Nuclear Response and Gamma Emissivity Studied by Proton Inelastic Scattering

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Outline

1. IS/IV spin-M1 response in $N=Z$ sd-shell nuclei

   Quenching in IS/IV spin-M1 transition strengths

2. Gamma Emissivity of the Giant Resonances in $^{12}$C and $^{16}$O

   NC $\nu$-Reaction in Water Cherenkov Detector
IS/IV spin-$M1$ responses and their quenching in $N=Z$ $sd$-shell nuclei

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and RCNP-E299 collaboration

$^1$National Institute of Radiological Sciences
$^2$RCNP, Osaka University
IS/IV spin-$M1$ response

$\nu$-opacity and $\nu$-transportation in SNe and PNS

SNe dynamics, nucleosynthesis, cooling of a proton neutron star

- GT, IS/IV-spinM1 response of nuclear matter
- IS-spinM1 response of pure neutron matter

Spin (magnetic) susceptibility and response to a strong magnetic field

\[
\frac{\chi_\sigma}{2n} = \frac{4}{3N} \sum_f \frac{1}{\omega} \left| \langle f | \sum_i \sigma_i | 0 \rangle \right|^2
\]

G. Shen et al., PRC 87, 025802 (2013)

Magnetic response of nuclear matter in a magnetar

The mechanism of quenching need to be understood well.
Measurement of IS/IV spin-$\mathcal{M}_1$ Transition Strengths in $N=Z$ Nuclei

Stable self-conjugate even-even nuclei:

\[(^4\text{He}), ^{12}\text{C}, ^{16}\text{O}, ^{20}\text{Ne}, ^{24}\text{Mg}, ^{28}\text{Si}, ^{32}\text{S}, ^{36}\text{Ar}, ^{40}\text{Ca}\]

We measured (p,p') for all the above nuclei except $^4\text{He}$. 

ground state: $0^+; T=0$
Spectrometer Setup for 0-deg (p,p') at RCNP

As a beam spot monitor in the vertical direction

Transport: Dispersive mode
Intensity: 3 ~ 8 nA
IS/IV $1^+$ states were identified from angular distribution for each of IS and IV transitions. The cross sections at the most forward angles have were converted to the spin-M1 strengths.
Angular Distribution

$\Delta T (IS \text{ or } IV)$ has also been identified from angular distribution.
Unit cross section (UCS)

- Conversion factor from cross-section to Squared Nuclear Matrix Elements (SNME)
- Calibration from $\beta$ and $\gamma$-decay measurements (on the assumption of the isospin symmetry).

\[
\frac{d\sigma}{d\Omega}(0^\circ) = \hat{\sigma}_T F(q, E_x) M_f(O)^2
\]

($T=\text{IS or IV}$)

UCS     Kinematical factor     SNME

\[
\hat{\sigma}_T(A) = N \exp(-xA^{1/3})
\]

- Function taken from the mass dependence of GT UCS

M. Sasano et al., PRC79, 024602 (2009)
Spin-M1 Strength Distribution

Sum of the strengths is taken up to 16 MeV for each of IS and IV transitions.
IS Spin-M1 Matrix Elements Are NOT Quenching from the shell-model prediction with USD

(a) Isoscalar : $\sum |M(\vec{\sigma})|^2$

1.01(9)

(b) Isovector : $\sum |M(\vec{\sigma}\tau_z)|^2$

0.61(6)

No quenching

Quenching similar to GT
Difference of IS and IV

Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil
Shell-Model: USD interaction
The ground state expectation value can be extracted from the sum-rules of the IS/IV spin-M1 transition matrix elements.

\[ \langle \vec{S}_n \cdot \vec{S}_p \rangle = \frac{1}{4} \langle (\vec{S}_n + \vec{S}_p)^2 - (\vec{S}_n - \vec{S}_p)^2 \rangle \]

\[ = \frac{1}{16} \left( \sum |M(\vec{\sigma})|^2 - \sum |M(\vec{\sigma}_z)|^2 \right) \]

**IS - IV**

\[ \langle \vec{S}_n^2 + \vec{S}_p^2 \rangle = \frac{1}{4} \langle (\vec{S}_n + \vec{S}_p)^2 + (\vec{S}_n - \vec{S}_p)^2 \rangle \]

\[ = \frac{1}{16} \left( \sum |M(\vec{\sigma})|^2 + \sum |M(\vec{\sigma}_z)|^2 \right) \]

