Spin-isospin responses by charge-exchange reactions and implications for astrophysics

Muhsin N. Harakeh
KVI, Groningen & GANIL, Caen

The 4th International Symposium on Neutrinos and Dark Matter in Nuclear Physics (NDM12)

Nara, Japan
11-15 June 2012
Spin-Isospin Modes

1. Importance of studying GT\(^+\) in \(fp\)-shell nuclei

2. Experimental method

3. Case Study: \(^{58}\text{Ni}\)

4. Measurements on several \(fp\)-shell nuclei

5. Measurements on \(2\beta\)-decaying nuclei
   (Dieter Frekers’ Talk)

6. Conclusions and outlook
Why are Gamow-Teller transitions in $fp$-shell nuclei important?

- Role of $fp$-shell nuclei in supernova explosions: Core of supernova star is composed of $fp$-shell nuclei.  
  $\Rightarrow$ electron capture

- Neutrino absorption cross sections by $fp$-shell nuclei are essential in understanding of nuclear synthesis in Supernova explosions in cosmos.

$\Rightarrow$ Difficulties in shell-model calculations for $fp$-shell nuclei.

$\Rightarrow$ Importance to measure spin-isospin responses of $fp$-shell nuclei to gauge theoretical calculations.
# Charge-exchange probes

<table>
<thead>
<tr>
<th>(p,n)-type ($\Delta T_z = -1$)</th>
<th>(n,p)-type ($\Delta T_z = +1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• $\beta^-$-decay</td>
<td>• $\beta^+$-decay</td>
</tr>
<tr>
<td>• (p,n)</td>
<td>• (n,p)</td>
</tr>
<tr>
<td>• (3He,t)</td>
<td>• (d,2He)</td>
</tr>
<tr>
<td>• heavy ion</td>
<td>• (t,3He)</td>
</tr>
<tr>
<td></td>
<td>• heavy ion; (7Li,7Be)</td>
</tr>
</tbody>
</table>

- Energy per nucleon ($>100$ MeV/u)
- Spin-flip versus non-spin-flip
- Complexity of reaction mechanism
- Experimental considerations
(³He,t) Reaction ≥ 100 MeV/u

- Energy dependence of effective interactions.

- At RCNP, Osaka
  - $E(³\text{He}) \approx 150$ MeV/u
  - $V₀$ part: Minimum.
  - $V_{στ}$ part: Relatively large.
  - $V_t$ part: Minimum.
The ($^3$He,$t$) reaction at 0 degree

- Cross sections at $E(^3\text{He})=450$ MeV, $q=0$ for ($^3$He,$t$) reactions

$$\frac{d\sigma}{d\Omega} = \frac{\mu_i \mu_f}{(\pi \hbar^2)^2} \left( \frac{k_f}{k_i} \right) \left( N^D_\tau | J_\tau |^2 B(F) + N^D_{\sigma\tau} | J_{\sigma\tau} |^2 B(GT) \right)$$


- Neutrino absorption cross sections

$$\sigma = \frac{1}{\pi \hbar^4 c^3} \left[ G^2_V B(F) - G^2_A B(GT) \right] \times F(Z, E_e) p_e E_e$$

$F(Z, E_e)$ is the relativistic Coulomb barrier factor

Importance of charge-exchange reactions at intermediate energies
Measuring GT strengths

\[
\frac{d\sigma}{d\Omega} (q = 0) = KN_D \left| J_{\sigma\tau} \right|^2 B(GT)
\]

- **kinematic factor**
- **distortion factor**
- **Gamow-Teller strength**
- **nucleon-nucleus interaction**

Calibration of $B(GT)$ to cross section for known transitions (e.g. from $\beta$-decay)
Experiments

- RCNP facility
  K=400 MeV ring cyclotron
  Grand Raiden spectrometer
- Beam: $^3\text{He}^{++}$, 450 MeV

