Collective excitations in nuclei: The isoscalar and isovector electric giant resonances and spin-isospin charge-exchange modes

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ΔL = 0

ΔL = 1

ΔL = 2

ΔT = 0
ΔS = 0

ΔT = 1
ΔS = 0

ΔT = 0
ΔS = 1

ΔT = 1
ΔS = 1
Spin-isospin excitations

Neutral ($\nu, \nu'$) and charged ($\nu_e, e^-$), ($\nu_e, e^+$) currents

NC $\Rightarrow$ Inelastic electron and proton scattering
$\Rightarrow M0, M1, M2$

CC $\Rightarrow$ Charge-exchange reactions

Isovector charge-exchange modes
$\Rightarrow$ IAS, GTR, IVSGMR, IVSGDR, etc.

Importance for nuclear astrophysics,
$\nu$-physics, $2\beta$-decay, $n$-skin thickness, etc.

$(p, n), (^{3}\text{He}, t) \{\text{GT}^-\}; (n, p), (d, ^2\text{He}) \& (t, ^3\text{He}) \{\text{GT}^+\}$
**Nucleus**  ➔  **Many-body system with a finite size**

**Vibrations**  ➔  **Multipole expansion with \( r, Y_{lm}, \tau, \sigma \)**

\[
\Delta S = 0, \Delta T = 0 \quad \Delta S = 0, \Delta T = 1 \quad \Delta S = 0, \Delta T = 1 \quad \Delta S = 1, \Delta T = 1 \quad \Delta S = 1, \Delta T = 1
\]

\( L=0 \): **Monopole**  
\[ \text{ISGMR} \quad r^2Y_0 \quad \tau Y_0 \quad \text{IVGMR} \quad \tau r^2Y_0 \quad \tau \sigma Y_0 \quad \text{IVSGMR} \quad \tau \sigma r^2Y_0 \]

\( L=1 \): **Dipole**  
\[ \text{ISGDR} \quad (r^3 - 5/3 \langle r^2 \rangle r)Y_1 \quad \text{IVGDR} \quad \tau rY_1 \quad \text{IVSGDR} \quad \tau \sigma rY_1 \]

\( L=2 \): **Quadrupole**  
\[ \text{ISGQR} \quad r^2Y_2 \quad \text{IVGQR} \quad \tau r^2Y_2 \quad \text{IVSGQR} \quad \tau \sigma r^2Y_2 \]

\( L=3 \): **Octupole**  
\[ \text{LEOR, HEOR} \quad r^3Y_3 \quad \text{Dropped } \Delta S = 1, \Delta T = 0 \text{ operators because excitations are very weak} \]
Non-Energy-Weighted Sum Rules
Intermezzo: Sum rules

Fermi, Gamow-Teller and higher multipole non-energy-weighted sum sum rules (NEWSR):

Gamow-Teller operator

\[ \beta_{\pm}(\mu) = \frac{1}{2} \sum_{k=1}^{A} \sigma_{\mu k} \tau_{\pm k} \]

\[ (\mu = -1, 0, +1), \quad \tau_{\pm} = (\tau_x \pm i \tau_y) \]

\[ \frac{1}{2} \tau_- |n \rangle = |p \rangle, \quad \frac{1}{2} \tau_+ |p \rangle = |n \rangle, \quad \tau_- |p \rangle = \tau_+ |n \rangle = 0 \]

\[ S_{\pm}(GT) = \sum_{f, \mu} |\langle f | \beta_{\pm}(\mu) | i \rangle|^2 \]

\[ S_{\pm}(GT) = \sum_{f, \mu} \langle f | \beta_{\pm}(\mu) | i \rangle^* \langle f | \beta_{\pm}(\mu) | i \rangle \]

\[ S_{\pm}(GT) = \sum_{f, \mu} \langle i | \beta_{\pm}^+(\mu) | f \rangle \langle f | \beta_{\pm}(\mu) | i \rangle \]

Using closure:
\[ S_{\pm}(GT) = \sum_{\mu} \langle i | \beta^+_{\pm}(\mu) \beta_{\pm}(\mu) | i \rangle \]

\[ \tau^+_{\pm} = \tau_{\pm} \]

\[ S_-(GT) - S_+(GT) = \sum_{\mu} \langle i | \beta^+_{-}(\mu) \beta_{-}(\mu) - \beta^+_{+}(\mu) \beta_{+}(\mu) | i \rangle \]

\[ S_-(GT) - S_+(GT) = \frac{1}{4} \langle i | \sum_{k=1}^{A} \sum_{\mu=-1}^{1} \left[ \sigma_{\mu k}^+ \tau_{+k} \sigma_{\mu k} \tau_{-k} - \sigma_{\mu k}^+ \tau_{-k} \sigma_{\mu k} \tau_{+k} \right] | i \rangle \]

\[ S_-(GT) - S_+(GT) = \frac{1}{4} \langle i | \sum_{k=1}^{A} \left[ \sigma_{k}^2 \tau_{+k} \tau_{-k} - \sigma_{k}^2 \tau_{-k} \tau_{+k} \right] | i \rangle \]

\[ S_-(GT) - S_+(GT) = \frac{3}{4} \langle i | \sum_{k=1}^{A} \left[ \tau_{+k} \tau_{-k} - \tau_{-k} \tau_{+k} \right] | i \rangle \]
\[ \sigma^2 = \sum_{\mu=-1}^{+1} [\sigma^\dagger \sigma] ; \quad \text{expectation value of } \sigma^2 \text{ is } 3. \]

\[ \tau_+ \tau_- |n\rangle = 4 |n\rangle \]
\[ , \quad \tau_- \tau_+ |p\rangle = 4 |p\rangle , \quad \tau_+ \tau_- |p\rangle = \tau_- \tau_+ |n\rangle = 0 \]

\[ S_-(GT) - S_+(GT) = \frac{3}{4} \times 4 (N - Z) = 3(N - Z) \]