**IV spin-M1 transition matrix elements**

\[ \langle (\vec{S}_n + \vec{S}_p)^2 \rangle = \frac{1}{4} \sum |M(\vec{\sigma})|^2 \]

**IS spin-M1 transition matrix elements**

\[ \langle (\vec{S}_n - \vec{S}_p)^2 \rangle = \frac{1}{4} \sum |M(\vec{\sigma}_z)|^2 \]
Correlated 2p-2h Admixture in the ground state

induced by tensor-type short-range correlation

\[\langle \vec{S}_n \cdot \vec{S}_p \rangle > 0\]
### $^4\text{He}$ with realistic $NN$ interaction

(Correlated Gaussian Method)

Spin matrix elements of the $^4\text{He}$ ground state

<table>
<thead>
<tr>
<th></th>
<th>$\langle \vec{S}_p^2 + \vec{S}_n^2 \rangle$</th>
<th>$\langle \vec{S}_p \cdot \vec{S}_n \rangle$</th>
<th>S=0</th>
<th>S=1</th>
<th>S=2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AV8'</strong></td>
<td>0.572</td>
<td>0.135</td>
<td>85.8%</td>
<td>0.4%</td>
<td>13.9%</td>
</tr>
<tr>
<td>Stronger tensor int.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>G3RS</strong></td>
<td>0.465</td>
<td>0.109</td>
<td>88.5%</td>
<td>0.3%</td>
<td>11.3%</td>
</tr>
<tr>
<td>Weaker tensor int.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Minnesota</strong></td>
<td>0.039</td>
<td>-0.020</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>No tensor int.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \vec{S} = \vec{S}_p + \vec{S}_n \]

*CG calc. by W. Horiuchi*


H. Feldmeier, W. Horiuchi et al., PRC84, 054003(2011)
Difference of IS and IV

Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil
Shell-Model: USD interaction

AV8': 0.135 (stronger tensor)
G3RS: 0.109 (weaker tensor)

Minneapolis: -0.020 (no-tensor)
Difference of IS and IV

Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil
Shell-Model: USD interaction
NCSM
P. Navratil

Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil
Shell-Model: USD interaction

$\langle S_n \cdot S_p \rangle$

$\langle S_p \cdot S_p \rangle$

Target mass

Exp. $(p,p')$ —
Exp. $(e,e')$ —
USD
USD-eff
SFO
CG-
AV8'
G3RS
Minnesota
NCSM-
Chiral NN
Minnesota

$N_{\text{max}}$
Summary of the 1st Part

- Study of the spin-M1 responses in nuclei and their quenching mechanism is important for the $\nu$-transportation in SNe or in PNS.

- The IS spin-M1 SNME in $N=Z$ sd-shell nuclei are NOT quenching from the shell model prediction with USD int, while the IV spin-M1 SNMEs are quenching as is the case of GT.

- The positive values of the IS-IV SNMEs hint the $np$-correlated 2p2h admixture in the gourd state, and are supported by the CG calculation of $^4$He with realistic tensor interaction and by NCSM calculations.
Gamma Emissivity of
the Giant Resonances in $^{12}$C and $^{16}$O

I. Ou and M. Sakuda (Okayama Univ.)

and

A. Tamii (RCNP, Osaka Univ.)

for the RCNP-E398 Collaboration
Supernova Neutrino Detection by NC Neutrino Reactions

* Expected number of events by a core-collapse supernova explosion @10kpc

- Super Kamiokande (H$_2$O)
  
  Beaaccom-Vogel, PRD58, 053010 (1998)

  \[ CC: \bar{\nu}_e + p \rightarrow e^+ + n \]
  \[ \sim 8000 \text{ ev.} \]

  \[ NC: \nu_x + {}^{16}O \rightarrow \nu_x + X + \gamma (\nu_x = \nu_\mu, \nu_\tau) \]
  \[ \sim 700 \text{ ev.} \]

- KamLAND (CH)
  
