9th RIBF discussion meeting --- July 31, 2014

「Isovector Spin Giant resonances at the extreme of large N/Z」

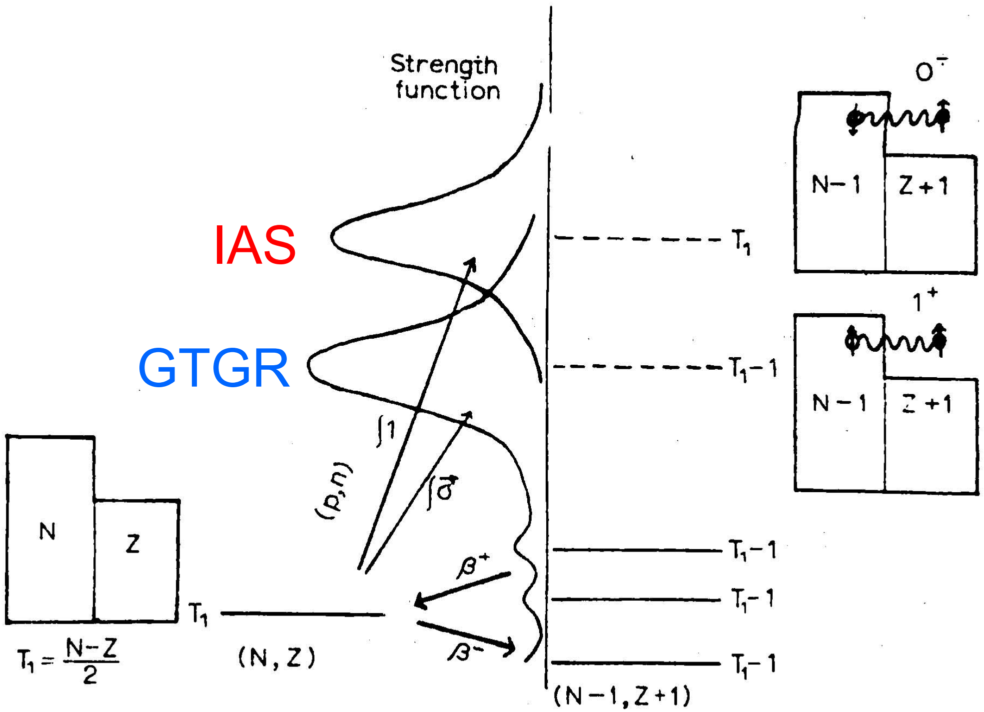
<u>Evolution of Spin-isospin collectivity toward the neutron drip line</u>

Hiroyuki Sagawa RIKEN/Aizu

1. 20th century Spin-Isospin response -history
2. 21st centrury -- new horizon in large N/Z >0.3

K. Ikeda, S. Fujii and J. I. Fujita: Phys. Lett. 2 (1962) 169, 3 (1963) 271

Existence of Gamow-Teller giant resonance



Anderson and Wong, 1961

$$[H, \boldsymbol{\sigma\tau}] \neq 0$$

$$[H, T_z] \approx 0$$

IAS is predicted higher than GTGR in energy! Isospin consideration.

Model-independent sum rule : GT(Ikeda) sum rule

$$
\begin{aligned}
S_{\beta-} - S_{\beta+} &= \frac{1}{2J_i + 1} \sum_f |\langle f \| \sum_{i=1}^{A} t_-(i)\boldsymbol{\sigma}_i \| i \rangle|^2 \\
&\quad - \frac{1}{2J_i + 1} \sum_f |\langle f \| \sum_{i=1}^{A} t_+(i)\boldsymbol{\sigma}_i \| i \rangle|^2 \\
&= \langle i | \sum_{i,j=1}^{A} (t_+(j)t_-(i) - t_-(i)t_+(j)) \, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \, | i \rangle
\end{aligned}
$$

$$
[t_+(j), t_-(i)] = \delta_{ij} \, 2t_z(i), \qquad \sum_{i=1}^{A} 2t_z(i) = 2T_z \qquad \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_i = 3
$$

$$
S_{\beta-} - S_{\beta+} = \langle i | \, 2T_z \cdot 3 \, | i \rangle = 3(N - Z)
$$

cf: Fermi transition

$$
S_{\mathrm{F}-} - S_{\mathrm{F}+} = \langle i | \, 2T_z \, | i \rangle = N - Z
$$