M. Fujiwara et al., NIM A422 (1999) 484
\[ E_x (\text{MeV}) \quad 0.195 + 0.339 \, (p,n) \quad 0.195 \, (^3\text{He},t) \quad 0.339 \, (^3\text{He},t) \]

\[ B(\text{GT}) \quad 0.32 \pm 0.04 \quad 0.20 \pm 0.04 \quad 0.11 \pm 0.02 \]

Used $^{164}\text{Dy}(^3\text{He},t)^{164}\text{Ho (g.s., 1+)}$ reaction for calibration: $\log ft \, 4.6 \rightarrow B(\text{GT}) = 0.293 \pm 0.006$

**Resolution** $\approx$ 100 to 130 keV

\( \nu_{pp} \leq 0.420 \) MeV
Beam line WS-course

Grand-Raiden Spectrometer

M. Fujiwara et al., NIM A422 (1999) 484

High-dispersive WS-course

T. Wakasa et al., NIM A482 (2002) 79
$^{26}\text{Mg}(p,n)^{26}\text{Al}$ & $^{26}\text{Mg}(^3\text{He},t)^{26}\text{Al}$ spectra

R. Madey et al.,

Y. Fujita et al.,
PRC 67 (2003) 064312

Prominent states are GT states and the IAS!

$E=140$ MeV/u, $\theta=0^\circ$
$\Delta E \approx 30-35$ keV
$^{136}\text{Xe}(^{3}\text{He},t)^{136}\text{Cs}$

$E(^{3}\text{He}) = 420$ MeV

$\Delta E = 42$ keV

$B_{\text{exp}}(\text{GT+}) = \frac{d\sigma(q = 0)}{d\Omega} \cdot \left[ \frac{d\hat{\sigma}(\text{GT})}{d\Omega} \right]^{-1}$

$\Delta L = 2$ & $\Delta L = 0$ incoherent

P. Puppe et al., PRC 84 (2011) 051305(R)
Theoretical Study
$^{26}\text{Mg}(^{3}\text{He},t)^{26}\text{Al}$

Effects of $\Delta L = 2$, $\Delta S = 1$
contributions mediated via the $T_\tau$ interaction that interfere with
$\Delta L = 0$, $\Delta S = 1$ contributions to Gamow-Teller transitions.

\[
\text{Rel. syst. error} = \frac{B(\text{GT})_{\text{DWBA}} - B(\text{GT})_{\text{SM}}}{B(\text{GT})_{\text{SM}}}
\]

R.G.T. Zegers et al., PRC74 (2006) 024309
Determination of GT$^+$ Strength and its Astrophysical Implications

In supernova explosions, electron capture (EC) on $fp$-shell nuclei plays a dominant role during the last few days of a heavy star with $M > 10 \, M_\odot$

Presupernova stage; deleptonization $\Rightarrow$ core collapse $\Rightarrow$ subsequent type IIa Supernova (SN) explosion

H.A. Bethe et al., Nucl. Phys. A324 (1979) 487
Electron capture in $fp$-shell

- The rate for EC is governed by the $GT^+$ strength distribution at low excitation energy; not accessible to $\beta$-decay.

- Fuller, Fowler and Newman (FFN) (1982-1985); estimates of stellar rates in stellar environments using s.p. model.

- Caurier et al., Martínez-Pinedo & Langanke (1999), Otsuka et al. ⇒ Large shell-model calculations ⇒ marked deviations from FFN EC rate; generally smaller EC rates.

- Experiments and theory relied on ($n,p$) data (TRIUMF) which have a rather poor energy resolution.
$fp$-shell nuclei: large scale shell model calculations

E. Caurier et al.
NPA 653 (1999) 439

- Stellar weak reaction rates with improved reliability
- Large scale shell model (SM) calculations
- Tuned to reproduce GT$^+$ strength measured in $(n,p)$
- $(n,p)$ data from TRIUMF
- GT$^+$ strength from SM
- Folded with 1 MeV energy resolution

Case study: $^{58}$Ni
Exclusive excitations $\Delta S = \Delta T = 1$: $(d, ^2\text{He})$

