Dipole resonances in $^4$He

$\sigma(^{7}\text{Li},^{7}\text{Be}), \sigma(\nu,\nu'),$ and $\sigma_\gamma$

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• Neutrino-induced reactions (neutral current)
  $^4\text{He}(\nu,\nu')$ in SN $\nu$-heating $\Leftrightarrow$ $^4\text{He}(^{7}\text{Li},^{7}\text{Be})$

• Application of the $^4\text{He}(^{7}\text{Li},^{7}\text{Be})$ reaction to $\sigma_\gamma$
  Astrophysical phenomena
  Deduction of $\sigma_\gamma$ as a function of $E_x$
  via $(^{7}\text{Li},^{7}\text{Be})$ spectra
Motivation

- Response of CE reaction are similar to weak and EM responses.
  
  Neutrino-induced reaction (neutral current)
  GT/M1 and E1-transitions in $(\nu,\nu')$
  GDR/SDR in $^4\text{He}$ (SN $\nu$-heating of $^4\text{He}$)

- Application to deduce $\sigma_\gamma$
  
  Astrophysical phenomena
  Low-multipole transitions in CE reaction
  GDR strength distribution in $^4\text{He}$

$E_\gamma$-Excitation function $\Leftrightarrow$ CEX Spectrum

$\sigma_{M1}(\gamma D)$ deduced from $D(^7\text{Li},^7\text{Be})$

Charge Exchange Reactions

- $\Delta T=1, \Delta T_z = -1$
  - $(p,n)$
  - $(^3\text{He},t)$
  - $(^6\text{Li},^6\text{He})$ etc...

- $\Delta T=1, \Delta T_z = +1$
  - $(n,p)$
  - $(d,^2\text{He})$
  - $(t,^3\text{He})$
  - $(^7\text{Li},^7\text{Be})$ etc...
$^7$Li + $^A$A $\rightarrow$ $^7$Be + B

$^7$Li–$^7$Be transition and spin-selectivities

$^7$Be-$\gamma$ coincidence
Separation between Be0 and Be1

Be0: Without $^7$Be-$\gamma$ coincidence
Be1: With $^7$Be-$\gamma$ coincidence

Electric-type Excitation ($\Delta S=0$)
Magnetic-type Excitation ($\Delta S=1$)

$$
\sigma(\Delta S = 0) = \sigma(\text{Be}_0) - \sigma(\text{Be}_1) \times R
$$
$$
\sigma(\Delta S = 1) = \sigma(\text{Be}_1) / B_{GT}(\text{Be}_1)
$$
$$
R = B_{GT}(\text{Be}_0) / B_{GT}(\text{Be}_1)
$$
$$
= 1.25 / 1.11 = 1.13
$$

Charge exchange Spin-flip & Spin-nonflip Reaction

Nakayama, S. et al.

$^7$Li, $^7$Be
Nucleon-nucleon Interactions of Charge Exchange Reactions

Central part:

\[ T_{10LL}^S = g_{10LL}^S \cdot \tau \cdot \left[ i^L r^L Y_L \right] ; \quad \text{Electric type excitation} \quad (\Delta S = 0) \]

\[ T_{11LL}^S = g_{11LL}^S \cdot \tau \cdot \left[ i^L r^L Y_L \times \sigma \right] ; \quad \text{Magnetic type excitation} \quad (\Delta S = 1) \]

\[ L = 0 \rightarrow \left( g_{1101}^s / g_{1000}^s \right)^2 \approx (E_L / 55)^2 / 3 \quad \text{from (p,n)} \]

Non-central part:

Tensor – force; \( V_T^S = V_T(r) \cdot \tau \cdot S_{12} \); \( S_{12} = 3 \frac{(\sigma_1 \cdot r)(\sigma_2 \cdot r)}{r^2} - \sigma_1 \cdot \sigma_2 \)

Tensor force has a sizable contribution for unnatural-parity transitions.
Probe for Nuclear Weak and EM Responses

Weak operators (neutral current);

\[ T_{10_{LJ}}^{W} = g_{10_{LJ}}^{W} \cdot \tau \cdot [i^{L}r^{L}Y_{L}]_{L} \]
\[ T_{11_{LJ}}^{W} = g_{11_{LJ}}^{W} \cdot \tau \cdot [i^{L}r^{L}Y_{L} \times \sigma]_{J} \]

\[ L = 0 \rightarrow (g_{1101}^{W} / g_{1000}^{W})^2 \approx 1.24 \text{ from } \beta \text{-decay} \]