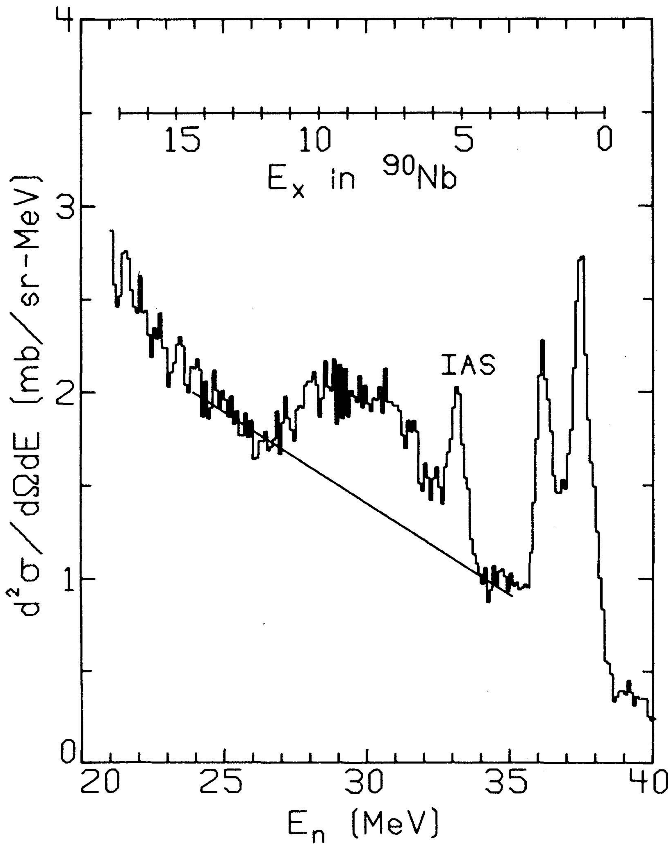
Observation of GT Giant Resonances

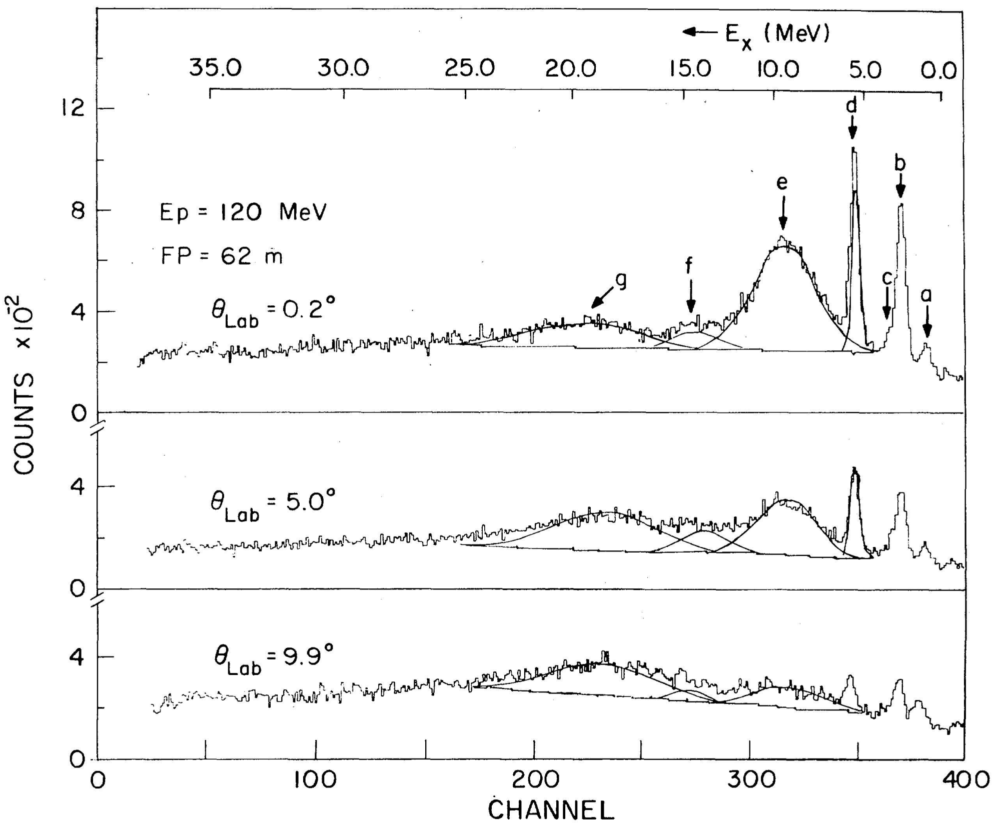
R.R. Doering *et al.* (MSU)
Phys. Rev. Lett. 35 (1975) 1691