  A. Suzuki, NPB-Suppl 77, 171 (1999)

  \[ CC: \bar{\nu}_e + p \rightarrow e^+ + n \]
  \[ \sim 300 \text{ ev.} \]

  \[ NC: \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma (15.1MeV) \]
  \[ \sim 60 \text{ ev.} \]

  \[ NC: \nu_x + {}^{12}C \rightarrow \nu_x + X + \gamma (E_X > 16MeV) \]
  \[ \sim 60 \text{ ev.} \]

NC events can be detected by $\gamma$-rays

* SN 1987A @50kpc
Importance of the NC Reactions in $^{16}$O

- The 2$^{nd}$ most type of events.
- $\mu, \tau$–$\nu$ events dominate NC.
  $\rightarrow T_{\nu\mu}, T_{\nu\tau} > T_{\nu e}$ Info. on equilibrium temp
- Effect of the $\nu$-oscillation

Essentially no data exist on $\gamma$-ray emissivity from giant resonances
$\rightarrow$RCNP-E398: measurement of the $\gamma$-ray emission probability($Pr$) and the energy from GDR and SDR.

Numerical simulations of Supernova

Estimated signal in SK
K. Langanke PRL76, 2629(1996)
$\gamma$-Emission from Giant Resonances in $^{16}\text{O}$

$\Sigma E_\gamma > 5 \text{ MeV}$

Statistical cal. (SMOKER)

$@ <E_x> = 25\text{MeV}$

$Pr(\text{NC }^{15}\text{N}^*\gamma) = 25\%$

$Pr(\text{NC }^{15}\text{O}^*\gamma) = 6\%$

Langanke PRL76, 2629(1996)
$\gamma$-Emission from Giant Resonances in $^{12}\text{C}$

$\Sigma E_{\gamma} > 2$ MeV
Probing Nuclear Matrix Elements by a Light-Ion (Hadronic) Reaction

(Cross Section) $\sim$ (Kinematical Factor) $\times$ [(Interaction) $\times$ (Matrix Element)]$^2$

Requires calibration

Neutral Current $\nu$ Reaction

Proton Inelastic Scattering

Common between the hadronic reaction and the neutrino reaction

$\nu_l, \bar{\nu}_l$, $\nu_l', \bar{\nu}_l'$

$\nu_l, \bar{\nu}_l$

$\langle f | O(\Delta S, \Delta T, \Delta L) | i \rangle$

$\langle f | O(\Delta S, \Delta T, \Delta L) | i \rangle$

IVGDR: $\Delta S=0$, $\Delta T=1$, $\Delta L=1$

IVSDR: $\Delta S=1$, $\Delta T=1$, $\Delta L=1$

(spin-M1, IS, …)
Probing Nuclear Matrix Elements by a Light-Ion (Hadronic) Reaction

(Cross Section) \( \sim (\text{Kinematical Factor}) \times (\text{Interaction}) \times (\text{Matrix Element})^2 \)

Requires calibration

Common between the hadronic reaction and the neutrino reaction

Neutral Current \( \nu \) Reaction

Proton Inelastic Scattering

\( \nu, \bar{\nu}, \nu' \)

\( p, n \)

IVGDR: \( \Delta S=0, \Delta T=1, \Delta L=1 \)

IVSDR: \( \Delta S=1, \Delta T=1, \Delta L=1 \)

(spin-M1, IS, …)
$^{16}\text{O}(p, p')$ at small angles

- $\nu\nu'$: SDR($2^-,1^-$) dominant. $\nu\nu'$: SDR & $1^+(15.11\text{MeV})$ dominant
- $O,C(p,p')$: SDR($1^-,2^-$) shows up at $\theta=3^\circ\sim5^\circ$

$^{16}\text{O}(p,p')$ at $E_p=392\text{ MeV}$ Kawabata PRC65, 064316(2012)

0°: GDR dominant ($\Delta L=1,\Delta S=0,\Delta T=1$)

4°: SDR dominant ($\Delta L=1,\Delta S=1,\Delta T=1$)
Excitation

* Proton Beam: 392 MeV, 0.5~1.5nA
* Target: \(^{nat}\text{C}\) (36.3 mg/cm\(^2\))
* Magnetic Spectrometer “Grand Raiden”
  * \(\theta_{\text{scat}} = 0^\circ\) (covers 0° ~ 3°)
  * Solid Angle = 5.6 msr
  * \(\Delta E_x \sim 100\) keV

