT resonance → useful to observe new collective motion
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