$^{90}Zr(p,n)^{90}Nb$ at E_p = 45 MeV

D.E. Bainum *et al.* (Indiana)
Phys. Rev. Lett. 44 (1980) 1751

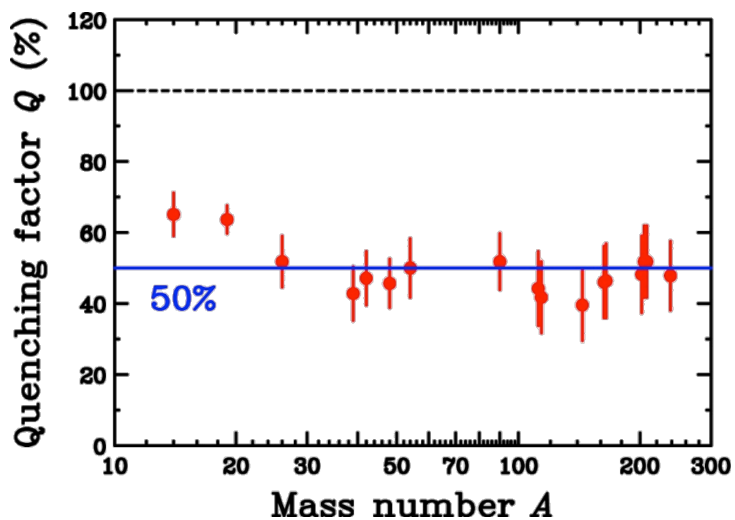
$^{90}Zr(p,n)^{90}Nb$ at E_p = 120 MeV

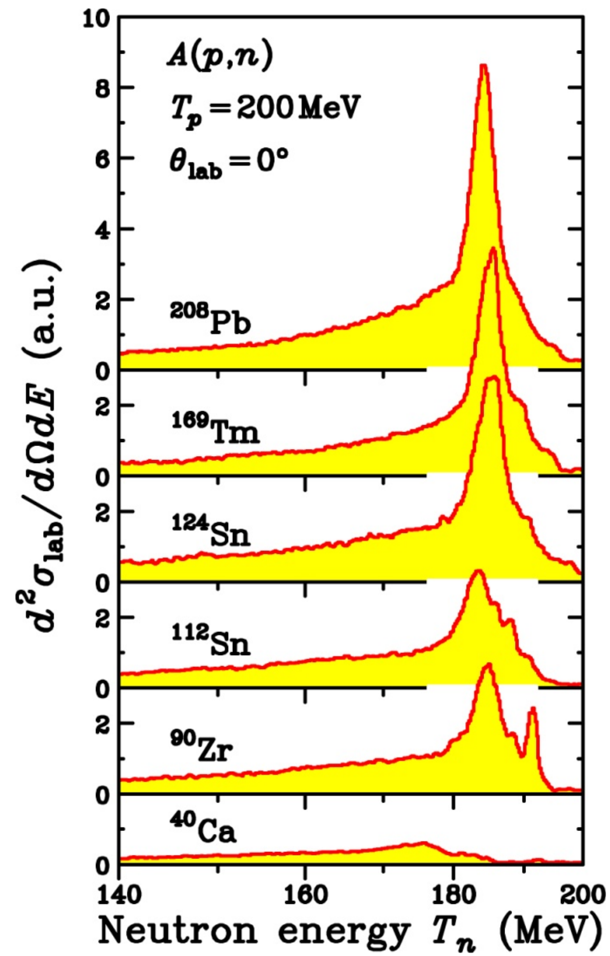




- GTGR : 1963 predicted by Ikeda, Fujii and Fujita
  - Discovered in 1975 (MSU)
  - Systematic Studies in 1980s at IUCF (C. Gaarde, Goodman,---)
- GT strength B(GT) and σ(0°) of (p,n)
  - σ(0°) ∝ B(GT) ***(Proportionality)***
  - GT sum-rule
    - $S_- - S_+ = 3(N-Z)$