$^3S_1$ deuteron $\Rightarrow ^1S_0$ di-proton ($^2\text{He}$)

$^1S_0$ dominates if (relative) 2-proton kinetic energy $\varepsilon < 1$ MeV

$(n,p)$-type probe with exclusive $\Delta S = 1$ character (GT$^+$ transitions)

But near $0^\circ$: tremendous background from $d$-breakup
Setup: ESN detector

Focal-Plane Detector:
(FPDS): 2 VDCs

Focal-Plane Polarimeter:
(FPP): 4 MWPCs & graphite analyzer

features a.o.:
fast readout
VDC readout pipeline
TDC’s
VDC decoding using imaging techniques
DSP based online analysis

Bari, Darmstadt, Gent, Iserlohn, KVI, Milano, Münster, TRIUMF

M. Hagemann et al., NIM A437 (1999) 459
V.M. Hannen et al., NIM A500 (2003) 68
• Good double tracking
• Use VDC information
• Good phase-space coverage for small relative proton energies

S. Rakers et al., NIM A481 (2002) 253
$(d,^2He)$ as GT$^+$ probe in $fp$-shell nuclei

$^{58}\text{Ni}(d,^2\text{He})^{58}\text{Co}$ $E=85$ MeV/u

$^{58}\text{Ni}(n,p)^{58}\text{Co}$ $E=198$ MeV

M. Hagemann et al.
PLB 579 (2004) 251
$^{58}\text{Ni}(d,^2\text{He})^{58}\text{Co} \ E=85\text{A MeV}$

$$B_{\text{exp}}(GT+) = \frac{d\sigma(q=0)}{d\Omega} \left[ \frac{d\hat{\sigma}(GT)}{d\Omega} \right]^{-1}$$
<table>
<thead>
<tr>
<th>$E_x$</th>
<th>$d\sigma/d\sigma(0.5^\circ)$</th>
<th>$\sigma(L=0)/\sigma(\tau\tau\tau)$</th>
<th>$B(GT+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[MeV]</td>
<td>[mb/sr]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.050</td>
<td>0.159±0.009</td>
<td>0.88</td>
<td>0.15±0.01</td>
</tr>
<tr>
<td>1.435</td>
<td>0.078±0.006</td>
<td>1.00</td>
<td>0.09±0.01</td>
</tr>
<tr>
<td>1.729</td>
<td>0.148±0.014</td>
<td>1.00</td>
<td>0.16±0.02</td>
</tr>
<tr>
<td>1.868</td>
<td>0.648±0.020</td>
<td>1.00</td>
<td>0.72±0.05</td>
</tr>
<tr>
<td>2.249</td>
<td>0.047±0.004</td>
<td>1.00</td>
<td>0.05±0.01</td>
</tr>
<tr>
<td>2.660</td>
<td>0.057±0.005</td>
<td>0.96</td>
<td>0.06±0.01</td>
</tr>
<tr>
<td>2.860</td>
<td>0.145±0.009</td>
<td>0.99</td>
<td>0.17±0.01</td>
</tr>
<tr>
<td>3.100</td>
<td>0.126±0.008</td>
<td>0.99</td>
<td>0.15±0.01</td>
</tr>
<tr>
<td>3.410</td>
<td>0.065±0.007</td>
<td>0.96</td>
<td>0.07±0.01</td>
</tr>
<tr>
<td>3.520</td>
<td>0.080±0.009</td>
<td>0.95</td>
<td>0.09±0.01</td>
</tr>
<tr>
<td>3.625</td>
<td>0.067±0.007</td>
<td>0.87</td>
<td>0.07±0.01</td>
</tr>
<tr>
<td>3.900</td>
<td>0.062±0.006</td>
<td>0.97</td>
<td>0.07±0.01</td>
</tr>
<tr>
<td>4.030</td>
<td>0.155±0.010</td>
<td>1.00</td>
<td>0.19±0.01</td>
</tr>
<tr>
<td>4.05-5.00</td>
<td>0.381±0.061</td>
<td></td>
<td>0.49±0.09</td>
</tr>
</tbody>
</table>
GT\(^+\) strength: comparison \((n,p)\), \((d,^2\text{He})\) & theory