This is the Ikeda sum rule. For the Fermi sum rule:

\[ S_\pm (F) = \frac{1}{4} \sum_{f,\mu} |\langle f | \tau_\pm | i \rangle|^2 \]

\[ S_-(F) - S_+(F) = \frac{1}{4} \times 4 (N - Z) = (N - Z) \]

Isovector non-spin-flip and isovector spin-flip higher multipole operators:
\[
O_{\pm}^{\lambda t} (M) = \frac{1}{2} \sum_{k=1}^{A} r_k^\lambda Y_{\lambda M} (\hat{r}_k) \tau_{\pm k} 
\]

\[
O_{\pm}^{\lambda \sigma t} (M\mu) = \frac{1}{2} \sum_{k=1}^{A} r_k^\lambda [Y_\lambda (\hat{r}_k) \otimes \sigma_k^\mu] J^\pi \tau_{\pm k} 
\]

\[
S_+^{\lambda J} - S_-^{\lambda J} (GT) = \frac{3(2J + 1)}{2\pi} \left( N \langle r_n^{2\lambda} \rangle - Z \langle r_p^{2\lambda} \rangle \right) 
\]

If spin-flip is involved the sum over possible J-values yields a factor 3(2\lambda+1).
Gamow-Teller excitations and Astrophysical Implications
Spin-isospin excitations

$\Delta L = 0$ $\Delta S = 1$ $\Delta T = 1$

GTR

- Gamow-Teller transitions;
  - Isospin ($\Delta T = 1$)
  - Spin ($\Delta S = 1$)

Advantages

- Cross section peaks at $\theta = 0^\circ$ ($\Delta L = 0$)
- Strong excitation of GT states at $E = 100$-$500$ MeV/u

FIG. 4. Zero-degree cross-section spectra for the $^{14}$C$(p,n)^{14}$N reactions at the indicated bombarding energies. The spectra have been arbitrarily normalized. From Gaarde (1985) and Rapaport (1989).

Spin-flip & GT transitions

\[ \Delta S = 1 \]

Difficult!
Charge-exchange probes

(p,n)-type ($\Delta T_z = -1$)

- $\beta^-$-decay
- $(p,n)$
- $(^3\text{He},t)$
- heavy ion

(n,p)-type ($\Delta T_z = +1$)

- $\beta^+$-decay
- $(n,p)$
- $(d,^2\text{He})$
- $(t,^3\text{He})$
- heavy ion; ($^7\text{Li},^7\text{Be}$)

- Energy per nucleon (> 100 MeV/u)
- Spin-flip versus non-spin-flip
- Complexity of reaction mechanism
- Experimental considerations
The \((p,n)\) reaction at 0 degree

- Cross sections at \(E_p \geq 100\) MeV, \(q = 0\) for \((p,n)\) reactions

\[
\frac{d\sigma}{d\Omega} = \frac{\mu_i\mu_f}{(\pi\hbar^2)^2} \left( \frac{k_f}{k_i} \right) \left( N_D^D |J_\tau|^2 B(F) + N_D^{\sigma|\tau}|J_{\sigma\tau}|^2 B(GT) \right)
\]


- Neutrino absorption cross sections

\[
\sigma = \frac{1}{\pi \hbar^4 c^3} \left[ G_v^2 B(F) + G_A^2 B(GT) \right] \times F(Z, E_e) p_e E_e
\]

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

Importance of charge-exchange reactions at intermediate energies
Time of flight (ToF) neutron spectra for $^{90}\text{Zr}(p, n)^{90}\text{Nb}$ reaction

$(p, n)$ excitation-energy spectra for Fe and Ni Isotopes from ToF measurements

The quenching problem of GT strength
1- Pushed to higher energies by tensor force, or
2- Coupling to Δ resonance

$^{90}\text{Zr} \ (p,n) \ ^{90}\text{Nb}$

**$B(GT)$ (MeV$^{-1}$)**

- **MD analysis**
- **Drożdż et al.**
- **Drożdż et al. (smeared)**
- **Bertsch and Hamamoto**

**Excitation energy (MeV)**

$$S_- - S_+ = 27.0 \pm 1.6 = (90 \pm 5)\% \text{ of Ikeda sum rule}$$

$\Rightarrow \Delta \text{ contribution is small}$

\( (^3\text{He}, t) \) Reaction \( \geq 100 \text{ MeV/u} \)

- Energy dependence of effective interactions.

- At RCNP, Osaka
  \[ E(^3\text{He}) \approx 150 \text{ MeV/u} \]
  - \( V_0 \) part: Minimum.
  - \( V_{\sigma t} \) part: Relatively large.
  - \( V_t \) part: Minimum.
  - \( V_\sigma \) part: Negligible
The \(^3\text{He}, t\) reaction at 0 degree
Measuring GT strengths

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

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

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

Calibration of \(B(\text{GT})\) to cross section for known transitions
(e.g., from \(\beta\)-decay)
Experiments at RCNP, Osaka University

- $(^3\text{He},t)$ reaction at 420 MeV
  - High-resolution spectrometer “Grand Raiden”
  - $\Delta E \sim 30$ keV
Used $^{164}$Dy($^3$He,$t$)$^{164}$Ho (g.s., 1+) reaction for calibration: log\(ft\) 4.6 $\rightarrow B(GT) = 0.293\pm 0.006$

\[ E_x (\text{MeV}) \quad 0.195 + 0.339 \ (p,n) \quad 0.195 \ (^3\text{He},t) \quad 0.339 \ (^3\text{He},t) \]

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

\( \nu_{pp} \leq 0.420 \ \text{MeV} \)