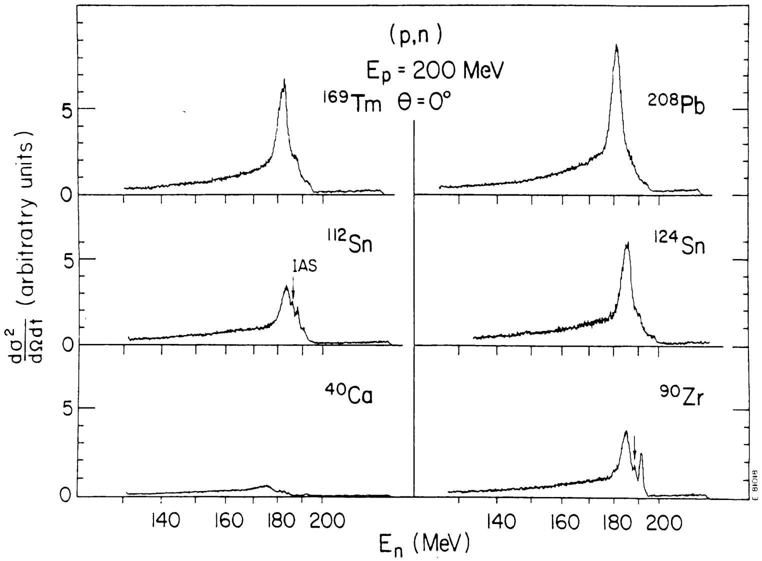
$$Q = \frac{S_-(p,n)}{3(N-Z)}$$





C. Gaarde, NP A396, 127c(1983)

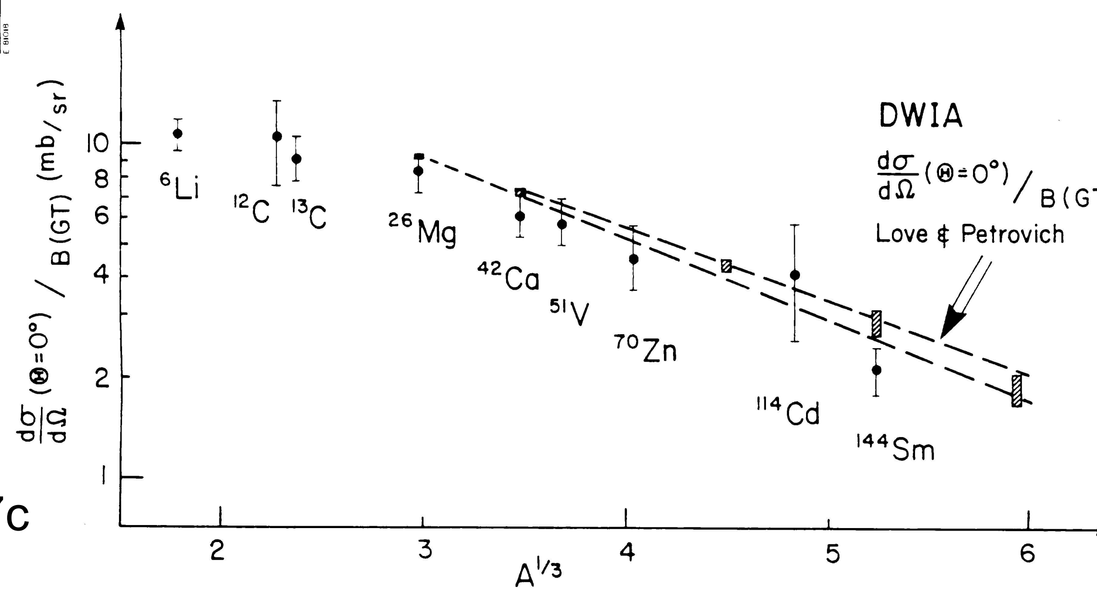
GT strengths by (*p,n*) reaction



The forward-angle cross section of (*p,n*) reaction is proportional to *B*(GT) at proton energies of 120-200 MeV.