EM operators ;

\[ T_{10_{LJ}}^{E} = g_{10_{LJ}}^{E} \cdot \tau_{3} \sqrt{2} \cdot [i^{L}r^{L}Y_{L}]_{L} [1 + f(\mu)] \]
\[ T_{11_{LJ}}^{M} = g_{11_{LJ}}^{M} \cdot \tau_{3} \sqrt{2} \cdot \left\{ [i^{L}r^{L}Y_{L} \times \sigma]_{J} + [i^{L}r^{L}Y_{L} \times \ell]_{J} \right\} \]

Spin part × Orbital part

Their contributions are strongly dependent on the relevant states.
Scenario of Super Nova Explosion

Core collapse
\( \rho_c \sim 10^{10} \text{ g/cc} \)
\( T_c \sim 1 \text{ MeV} \)
e-capture
\( \nu \)-trapping
\( \rho_c \sim 10^{12} \text{ g/cc} \)
\( T_c \sim 2 \text{ MeV} \)

1. A massive star becomes gravitationally unstable, and outgoing shock wave is driven

Core bounce
\( \rho_c \sim 10^{14} \text{ g/cc} \)
\( T_c \sim 5 \text{ MeV} \)
Shock wave
\( \nu \)-heating
Neutron star
\( E_\nu \sim 10^{53} \text{ erg} \)
\( E_{\text{matter}} \sim 10^{51} \text{ erg} \)
Explosion
R-process

2. Outgoing shock wave loses due to iron-dissociation, \( \nu \)-radiation, etc.
3. The shock wave is then revived due to \( \nu \)-heating of collapsing layers.
   (protons, neutrons, electrons, and \( ^4\text{He} \) nuclei)
4. R-process nucleosynthesis proceeds via \( \nu \)-spallations in \( ^4\text{He} \)-layer.

But this scenario can not be proven via thermo-dynamical simulation !!
Trajectories of Mass Elements

“Delayed explosion”


v-heating

bounce
$^4\text{He}$-Abundance in SN

Composition at $t = 150$ ms from bounce

Neutrino-energy distribution in SN

Nuclear excitations up to $E_x \sim 50\text{MeV}$ are useful to study nuclear responses to weak neutral current.

\[ f(E) = N \frac{E^2 / T^3}{1 + \exp[E / T - \alpha]} \]

- $\nu_{\mu}, \nu_{\tau} : < E > = 25 \text{ MeV} \\
  \quad \quad (T, \alpha) = (8 \text{ MeV}, 0) \\
  \quad \quad = (6.25 \text{ MeV}, 3)$

- $\nu_{e} : < E > = 11 \text{ MeV} \\
  \quad \quad (T, \alpha) = (3.5 \text{ MeV}, 0)$

- $\bar{\nu}_{e} : < E > = 16 \text{ MeV} \\
  \quad \quad (T, \alpha) = (5 \text{ MeV}, 0)$
Neutrino-neutral reaction on $^4$He

$^4$He($\nu,\nu'$)

@ $T = 10$ MeV

Experimental procedure

- Beam: 455 MeV, $^7\text{Li}^{3+}$ at RCNP, Osaka Univ.

- Targets: $^4\text{He}$ (7mg/cm$^2$), Aramid (12μm x4) $(\text{C}_{14}\text{O}_2\text{N}_2\text{H}_{10})_n$

- $^7\text{Be}$: Grand RAIDEN
  $\theta_L = 0$ and 3 deg.
  $\Delta E \sim 500$ keV

- $\gamma$-rays: NYMPHS
  $\varepsilon = 12.5\%$
  for 0.43-MeV $\gamma$
Singles and coincidence spectra for $^4$He($^7$Li,$^7$Be)$^4$H

(a) Singles spectrum, $\theta_L < 1$ deg.

(b) Coincidence spectrum, $\theta_L < 1$ deg.

EXCITATION ENERGY in $^4$He

$\Delta L = 1$

$\Delta L = 1$
Comparison with $^4$He(p,p') spectrum

$^4$He(p,p') at $E_L=300$ MeV and $\theta_L=8$ deg. ($\Delta L=1$ dominance)

Derivation of $\Delta S=0$ and $\Delta S=1$ spectra for $^4\text{He}(^7\text{Li},^7\text{Be})^4\text{H}$

(a) Singles spectrum, $\theta_L < 1$ deg.