Resolution $\approx$ 100 to 130 keV

M. Fujiwara et al., PRL 85 (2000) 4442

$^{176}$Yb($^3$He,$t$) $E = 450 \ \text{MeV}$
$\theta = 0^\circ$
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

RCNP Ring Cyclotron
Evolution of Resolution in Charge-Exchange Reactions at Intermediate Energies

$^{58}\text{Ni}(p,n)$
$E_p=160\text{MeV}, 0$-deg., IUCF

$\Delta E=\sim 400\text{keV}$

RCNP

$^{58}\text{Ni}(^{3}\text{He},t)^{58}\text{Cu}$
$E(^{3}\text{He})=450\text{ MeV}, 0=0$

Y. Fujita et al.

WS

$^{58}\text{Ni}(^{3}\text{He},t)$
$E_{\text{He}}=140\text{MeV/u}, 0$-deg
2001 RCNP

$\Delta E=35\text{keV}$

H. Fujita et al.
PhD thesis

Y. Fujita et al.
($E_X \leq 8\text{ MeV}$)
Decomposition of the isospin components of the excited states in $^{58}\text{Cu}$.

- **Isospin of $^{58}\text{Ni}$ g.s.** : $T_0 = 1$

- **In principle**, comparison among $(n,p)$, $(p,p')$, $(p,n)$ spectra → separates isospin components

But, very difficult in practice because of high level density for $T = 1$ and $T = 2$ states.

- **Clebsch-Gordon coefficients for** ($T_0 = 1$)

  \[ \sigma_{T=0} \cdot \sigma_{T=1} \cdot \sigma_{T=2} = 2:3:1 \text{ for } (p,n) \]

  \[ \Rightarrow \sigma_{T=1} \cdot \sigma_{T=2} = 1:1 \text{ for } (p,p'), (e,e') \]
Comparison of ($^3\text{He},t$) and ($e,e'$) spectra

- Comparison of $1^+$ levels in ($^3\text{He},t$) with ($e,e'$) and ($t,^3\text{He}$) spectra
  - Try to separate isospin components
- Fig. (b) is shifted by 0.20 MeV (IAS)
  - b-1) $B(M1)$ distribution obtained in ($e,e'$)
  - b-2) $B(M1)$ convoluted with 140 keV resolution
  - In b-1) $1^+$ levels observed in ($t,^3\text{He}$) spectra are marked with small circles
  - Furthermore, comparing with ($n,p$) spectra assume all levels above 11.5 MeV have $T=2$
  - b-3) Same as b-2) but with $T=2$ strength reduced artificially by a factor 3
- At $E_x \sim 6$-10 MeV ($T=1$ region)
  - Rather good correspondence
- At $E_x \sim 10$-15 MeV ($T=2$ region)
  - Reasonable correspondence


$\sigma(T=1) : \sigma(T=2) = 1 : 1$
$\Gamma_{\text{FWHM}} = 30 \text{ keV}$

$\sigma(T=1) : \sigma(T=2) = 3 : 1$
$\Gamma_{\text{FWHM}} = 140 \text{ keV}$

At $E_x \sim 6$-10 MeV ($T=1$ region)
- Rather good correspondence

WS beam line
$\Gamma_{\text{FWHM}} = 50 \text{ keV}$
Disentangling the isospin components of the GT strength in $^{58}$Cu

$^{26}\text{Mg}(p,n)^{26}\text{Al} \& \; ^{26}\text{Mg}(^{3}\text{He},t)^{26}\text{Al}$ spectra

R. Madey et al.,

$^{26}\text{Mg}(^{3}\text{He},t)^{26}\text{Al}$
E=140 MeV/u, $\theta=0^\circ$
$\Delta E \approx 30-35$ keV

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

Prominent states are GT states and the IAS!
$^{54}\text{Fe}(p,n) \ & \ ^{54}\text{Fe}(^3\text{He},t)$

B.D. Anderson et al.,
PRC

$^{54}\text{Fe}(p,n)^{54}\text{Co}$

$B(GT)\ 0.74(5)$

$^{54}\text{Fe}(^3\text{He},t)^{54}\text{Co}$

$B(GT)\ 0.50(6)$

E = 140 MeV/u, $\theta = 0^\circ$
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 nucleosynthesis 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.**
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
Nuclear processes and energy household of supernovae

initial condition: \( M > 10 \, M_{\odot} \)

energy: fusion \( 4p \rightarrow ^4\text{He} \)

at: \( T \sim 10^7 - 10^8 \, K \)

time: \( 10^6 - 10^7 \, \text{y} \)
after $10^6 - 10^7$ y

- end of H-burning
- contraction of star
- temperature increase
- Red Giant (Super-Giant)
- lifetime: $5 \times 10^5$ y
end of stellar evolution \( M_{\text{star}} \sim 15 M_\odot \)

- H (11 \( M_\odot \))
- He (2 \( M_\odot \))
- Fe (1.35)
- C (0.2 \( M_\odot \))
- O (0.8 \( M_\odot \))
- Si (0.2 \( M_\odot \))

stellar onion
Determination of GT Strength is imperative

Supernovae
Cassiopeia A
Chandra

Courtesy of D. Frekers
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. \(\Rightarrow\) Large shell-model calculations \(\Rightarrow\) marked deviations from FFN EC rates; 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 $\Delta S = \Delta T = 1$: ($d,^2\text{He}$)

$^3\text{S}_1$ deuteron $\Rightarrow ^1\text{S}_0$ di-proton ($^2\text{He}$)

$^1\text{S}_0$ dominates if (relative) 2-proton kinetic energy $\varepsilon < 1 \text{ MeV}$

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

But near $0^\circ$, tremendous background from $d$-breakup
Fiera di Primiero, Italy; 2-6 October 2017
Si-ball
16 Si-detectors at
10 cm from the target
total solid angle: 1 sr