$$\left.\frac{d\sigma}{d\Omega}\right|_{\theta=0^\circ} = \left(\frac{\mu}{\pi\hbar^2}\right)^2 \frac{k_f}{k_i} N_{\sigma\tau} J_{\sigma\tau}^2 B(\mathrm{GT})$$

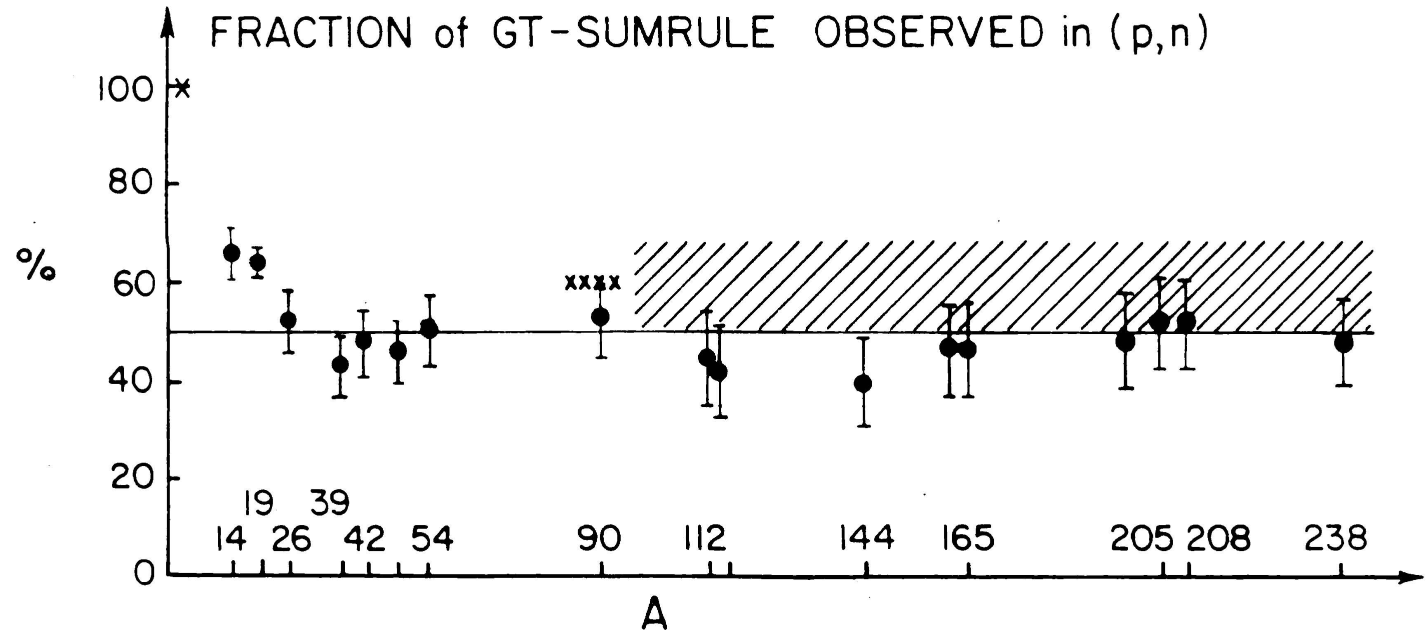
C. Gaarde *et al*.
Nucl. Phys. A369 (1981) 258



C. Gaarde
Nucl. Phys. A396 (1983) 127c

Missing strength

C. Gaarde, Nucl. Phys. A396 (1983) 127c

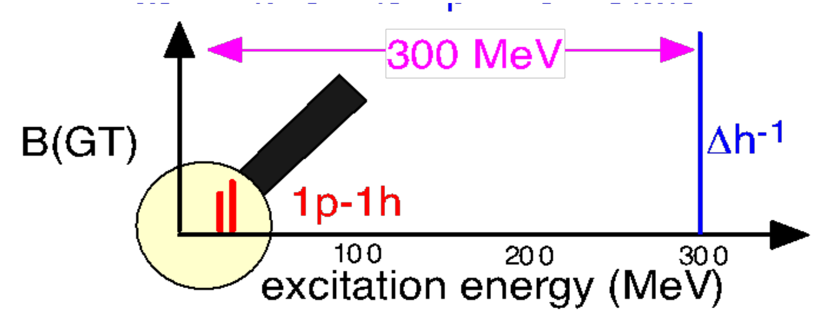


The quenching of low-lying GT transitions was attributed to giant resonance.