Gamma-ray

* \(\gamma\)-detector: NaI(Tl) \(\times 25\) Array
  * Solid Angle \(\times\) Detection Efficiency
    * \(~ 2\% @ 6\) MeV (GEANT4)
  * each NaI: 25\(\times 25\times 15\) cm, \(\Delta E\sim 5\% @ 1.33\) MeV
  * Front: Plastic Scintillator Veto (3mm thick)
The peak energies agreed with the known values in ~40 keV.
\(^{16}\text{O} \text{ Spectrum after subtraction of } ^{12}\text{C}\)

*Subtraction with normalization to \(^{12}\text{C}(1^+: 15.1\text{MeV})\)*

Subtraction worked good.
GRs in \(^{16}\text{O}\) were clearly observed.

Reference: \(\text{H}_2\text{O(Ice)}\) target

T. Kawabata PRC65, 064316 (2002)
**γ-Detector (in-situ 15.1MeV γ-ray calibration)**

*In situ* γ-rays from $^{12}\text{C}(15.1\text{MeV}, 1^+, \text{Pr}_{\gamma-15.1} = 88\% \pm 3\%)$ are used to *calibrate* the energy scale and the efficiency of the NaI-Array.

The γ-ray emission probability can be calibrated precisely.

$^{12}\text{C}(p,p')$ 0.5nA, 2hrs

**E$_\gamma$ Spectrum**

$\gamma$-15.1MeV peak
(+single escape +double escape)

Solid Angle $\times$ Detection efficiency (Single NaI) $= \frac{817}{(3.9 \times 10^5 \times 0.88)}$

*Angular correlation is not include yet.

$= 0.24\%$
Gamma-Rays from $^{16}$O Giant Resonances

$\gamma$-rays from GRs in $^{16}$O were observed
Gamma-Rays from $^{16}$O Giant Resonances

5-9 MeV $\gamma$-rays after $n/p$ decay to $^{15}$O/$^{15}$N
## Estimated Number of γ Events from Giant Resonances

### Number of γ-ray events in 2hrs run (analyzed)

<table>
<thead>
<tr>
<th>Ex</th>
<th>ΔT</th>
<th>Ex=16~27MeV</th>
<th>Ex=16~21MeV</th>
<th>Ex=21~27MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>2hrs</td>
<td>20359</td>
<td>2129</td>
<td>18230</td>
</tr>
<tr>
<td>16</td>
<td>2hrs</td>
<td>11164</td>
<td>2797</td>
<td>8367</td>
</tr>
</tbody>
</table>

### Estimated γ-ray events in total run

<table>
<thead>
<tr>
<th>Ex</th>
<th>ΔT</th>
<th>Ex=16~27MeV</th>
<th>Ex=16~21MeV</th>
<th>Ex=21~27MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>40hrs</td>
<td>4.1×10</td>
<td>4.3×10</td>
<td>3.6×10</td>
</tr>
<tr>
<td>16</td>
<td>30hrs</td>
<td>1.7×10</td>
<td>4.2×10</td>
<td>1.3×10</td>
</tr>
</tbody>
</table>

Gamma emission probabilities will be determined with an accuracy (Stat. + Sys.) of ~10% in 1 MeV Ex bin.

Expected systematic uncertainties

- Detection efficiency < ~10% ← under analysis
- Subtraction of $^{12}$C from $C_6H_{10}O_5$ < ~5%
Summary of the 2nd Part

γ-ray from giant resonances in $^{12}$C & $^{16}$O are important for SN neutrino Physics.

$\nu$-Flux $\times \sigma_{NC} \times Pr \ (E398 \ Data) \rightarrow$ Estimation for NC-γ events from SN

E398: Measurement of γ-rays from Giant Resonances

Data Analysis

- Excitation Energy Spectrum ✔️
- Demonstration of In-situ γ-ray Calibration ✔️

γ-rays from giant resonances of $^{12}$C and $^{16}$O have been measured

Next Step

Analysis of the γ-ray emission probability.

Correlation $P_\gamma$ and $\theta_{scat}$ (0~1°, 1~2°, 2°~3°) $\rightarrow$ decomposition of GDR & SDR

$Pr(^{16}O*\rightarrow^{15}O*+n/^{15}N*+p\rightarrow5\text{-}10\text{MeV-γ})$ is expected to be determined with $\sim 10\%$ accuracy in 1 MeV $E_x$ bin)