EDEN (32 detectors), NE213
total solid angle: 0.37 sr

KVI Big-Bite Spectrometer (BBS)
Setup: ESN detector

Focal-Plane Detector: (FPDS): 2 VDCs

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

Features:
- fast readout
- VDC readout pipeline
- TDC’s
- VDC decoding using imaging techniques
- DSP based online analysis

M. Hagemann et al., NIM A437 (1999) 459
V.M. Hannen et al., NIM A500 (2003) 68

Bari, Darmstadt, Gent, Iserlohn, KVI, Milano, Münster, TRIUMF
• Good double tracking
• Use VDC information
• Good phase-space coverage for small relative proton energies

S. Rakers et al., NIM A481 (2002) 253
Exclusive measurement of $\Delta S = \Delta T = 1$ strength

$^{12}\text{C}(d,^2\text{He})^{12}\text{B}$

$E_0 = 171$ MeV, $\theta = 0^\circ$

- shell model calculations $4\hbar\omega$ & $6\hbar\omega$ (G. Martinez-Pinedo)
- $B\ (GT^\pm)$ (S. Rakers)
(p,n) vs (d,²He): calibration

S. Rakers et al., PRC 65 (2002) 044323
Experimental cross section and GT strength

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


## GT Strength in $^{12}\text{B}$ and $^{24}\text{Na}$ from (d, $^2\text{He}$) reaction

<table>
<thead>
<tr>
<th>Target</th>
<th>Reference data</th>
<th>Present data</th>
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<tbody>
<tr>
<td></td>
<td>$E_x$</td>
<td>$B($GT$_-)$</td>
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<tr>
<td></td>
<td>[MeV]</td>
<td>[MeV]</td>
</tr>
<tr>
<td>$^{12}\text{B}$</td>
<td>0.00</td>
<td>0.998</td>
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<tr>
<td>$^{24}\text{Na}$</td>
<td>0.44</td>
<td>0.050</td>
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<td>1.07</td>
<td>0.613</td>
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<td></td>
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<td>0.029</td>
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(\(d, ^2\text{He}\)) as GT\(^+\) probe in \(fp\)-shell nuclei

\[58\text{Ni}(d, ^2\text{He})^{58}\text{Co} \ E = 170 \text{ MeV}\]

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

M. Hagemann et al., PLB 579 (2004) 251
$^{58}\text{Ni}(d,^2\text{He})^{58}\text{Co}$  $E_d = 170$ MeV

\[ B_{\text{exp}}(\text{GT+}) = \frac{d\sigma(q=0)}{d\Omega} \cdot \left[ \frac{d\hat{\sigma}(\text{GT})}{d\Omega} \right]^{-1} \]
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
## GT Strength in $^{58}$Co from $(d,^2\text{He})$ reaction

<table>
<thead>
<tr>
<th>$E_x$ [MeV]</th>
<th>$d\sigma/d\sigma(0.5^\circ)$ [mb/sr]</th>
<th>$\sigma(L=0)/\sigma(\tau\tau)$</th>
<th>B(GT+) [MeV][mb/sr]</th>
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<tbody>
<tr>
<td>1.050</td>
<td>0.159±0.009</td>
<td>0.88</td>
<td>0.15±0.01</td>
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<td>1.435</td>
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<td>2.660</td>
<td>0.057±0.005</td>
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<td>0.17±0.01</td>
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<td>3.100</td>
<td>0.126±0.008</td>
<td>0.99</td>
<td>0.15±0.01</td>
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<tr>
<td>3.410</td>
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<td>0.96</td>
<td>0.07±0.01</td>
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<td>3.520</td>
<td>0.080±0.009</td>
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<td>0.09±0.01</td>
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<td>1.00</td>
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<td>4.05-5.00</td>
<td>0.381±0.061</td>
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<td>0.49±0.09</td>
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</tbody>
</table>
GT\(^+\) strength: comparison \((n,p), (d,^2\text{He})\) & theory

Up to 4 MeV excitation:

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

Strength re-binned in 1 MeV bins

Significant differences

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

$E_t = 115 \text{ MeV/u}$

Resolution = 250 keV

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

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

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.
$T_9 = 4.05$
$\rho = 3.18 \times 10^7 \text{ g/cm}^3$
$Y_e = 0.48$


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

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

- 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 (2003) 031303(R)
C. Bäumer et al.,
PRC 68 (2003) 031303(R)
$^{51}\text{V}(d,^2\text{He})$: Angular distributions of $d\sigma/d\Omega$
$^{51}\text{V}(d,^2\text{He})$: Comparison with shell-model calculations

$\Delta L = 0.1$

$\Gamma_{\text{TR}}$ (FFN)

Full $fp$-shell model calculations quenching factor $(0.74)^2$

G. Martínez-Pinedo, K. Langanke
50V(d, 2He): GT\(^+\) transitions from odd-odd nucleus

\[
50V (d, 2He) \rightarrow 50Ti
\]

\[J^\pi=6^+ \rightarrow J^\pi=5^+, 6^+, 7^+, T=3\]

GT-centroid located at ~ 9 MeV
$^{56}\text{Fe}(d,^{2}\text{He})$: Comparison with shell-model calculations

Experiment

Full $fp$-shell model calculations (KB3G) (G. Martínez-Pinedo)
\[ {^{61}\text{Ni}}(d,^{2}\text{He})^{61}\text{Co}: \text{GT}^+ \text{ distribution} \]

\[ {^{57}\text{Fe}}(d,^{2}\text{He})^{57}\text{Mn}: \text{GT}^+ \text{ distribution} \]
$^{67}\text{Zn}(d,^2\text{He})^{67}\text{Cu}: \text{GT}^+ \text{ distribution}$

No shell-model calculations yet
## Comparison of centroids (MeV) of GT\(^+\) Strength distribution