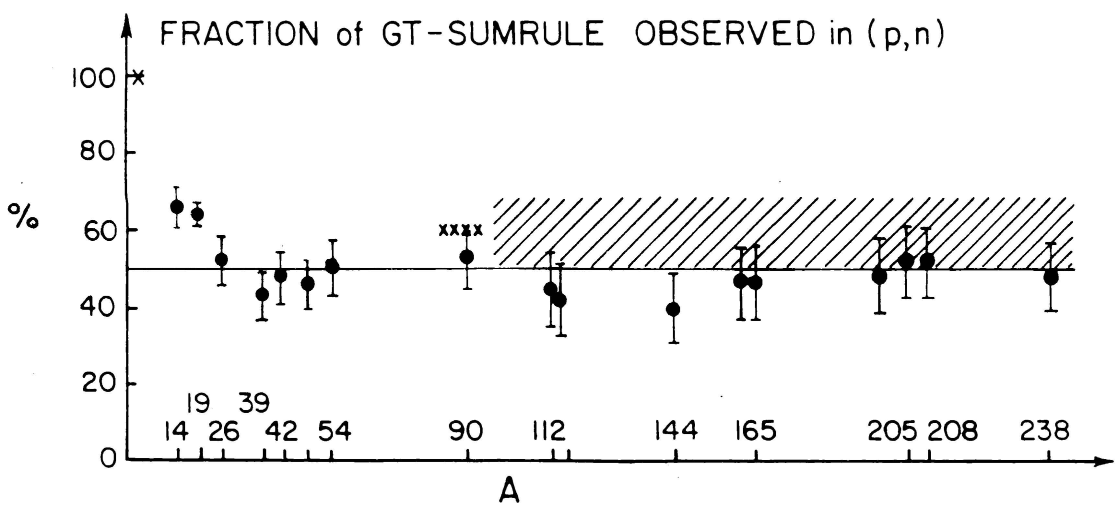
But, the giant resonance was found to carry only a half of the GT strength expected from the model-independent sum rule.

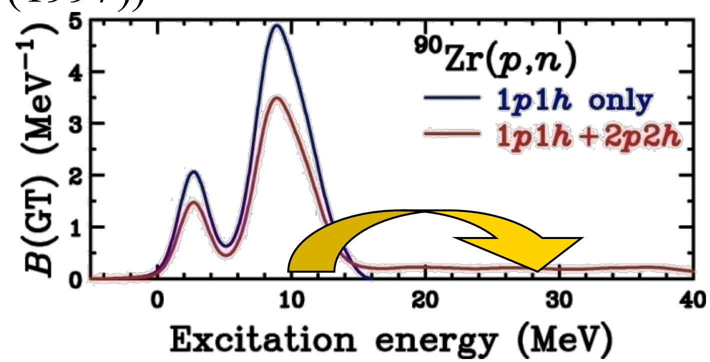
Missing GT strength

Δ – hole coupling (E. Oset and M. Rho(1979), A.Bohr and B.R.Mottelson(1981))



Many - particle many - hole couplings (G.F.Bertsch and I. Hamaomo(1982),
S. Drozdz et al., (1987), A. Arima et al., (1997))





Possible Theoretical explanation of the quenching

Magnetic moments: Coupling to 2*p*-2*h* states up to high excitation energies due to tensor force

K. Shimizu, M. Ichimura and A. Arima, Nucl. Phys. A 226 (1974) 282

I.S. Towner and F.C. Khanna, Phys. Rev. Lett. 42 (1979) 51.

Gamow-Teller: G.F. Bertsch and I. Hamamoto, Phys. Rev. C26 (1982) 1323
A perturbative calculation of the coupling to 2*p*-2*h*.