Up to 4 MeV excitation:

13 GT transitions measured \((d,^2\text{He})\)

Strength re-binned in 1 MeV bins

Significant differences

Updated shell model calculations by Martínez-Pinedo/Langanke using KB3G interaction
$^{58}\text{Ni}(t, ^3\text{He})^{56}\text{Co}$

$E_t = 115$ MeV/u

Resolution = 250 keV

A.L. Cole et al., PRC74 (2006) 034333
Electron capture rate

\[ \lambda_{ec} \approx \sum_{i} B_i(GT) \int_{\omega_i}^{\infty} \omega p \left( Q_i + \omega \right)^2 F(Z, \omega) S_e(\omega, T) d\omega \]

With

- \( B_i(GT) \) Gamow-Teller strength distribution
- \( \omega \) and \( p \) energy and momentum of electrons
- \( F(Z, \omega) \) is the relativistic Coulomb barrier factor
- \( S_e(\omega, T) \) Fermi-Dirac distribution electron gas at temperature \( T \)
$e^{-}$-capture rates using experimental strengths

(Martínez-Pinedo, Langanke)

Evolution of core of 25 $M_\odot$ star. Conditions following silicon depletion.

$T_9 = 4.05$

$\rho = 3.18 \times 10^7$ g/cm$^3$

$Y_e = 0.48$


Calculate EC rates as function of $T_9$ for GT transitions from $^{58}$Ni$_{g.s.}$

Strength deviations at low excitation $\Rightarrow$ rates deviation at low $T$
$^{58}\text{Ni}$: comparison of $e$-capture rates
theory/experiment

- Influence of GT strength distribution on calculated capture rate is dramatic, especially at low temperatures
- Rates vary up to a factor 5-6
- FFN not too far off
- Large scale shell-model calculations fail at low T
- Calculations with improved residual interaction (KB3G) in reasonable agreement
$^{51}\text{V}(d,^2\text{He})^{51}\text{Ti}$: B(GT$^+$) for proton-odd $fp$-shell nucleus

$^{51}\text{V}$ g.s. ($J^\pi=7/2^-$, $T=5/2$) $\Rightarrow$ $^{51}\text{Ti}$ ($J^\pi=5/2^-$, 7/2$^-$, 9/2$^-$, $T=7/2$)

Independent single-particle model (FFN): $E_x$(GTR)=3.83 MeV

C. Bäumer et al., PRC 68, 031303(R) (2003)
\[ ^{51}\text{V}(d,^{2}\text{He})^{51}\text{Ti} \]: Comparison with shell-model calculations

- Experimental result
- Full \( fp \)-shell model calculations quenching factor \((0.74)^2\)

G. Martínez-Pinedo, K. Langanke
$^{56}\text{Fe}(d,^2\text{He})$: Comparison with shell-model calculations

$^{56}\text{Fe}(d,^2\text{He})$

$E_x = 110$ keV

$E_d = 172$ MeV

FWHM = 110 keV

$\Theta_{\text{cm}} \sim 0^\circ$

Experiment

Full $fp$-shell model calculations (KB3G)

(G. Martínez-Pinedo)
Comparison of centroids (MeV) of GT$^+$ Strength distribution