<table>
<thead>
<tr>
<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>
</tr>
<tr>
<td>(^{56}\text{Fe})</td>
<td>3.8</td>
<td>2.2</td>
<td>1.9</td>
</tr>
<tr>
<td>(^{58}\text{Ni})</td>
<td>3.8</td>
<td>3.6</td>
<td>3.4</td>
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<tr>
<td><strong>Odd A-Odd (p)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{51}\text{V})</td>
<td>3.8</td>
<td>4.7</td>
<td>4.1</td>
</tr>
<tr>
<td><strong>Odd A-Odd (n)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{57}\text{Fe})</td>
<td>5.3</td>
<td>4.1</td>
<td>2.9</td>
</tr>
<tr>
<td>(^{61}\text{Ni})</td>
<td>3.5</td>
<td>4.6</td>
<td>4.2</td>
</tr>
<tr>
<td>(^{67}\text{Zn})</td>
<td>4.4</td>
<td>--</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>Odd-Odd</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{50}\text{V})</td>
<td>9.7</td>
<td>8.5</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. [GXP]) \(\Rightarrow\) 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 \(T\).

Fiera di Primiero, Italy; 2-6 October 2017
Double-Beta Decay
$2\nu\beta\beta$ decay

Allowed in SM and observed in many cases

$$
\left[ t_{1/2}^{(2\nu)} \right]^{-1} = G^{(2\nu)} |M_D^{(2\nu)}|^{2},
$$

$$
M_D^{(2\nu)} = \sum_m \frac{(0^{(f)} \| \sum_i \sigma(i) \tau^\pm(i) \| 1_m^+)(1_m^+ \| \sum_i \sigma(i) \tau^\pm(i) \| 0^{(i)}_{g.s.})}{[\frac{1}{2} Q_{\beta\beta}(0^{(f)}_{g.s.}) + E(1_m^+) - M_i]/m_e + 1}
$$

Accessible through charge-exchange reactions in $(n,p)$ and $(p,n)$ direction [e.g. $(d,^{2}\text{He})$ or $(^{3}\text{He},t)$]
Forbidden in MSM
Lepton number violated
Neutrino enters as virtual particle, \( q \sim 0.5 \text{ fm}^{-1} \)

nuclear neutrino-less double-beta decay

\[ 0\nu{2}\beta \]

\[ Z, A \rightarrow Z + 2, A \]

\[ e^- \equiv \beta \]

\[ \langle m_\nu \rangle \]

Mass of Majorana neutrino!!
Approach

Study the spectroscopy of virtual states in the 2-quantum process

theory:

\[ NME^{0\nu\beta} = \sum_m \frac{\langle J_i^{\pi} || \text{Operator} || J_m^{\pi} \rangle \langle J_m^{\pi} || \text{Operator} || J_f^{\pi} \rangle}{f(E_m)} \]
Intensively studied $\beta\beta$-emitter

$T_{1/2}$ determined by the Heidelberg-Moscow group: $1.55 \times 10^{21}$ y

$T_{1/2}$ deduced from (n,p) and (p,n) data with poor energy resolution

Multipole decomposition: $7.4 \times 10^{20}$ y

$0^\circ$-$6^\circ$ subtraction method: $8.7 \times 10^{21}$ y

$Q_{\beta^-\beta^-} = 2040$ keV

$\Sigma B(GT^+) \sim 0.56$
$^{76}\text{Se}(d,^{2}\text{He})^{76}\text{As}$
\[ \Theta_{\text{c.m.}} \approx 0.4^\circ \]
\[ \Delta E = 120 \text{ keV} \]

$^{76}\text{Ge}(p,n)^{76}\text{As}$
\[ \Theta_{\text{c.m.}} \approx 0.3^\circ \]
\[ \Delta E = 350 \text{ keV} \]
IUCF 1989

$2\nu\beta\beta$-matrix element

$0.16 \pm 0.04 \text{ MeV}^{-1}$

with

$G(2\nu) = 3.4 \times 10^{-20} \text{ MeV}^2 \text{ a}^{-1}$

$2\nu\beta\beta$ - half-life

$(1.1 \pm 0.2 ) \times 10^{21} \text{ a}$

recommended exp. value:

$(1.5 \pm 0.1 ) \times 10^{21} \text{ a}$

Fiera di Primiero, Italy; 2-6 October 2017

$2\nu\beta\beta$-matrix element

$0.16 \pm 0.04 \text{ MeV}^{-1}$

with

$G(2\nu) = 3.4 \times 10^{-20} \text{ MeV}^2 \text{ a}^{-1}$

$2\nu\beta\beta$ - half-life

$(1.1 \pm 0.2) \times 10^{21} \text{ a}$

recommended exp. value:

$(1.5 \pm 0.1) \times 10^{21} \text{ a}$

$^{96}\text{Zr} - ^{96}\text{Nb} - ^{96}\text{Mo}$

- $T_{1/2}$ available:
  - counting experiments: $2.1 \times 10^{19}$ y
  - geochemical methods: $9.4 \times 10^{18}$ y

- g.s. transition forbidden
- Strength concentrated in one transition

$^{96}\text{Mo}(d,^2\text{He})^{96}\text{Nb}$

- $\Theta_{\text{c.m.}} < 1.3^\circ$
- $\Delta E \sim 120$ keV

$Q_{\beta^- \beta^-} = 3351$ keV

$B(\text{GT}^+) \sim 0.3$
In \((p,n)\) direction:

1. exceptionally small \(B(GT^-)\) below 6 MeV
2. concentrated in one low-lying level only
\( B(GT^+) = 0.3 \)

\( B(GT^-) = 0.15 \)

With this 1 level only

\[ T_{1/2}^{calc.} \, (2\nu\beta\beta) = (2.4 \pm 0.3) \cdot 10^{19} \text{ years} \]

\[ T_{1/2}^{exp.} \, (2\nu\beta\beta) = (2.2 \pm 0.4) \cdot 10^{19} \text{ years} \, \text{(NEMO3-result)} \]
Conclusions

- Charge-exchange reactions provide important input for $2\nu\beta\beta$ decay ME; i.e. $(d,^2\text{He}) (t,^3\text{He})$ for GT$^+$ leg and $(^3\text{He},t)$ for the GT$^-$ leg.