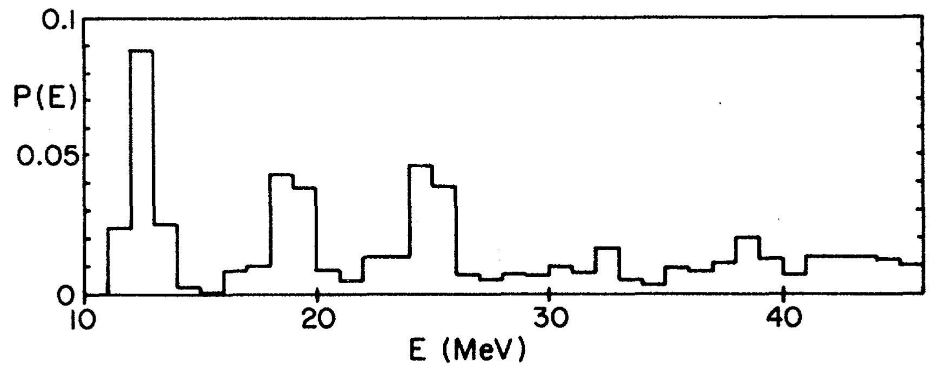
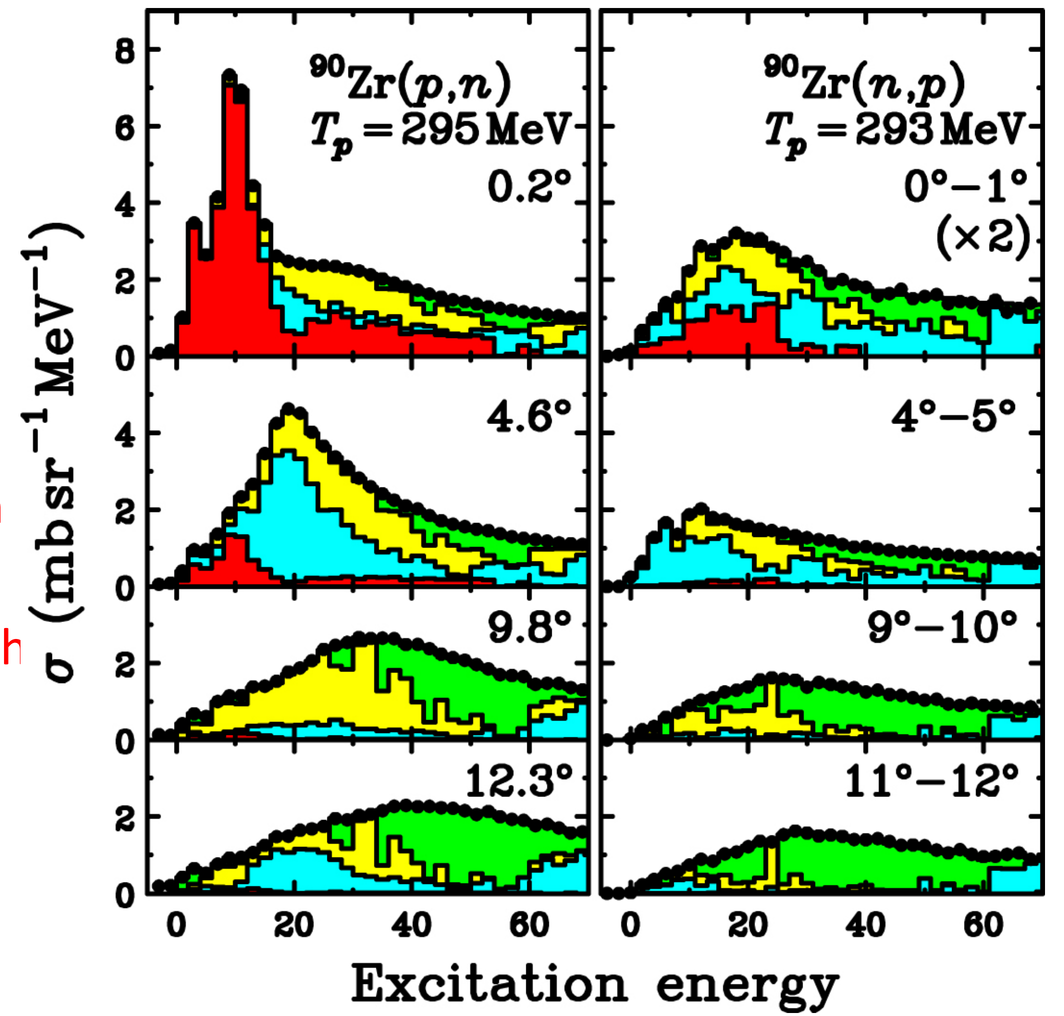


FIG. 4. Calculated strength distribution $P(E)$ for the Gamow-Teller operator in ^{90}Zr. Energies are measured with respect to the ground state of ^{90}Nb.