(b) Coincidence spectrum, $\theta_L < 1$ deg.

$\sigma(\text{singles}) = \sigma(\Delta S=0) + 1.25 \times \sigma(\Delta S=1)$

$\sigma(\text{coin}) = 1.11 \times \sigma(\Delta S=1)$

$\sigma(\Delta S=0) = \sigma(\text{singles}) - 1.13 \times \sigma(\text{coin})/\varepsilon$

$\sigma(\Delta S=1) = 0.9 \times \sigma(\text{coin})/\varepsilon$

In-beam calibration

Aramid-target ($^{12}\text{C}$)

$^{12}\text{C} \ 0^+ \rightarrow^{12}\text{B} 1^+(g.s), 2^-(E_x=4.4 \text{ MeV})$

= Spin-flip ($\Delta S=1$) transitions

• Derivation of $^4\text{He}$ spectra
• $\gamma$-detection efficiency $\varepsilon$ for NYMPHS
Efficiency $\varepsilon$ for NYMPHS

Dependence of $\gamma$-detection efficiency $\varepsilon$

$\Delta S=0$ spectrum for Aramid

EXCITATION ENERGY in $^4$He (MeV)

COUNTS (relative)

$^{12}$C, g.s. 1+
$^{12}$C, 4.4 MeV 2-

$\varepsilon=11.2\% \times 1.0$
$\varepsilon=11.8\% \times 0.9$
$\varepsilon=12.5\% \times 0.8$
$N=13.3\% \times 0.7$
GDR ($\Delta S=0$) and SDR ($\Delta S=1$) for $^{12}$C

$\varepsilon=12.5\%$ for 0.43-MeV $^7$Be $\gamma$-ray

Aramid ($^7$Li,$^7$Be)

$E_L=455$ MeV, $\theta_L<1$ deg.

$^{12}$C, $g.s., 1^+$

$^{12}$C, 4.4 MeV 2$^-$

$\Delta S=0$

$\Delta S=1$
$\Delta S=0$ spectrum for $^4\text{He}$

![Graph showing $\Delta S=0$ spectrum for $^4\text{He}$]
GDR ($\Delta S=0$) and SDR ($\Delta S=1$) for $^4$He

$\varepsilon=12.5\%$ for 0.43-MeV $^7$Be $\gamma$-ray
ΔS=0 and ΔS=1 strength distributions in $^{12}$C

$^{12}$C($^7$Li,$^7$Be) 
$E_L=455$ MeV, $\theta_L < 1$ deg.

1$^+$, GT
SDR
GDR

e.g., $\Delta L = 0 \rightarrow (g_{1101}^s / g_{1000}^s)^2 \approx 0.5$ from H($^7$Li,$^7$Be) @65MeV/A
$\rightarrow (g_{1101}^W / g_{1000}^W)^2 \approx 1.25$ from $\beta$-decay
$\Delta S=0$ and $\Delta S=1$ strength distributions in $^4$He

$^4$He($^7$Li,$^7$Be) $E_L=455$ MeV, $\theta_L < 1$ deg.

- $\Delta S=0$
- $\Delta S=1$

EXCITATION ENERGY in $^4$He (MeV)

COUNTS (relative)
Giant Dipole Resonance in $^4\text{He}$

- There is no excited state up to $E_x=20$ MeV in $^4\text{He}$.
- Strongly suppressed GT
- Dominant dipole excitation
- But, GDR shape is not still settled.
- The $(^7\text{Li},^7\text{Be})$ may provide relative distribution of GDR.
- Huge abundance of $^4\text{He}$
  - $^4\text{He}$, $^{12}\text{C}(\gamma,\gamma'\alpha)$, $^{16}\text{O}(\gamma,\gamma'\alpha)$, ...
- $^4\text{He}$ may play an important role in $\nu$-heating during SN explosion.
- How does the GDR of $^4\text{He}$ distribute?
Interaction of GDR/SDR excitation

1. GDR

**E$_1^\gamma$-excitation:** \( V = g^{E}_{1011} \tau_3 [i r Y_1]_1 \)

**CEX$_E^E$-excitation:** \( V = g^{s}_{1011} \tau_+ [i r Y_1]_1 \)

\[
\frac{dB(E1)}{dE} = \frac{1}{2I_i + 1} |< I_f || \sum_j t_+(j) r Y_1(j) || I_i > |^2 \rho(I_f, E) \\
= K_{\tau} \frac{d^2 \sigma}{dEd\Omega}(\Delta S = 0, \Delta L = 1)
\]