- $^{96}\text{Zr}$ and $^{100}\text{Mo}$ exhibit Single-State Dominance (at 0.69 MeV ($^{96}\text{Zr}$) and g.s. ($^{100}\text{Mo}$)).
Claim of the observation of $0\nu 2\beta$-decay in $^{76}\text{Ge}$

- Contribution of many multi-poles
- Dominance of dipole components
- The $g_{pp}$ parameter affects mainly the $J^\pi = 1^+$ component
- It becomes imperative to study experimentally higher multi-pole components
Experiments at RCNP, Osaka University

- \((^3\text{He},t)\) reaction at 420 MeV
  - High-resolution spectrometer “Grand Raiden”
  - \(\Delta E \sim 30\) keV
$^{136}$Xe($^3$He,$t$)$^{136}$Cs

E($^3$He) = 420 MeV

$\Delta E = 42$ keV

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

DWM-extrapolated
d unit cross section

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

Double-beta decay nuclei $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{128}$Te, $^{130}$Te, $^{150}$Nd show clear spin-dipole and Gamow-Teller states.

- RCNP high-resolution system is the unique and only opportunity to determine $2^-$ levels.

Select spin-dipole (SD) component and derive $B(SD)$ from DWBA fit at the peak region where SD $\langle \sigma \tau Y_1 \rangle^{2-}$ is dominant.

- Angular distributions of SD are peaked around 2 deg.
- Small deviation of (0.1 mb/sr) at 0.5 deg!

IV(S)GDR & GTR
Neutron-Skin Thickness
Determining neutron-skin thickness from IVSGDR

Summed $\Delta L=1$ strength depends on the neutron-skin thickness as follows:

$$S_{IVSGDR}^- - S_{IVSGDR}^+ = \frac{9}{2\pi} \left( N\langle r^2 \rangle_n - Z\langle r^2 \rangle_p \right)$$

Here, $S^-$ and $S^+$ are the spin-dipole total strengths in $\beta^-$ and $\beta^+$ channels.

Using the calculated $B = S^+/S^-$ ratios the neutron-skin thicknesses can be deduced

$$\langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2} = \frac{\alpha \sigma_{exp} (1 - B) - (N - Z)\langle r^2 \rangle_p}{2N\langle r^2 \rangle_p^{1/2}},$$  \hspace{1cm} (3)$$
$^{A\text{Sn}}(^{3}\text{He},t)$

At 450 MeV

Summary of the neutron-skin thicknesses \((\langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}\) in fm) obtained in different methods.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{112}\text{Sn})</td>
<td>(</td>
<td>0.15\pm0.05</td>
<td>)</td>
<td>(0.02\pm0.12)</td>
</tr>
<tr>
<td>(^{114}\text{Sn})</td>
<td>(\leq0.09)</td>
<td>(0.13\pm0.06)</td>
<td>(0.12\pm0.02)</td>
<td>(0.12\pm0.02)</td>
</tr>
<tr>
<td>(^{116}\text{Sn})</td>
<td>(0.18^a))</td>
<td>(0.18\pm0.07)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{120}\text{Sn})</td>
<td>(0.22\pm0.07)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{122}\text{Sn})</td>
<td>(0.25\pm0.05)</td>
<td>(0.21\pm0.11)</td>
<td>(0.19\pm0.07)</td>
<td>(0.19\pm0.02)</td>
</tr>
<tr>
<td>(^{208}\text{Pb})</td>
<td>(0.14\pm0.04)</td>
<td>(0.20\pm0.04)</td>
<td>(0.19\pm0.09)</td>
<td>(0.15\pm0.02)</td>
</tr>
</tbody>
</table>

\(^a)\) Normalized to the theoretical value of Angeli et al. [21].
The full dots with error bars show the neutron-skin thicknesses of the Sn isotopes determined from the IVSGDR data as a function of the mass number. The experimental Values determined by the \((p,p)\), And the antiprotonic methods are Shown as full triangles and full Squares with error bars, respectively. The numbered full lines represent different theoretical results.

K. Pham et al., PRC 51 (1995) 526
\(^3\text{He}, t\) charge-exchange reaction on all stable Sn nuclei at IUCF, Bloomington
\(E(3\text{He}) = 200\) MeV
Excitation-energy spectra are plotted relative to IAS.

K. Pham et al., PRC 51 (1995) 526
Excitation energy of main component of GTGR relative to IAS.

Comparison of theoretical calculations to experimental results for excitation energy of main component of GTGR relative to IAS. Inset shows IAS energies

Theoretical pn-RQRPA and experimental differences of GTGR and IAS excitation energies as function of neutron-skin thickness (data from K. Pham). Lower panel shows comparison between theoretical neutron-skin thickness and experimental data (data from A. Krasznahorkay).

D. Vretenar et al., PRL 91 (2003) 262502
A. Krasznahorkay et al., PRL 83 (1999) 3216; \( r_n - r_p \)
Proton Decay
IAS, GTR, IVSGDR, IV(S)GMR
Microscopic Structure of GTR and IVSGDR in $^{208}$Bi

- Proton decay of $^{208}$Bi
  - Direct decay dominant
    - $E_x > E_{th}(n) > E_{th}(p)$
    - High Coulomb Barrier ($Z=83$)
  - Statistical proton decay negligible.