<table>
<thead>
<tr>
<th></th>
<th>Nucleus</th>
<th>FFN</th>
<th>SM</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Even-Even</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{56}$Fe</td>
<td>3.8</td>
<td>2.2</td>
<td></td>
<td>1.9</td>
</tr>
<tr>
<td>$^{58}$Ni</td>
<td>3.8</td>
<td>3.6</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td><strong>Odd A-Odd $p$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{51}$V</td>
<td>3.8</td>
<td>4.7</td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td><strong>Odd A-Odd $n$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{57}$Fe</td>
<td>5.3</td>
<td>4.1</td>
<td></td>
<td>2.9</td>
</tr>
<tr>
<td>$^{61}$Ni</td>
<td>3.5</td>
<td>4.6</td>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td>$^{67}$Zn</td>
<td>4.4</td>
<td></td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td><strong>Odd-Odd</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{50}$V</td>
<td>9.7</td>
<td>8.5</td>
<td></td>
<td>8.8</td>
</tr>
</tbody>
</table>
WW = Woosley-Weaver Model calculations (FFN rates)
LMP = Langanke-Martínez-Pinedo Large shell-model calculations {G. Martínez-Pinedo et al., NPA 777 (2006) 395}
Conclusions

- Presupernova models depend sensitively on EC rates.
- $GT^+$ transitions in $fp$-shell nuclei play a decisive role in determining EC rates and thus provide input into modeling of explosion dynamics of massive stars.
- Large shell-model calculations are needed especially as function of $T$. (Caurier et al.; Martínez-Pinedo & Langanke [KB3G]; Otsuka et al. [GXPFL]) $\Rightarrow$ smaller EC rates for $A=45-60$ than FFN $\Rightarrow$ Larger $Y_e$ (electron to baryon ratio) and smaller iron core mass (Heger et al.)
- New high resolution ($d,^2\text{He}$) experiments provide essential tests for shell model calculations at 0 $T$. 
Outlook

Radioactive ion beams will be available at energies where it will be possible to study GT transitions (RIKEN, NSCL, FAIR, EURISOL)

- Determine $\text{GT}^\pm$ strength in unstable $sd$ & $fp$ shell nuclei
  - Electron capture rates (presupernova) and neutrino capture rates and inelastic scattering cross sections
- Use $\text{IV}(S)\text{GDR}$ as tool to determine n-skin
  - Charge-exchange cross section proportional to n-skin
EuroSuperNova Collaboration

C. Bäumer¹, R. Bassini², A.M. van den Berg³, N. Blasi², B. Davids³, D. De Frenne⁴, R. De Leo⁵, D. Frekers¹, E.-W. Grewe¹, P. Haefner¹, M. Hagemann⁴, V.M. Hannen³, M.N. Harakeh³, J. Heyse⁴, F. Hofmann⁶, M. Hunyadi³, M. de Huu³, E. Jacobs⁴, B.C. Junk¹, A. Korff¹, K. Langanke⁷, A. Negret⁴, P. von Neuman-Cosel⁶, L. Popescu⁴, S. Rakers¹, A. Richter⁶, H. Sohlbach⁸, H.J. Wörtche³

¹ Westfälische Wilhelms-Universität, Münster
² INFN, Milan
³ Kernfysisch Versneller Instituut Groningen
⁴ University Gent
⁵ University Bari
⁶ Technische Universität Darmstadt
⁷ University Aarhus
⁸ Märkische Fachhochschule Iserlohn
Thank you for your attention
Nuclear structure studies with CE reactions in inverse kinematics

- Possible at FAIR and RIKEN
  (intermediate beam energies are needed!)

\[(d, ^2 \text{He})\]

Approach (at FAIR):
measure the recoiling protons

Inconvenience:
difficulty to detect the low-energy protons
How low?

Example:

\[ ^2H(^{64}\text{Ni},^{64}\text{Co})^2\text{He} \]

\[ E(^{64}\text{Ni}) = 350\text{MeV/u} \]
How low?

\[ E(\text{^{64}Ni,^{64}Co})^{2}\text{He} \]
\[ E(\text{^{64}Ni}) = 350 \text{MeV/u} \]

Example:

region of interest
low-energy protons!

kinematic calculations
Detection system @ FAIR

- Use of EXL recoil detector is under evaluation
- Design & implementation of a dipole magnet for the momentum analysis of the protons

Figure 1: Schematic view of the EXL detection systems. Left: Set-up built into the NESR storage ring. Right: Target-recoil detector surrounding the gas-jet target.