2. SDR

**CEX$_M^M$-excitation:** \( V = g^{s}_{101J} \tau_+ [i r Y_1 \times \sigma]_{J=0,1,2} \)

SDR strength distribution \( \rightarrow \nu \) heating in SN?

\[
\frac{dB(M2)}{dE} = \frac{1}{2I_i + 1} |< I_f || \sum_j t_+(j) [r Y_1(j) \times \sigma] || I_i > |^2 \rho(I_f, E) \\
= K_{\sigma \tau} \frac{d^2 \sigma}{dEd\Omega}(\Delta S = 1, \Delta L = 1), \quad K_{\sigma \tau} = \text{const.}
\]

\( \sigma_\gamma(GDR) \) from E1\( \gamma \) strength

E1\( \gamma \) width \( [= \Gamma_\gamma(E1)] \) is described in terms of B(E1)

For a discrete transition:

\[
\Gamma_\gamma(E1) = \frac{16\pi}{9} \hat{\lambda}^{-3} B(E1)
\]

where \( \hat{\lambda} = \hbar c/\gamma \), \( E_\gamma = \hbar \omega \)

Application to a continuum transition:

One replaces B(E1) into dB(E1)/dE\( \gamma \)

\[
\Gamma_\gamma(E_\gamma, 0^+ \rightarrow 1^-) = \frac{16\pi}{9} \hat{\lambda}^{-3} \frac{dB(E1)}{dE_\gamma}
\]

Here the cross section \( \sigma \) is defined with \( \Gamma_\gamma \) as follows

\[
\sigma(E_\gamma, 0^+ \rightarrow 1^-) = \pi^2 \hat{\lambda}^2 \Gamma_\gamma(E_\gamma, 0^+ \rightarrow 1^-)
\]

\[
= 4.0 \times E_\gamma \frac{d\sigma(E_\gamma, 0^+ \rightarrow 1^-)}{dE_\gamma}
\]

Finally one gets

\[
\sigma_{E1}(E_\gamma, 0^+ \rightarrow 1^-) = 4.0 K_\tau \times E_\gamma \frac{d^2\sigma}{dEd\Omega} (\Delta S = 0, \Delta L = 1)
\]

\( K_\tau \) is determined by normalizing \( \sigma(\Delta S=0) \) to the \( \sigma_\gamma \) data around \( E_x=40 \) MeV.
$\Delta S=0$ spectrum and $\sigma_\gamma$ in $^4$He

$$\sigma_{E1}(E_\gamma, 0^+ \rightarrow 1^-) = 4.0K_\tau \times E_\gamma \frac{d^2\sigma}{dE d\Omega} (\Delta S = 0, \Delta L = 1), \quad K_\tau = 0.033$$

- Present work
- Shima et al., PRC72, 0440004 (2005)
- Nilsson et al., PLB626, 65 (2005)
- Wells et al., PRC46, 449 (1992)
- Calarco et al., PRC27, 1866 (1983)

Gazit et al., PRL96, 112301 (2006)

FSI via LIT method with AV18(NN)
FSI via LIT method with AV18(NN)+UIX(3NF)
Summary

- Neutrino-heating for $^4\text{He}$ during SN explosion
  
  SDR in $^4\text{He}$ has a shape peak around at $\text{Ex}=24$ MeV. For $\nu$-heating in SN, is the SDR more important than GDR?

- CE reaction for self-conjugate nuclei is feasible to deduce the $\sigma_\gamma$ as a function of excitation energy.
  
  $\sigma(^7\text{Li},^7\text{Be}) \leftrightarrow \sigma_\gamma$
  
  CE spectrum $\leftrightarrow$ Excitation function of $\gamma$-energy

- Application to deduce $\sigma_\gamma$ to E1 excitations
  
  Resonance shape for the GDR in $^4\text{He}$ has a pronounced peak around $\text{Ex}=27$ MeV
Collaboration for E263

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- **Kobe Tokiwa Jr. College**
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- **ICU**
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Calculations for $\sigma_\gamma$

Quaglioni et al., PRC69, 044002 (2004)
LIT method with MTI-III including full FSI

Gazit et al., PRL96, 112301 (2006)
LIT method with MTI-III including full FSI