- Angular correlations
  - For IAS and GTR decay isotropic $\Delta L=0$
  - For IVSGDR anisotropic but not strongly

- Direct decay is influenced by:
  - Low $n$-decay threshold
  - High Coulomb barrier.
- $\Gamma_{GTR}^\uparrow/\Gamma \ll \Gamma_{IAS}^\uparrow/\Gamma \approx 0.5$
- IAS $n$-decay: isospin forbidden.
- Centroid energy shift: cut off by Coulomb barrier
- $\Gamma_{IVSGDR}^\uparrow/\Gamma > \Gamma_{GTR}^\uparrow/\Gamma$
- Higher proton energy

- **Width $\Gamma$**

$$\Gamma = \Gamma^\uparrow + \Gamma^\downarrow$$

Escape: Direct decay
Spreading: Statistical Decay

$$\Gamma^\uparrow = \Gamma_p^\uparrow = \sum_i \Gamma_{pi}^\uparrow$$

Partial Escape Width

$$\frac{\Gamma_{pi}^\uparrow}{\Gamma} = \frac{\int d^2\sigma_{pi}/(d\Omega_t d\Omega_p) d\Omega_p}{d\sigma/d\Omega_t}$$

Branching ratio
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
Set-up of the Proton Counter

- Si(Li) detectors with a thickness of 5 mm, covering a solid angle of 5.7% in total.
- 35 keV ($^{241}\text{Am}$ test)
Spin-isospin-flip transitions in charge-exchange reactions and proton decay

$^{208}\text{Pb}(^3\text{He},t)$ reactions $E(^3\text{He})=450\text{ MeV}$

A. Krasznahorkay et al., PRC 64 (2001) 067302.
Experimental Results and Theoretical Calculations

Partial escape width for GTR

<table>
<thead>
<tr>
<th>Channel</th>
<th>$E_x$ (keV)</th>
<th>Theory $\Gamma_i$ (keV)</th>
<th>This work $\Gamma_i$ (keV)</th>
<th>Branch (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3p_{1/2}$</td>
<td>0</td>
<td>48.7</td>
<td>58.4 ± 19.8</td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td>$2f_{5/2}$</td>
<td>570</td>
<td>46.2</td>
<td>inc. in $p_{3/2}$</td>
<td></td>
</tr>
<tr>
<td>$3p_{3/2}$</td>
<td>898</td>
<td>44.7</td>
<td>101.5 ± 31.3</td>
<td>2.7 ± 0.6</td>
</tr>
<tr>
<td>$1i_{13/2}$</td>
<td>1633</td>
<td>0.87</td>
<td>8.3 ± 9.4</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td>$2f_{7/2}$</td>
<td>2340</td>
<td>5.89</td>
<td>15.6 ± 7.6</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>$1h_{9/2}$</td>
<td>3413</td>
<td>0.24</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>146.6</td>
<td>184 ± 49</td>
<td>4.9 ± 1.3</td>
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</table>

Partial escape width for IVSGDR

<table>
<thead>
<tr>
<th>Channel</th>
<th>$E_x$ (keV)</th>
<th>Theory $\Gamma_i$ (keV)</th>
<th>Branch (%)</th>
<th>This work $\Gamma_i$ (keV)</th>
<th>Branch (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3p_{1/2}$</td>
<td>0</td>
<td>103.4</td>
<td>1.23</td>
<td>83.4 ± 24.3</td>
<td>0.99 ± 0.29</td>
</tr>
<tr>
<td>$2f_{5/2}$</td>
<td>570</td>
<td>178.1</td>
<td>2.12</td>
<td>170.8 ± 49.3</td>
<td>2.12 ± 0.61</td>
</tr>
<tr>
<td>$3p_{3/2}$</td>
<td>898</td>
<td>210.1</td>
<td>2.5</td>
<td>240 ± 69.6</td>
<td>2.86 ± 0.83</td>
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<tr>
<td>$1i_{13/2}$</td>
<td>1633</td>
<td>299.8</td>
<td>3.57</td>
<td>330.4 ± 95.7</td>
<td>3.74 ± 1.08</td>
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<tr>
<td>$2f_{7/2}$</td>
<td>2340</td>
<td>249.3</td>
<td>2.97</td>
<td>282.2 ± 86.8</td>
<td>3.36 ± 0.97</td>
</tr>
<tr>
<td>$1h_{9/2}$</td>
<td>3413</td>
<td>52.6</td>
<td>0.63</td>
<td>86.7 ± 25.1</td>
<td>1.03 ± 0.29</td>
</tr>
<tr>
<td>Total</td>
<td>1209.6</td>
<td>14.4</td>
<td>1180 ± 340</td>
<td>14.1 ± 4.2</td>
<td></td>
</tr>
</tbody>
</table>

Theory:
E. Moukhai,
V.A. Rodin,
M.H. Urin
Continuum RPA
Summary: $^{208}\text{Pb}(^3\text{He},tp)$

- GTR: $\Gamma^\uparrow/\Gamma \sim 4.9\%$, $\Gamma^\uparrow = 184 \pm 49$ keV
  - Small branching ratio:
    - Spreading effect is very important.
    - Coupling to underlying 2p-2h states.
    - Centroid energy shift caused by High Coulomb barrier.
- IVSGDR: $\Gamma^\uparrow/\Gamma \sim 14.1\%$, $\Gamma^\uparrow = 1180 \pm 340$ keV
  - Larger p-decay $\Gamma^\uparrow/\Gamma$ compared to GTR.
    - $E_p$: enough higher than Coulomb barrier, centrifugal barrier.
  - Enhancement of decay to high-spin $1n$-hole states
Isovector giant monopole resonances

\[ \Delta L = 0 \quad \Delta S = 0 \quad \Delta T = 0 \]
ISGMR

\[ \Delta L = 0 \quad \Delta S = 0 \quad \Delta T = 1 \]
IVGMR

\[ \Delta L = 0 \quad \Delta S = 1 \quad \Delta T = 1 \]
IVSGMR

\[ O = r^\lambda [\sigma \otimes Y_L]_J \tau_- \]

- IAS: \( \lambda = 0 \quad S = 0 \quad L = 0 \quad J = 0 \)
- GTR: \( \lambda = 0 \quad S = 1 \quad L = 0 \quad J = 1 \)
- IVGMR: \( \lambda = 0 \quad S = 0 \quad L = 0 \quad J = 0 \)
- IVSGMR: \( \lambda = 0 \quad S = 1 \quad L = 0 \quad J = 1 \)
- IVSGDR: \( \lambda = 1 \quad S = 1 \quad L = 1 \quad J = 0,1,2 \)
Decay studies

- **Successful:**
  - GTR, IVSGDR in $^{208}\text{Pb}(^3\text{He},t+p)$ at 450 MeV (Akimune et al.)
  - IVGMR/IVSGMR in $^{208}\text{Pb}(^3\text{He},t+p)$ at 177 MeV at KVI
    & 410 MeV at RCNP (Zegers et al.)

- **Unsuccessful:**
  - IVGMR/IVSGMR $^{124}\text{Sn}(^3\text{He},t+n)$ at 200 MeV at IUCF
Proton decay from the IVSGMR

-30 MeV
IVGMR/SIVM -37.9
IVGQR -34.3

-20 MeV
IVGDR -28.6
SDR -26.9

-10 MeV
GTR -18.5
IAS -18.1

Q
$E_x$
$E_p$

$Q(g.s) = -2.9$
$S_p = -3.7$

$^{208}_{\text{Pb}}$ $^{208}_{\text{Bi}}$ $^{207}_{\text{Pb}}$
Measurement of IVSGMR via $^{208}$Pb($^3$He,$t$+$p$)

$E_x \sim 38$ MeV  
$\Gamma = 10$ MeV

- DW81 (Raynal)
- Effective $^3$He-N potential
  - $V_\tau = 0.73 \pm 0.01$ MeV (IAS)
  - $V_{\sigma\tau} = -2.1 \pm 0.2$ MeV (known ratio to $V_\tau$)
  - $V_{T\tau} = -2.0$ MeV/fm$^2$
- most coherent 1p-1h wave-function (normal modes).

Use difference-of-angle to identify the monopole excitations
Results

\[ \text{t singles} \]

R.G.T. Zegers et al., PRL 90 (2003) 202501

\[ \text{t-p coincidences} \]

Difference of angles

\[ \sqrt[208]{\text{Pb}}(\text{He},t) \]

\[ E(\text{He}) = 4.10 \text{ MeV} \]

\[ \sqrt[208]{\text{Pb}}(\text{He,tp}) \]

\[ E(\text{He}) = 4.10 \text{ MeV} \]

IAS

GTR

SDR

IVSGMR

\[ \theta_{\text{cm}} = 0.57^\circ \]

\[ \theta_{\text{cm}} = 1.2^\circ \]

\[ d^2\sigma/dQdE_x \] (mb/sr² MeV)

\[ d^3\sigma/dQdQ_dE_x \] (mb/sr³ MeV)

Fiera di Primiero, Italy; 2-6 October 2017

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Angular distribution

Use difference-of-angle method between narrow angular bins to extract angular distribution of the resonance

IVSGMR angular distribution confirmed
Strength exhaustion

Summed strength: \((46\pm4\pm10) \cdot 10^3 \text{ fm}^4\) (contribution from IVGMR subtracted)

<table>
<thead>
<tr>
<th>Method</th>
<th>Exhaustion(%) ((\pm\sigma_{\text{stat}} \pm \sigma_{\text{sys}}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal modes</td>
<td>60(\pm)5(\pm)14</td>
</tr>
<tr>
<td>Tamm-Dancoff</td>
<td>68(\pm)6(\pm)17</td>
</tr>
<tr>
<td>Continuum RPA</td>
<td>103(\pm)9(\pm)25</td>
</tr>
<tr>
<td>HF-RPA*</td>
<td>210(\pm)16(\pm)45</td>
</tr>
</tbody>
</table>

* Different operator, includes GT

Systematic errors
- extrapolation of continuum: 5%
- high-lying GT strength: small
- tail of the IVSGDR: 10%
- DWBA: 10% of measured value
Final state spectra

Comparison with $^{208}\text{Pb}(^3\text{He},\alpha)$
## Final state population in $^{207}$Pb

<table>
<thead>
<tr>
<th>Final state</th>
<th>Data(%)</th>
<th>Theory(%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3p_{1/2} 2f_{5/2} 3p_{3/2}$</td>
<td>&lt; 3</td>
<td>11.3</td>
</tr>
<tr>
<td>$1i_{13/2}$</td>
<td></td>
<td>21.4</td>
</tr>
<tr>
<td>$2f_{7/2} 1h_{9/2}$</td>
<td>13±5</td>
<td>9.5</td>
</tr>
<tr>
<td>$1h_{11/2}$</td>
<td>22±8</td>
<td>22.8</td>
</tr>
<tr>
<td>$1g_{7/2} 1g_{9/2}$</td>
<td>17±8</td>
<td></td>
</tr>
<tr>
<td><strong>All</strong></td>
<td>52±12</td>
<td>66</td>
</tr>
</tbody>
</table>

*Rodin & Urin NPA 687, 276c (continuum RPA)

Large discrepancies for partial branchings!!
Outlook

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

- Determine GT strength in unstable $sd$ & $fp$ shell nuclei
- Measure ISGMR and ISGDR in extended isotope chain
- Unravel the nature of the pygmy dipole resonance
- Use IV(S)GDR as tool to determine $n$-skin [IV(S)GDR]
- Exotic excitations such as double GT (SHARAQ)
Thank you for your attention