Results of MDA for ^{90}Zr(p,n) & (n,p) at 300 MeV

T. Wakasa et al.,PRC **55**, 2909 (1997) *K.Yako et al.,PLB 615, 193 (2005)*

- Multipole Decomposition (MD) Analyses
  - (p,n)/(n,p) data have been analyzed with the same MD technique
  - (p,n) data have been re-analyzed up to 70 MeV
- Results
  - (p,n)
    - Almost L=0 for GTGR region (No Background)
    - Fairly large L=0 (GT) strength up to 50 MeV excitation
  - (n,p)
    - L=0 strength up to 30MeV



Observation of "the missing strength"

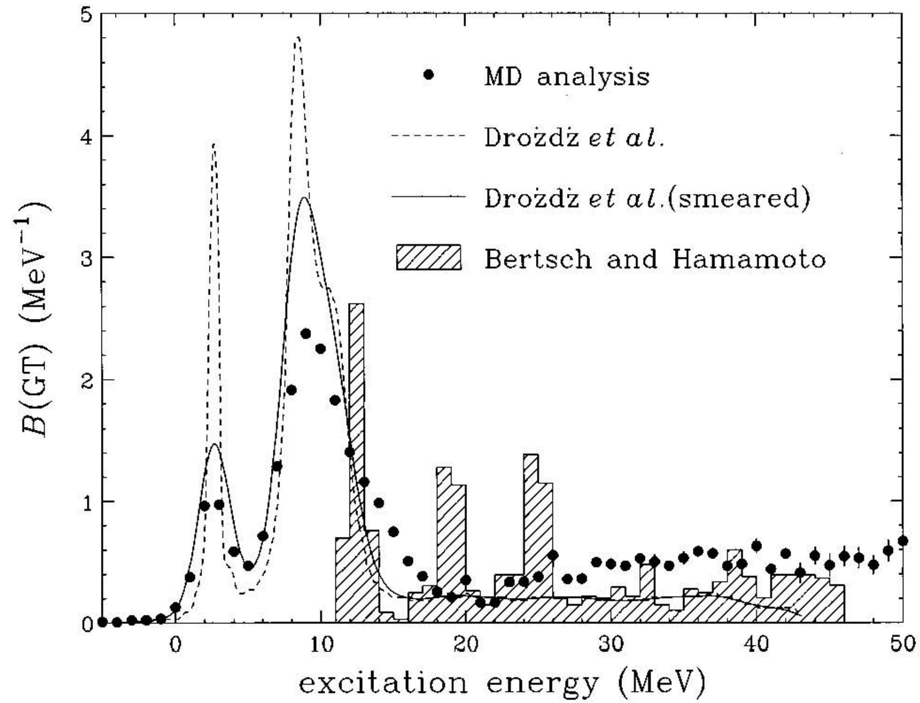


FIG. 13. Gamow-Teller strength distribution (filled circles) obtained from the 0° $L=0$ cross section which is deduced from the MD analysis. The dashed curves and hatched histogram represent the SRPA calculation by Drożdż *et al.* [22] and the perturbative calculation by Bertsch and Hamamoto [15], respectively. The SRPA calculation smeared out to reproduce the experimentally obtained width of the GT transition at E_x=2.3 MeV is shown by the solid curve.

T. Wakasa *et al.,*
Phys. Rev. C55 (1997) 2090

See also
M. Ichimura, H. Sakai and
T. Wakasa, Prog. Part. Nucl.
Phys. 56 (2006) 446.

Subtraction of IVSM and GT Quenching Factor Q

- Correlations between (p,n) /(n,p) Results
  - Reduce the uncertainty originating from IVSM

$$S_{\beta^-}^{IVSM} - S_{\beta^+}^{IVSM} = (4.2 \pm 0.9) - (2.5 \pm 0.3) = 1.7 \pm 0.7(\mathrm{IVSM})$$

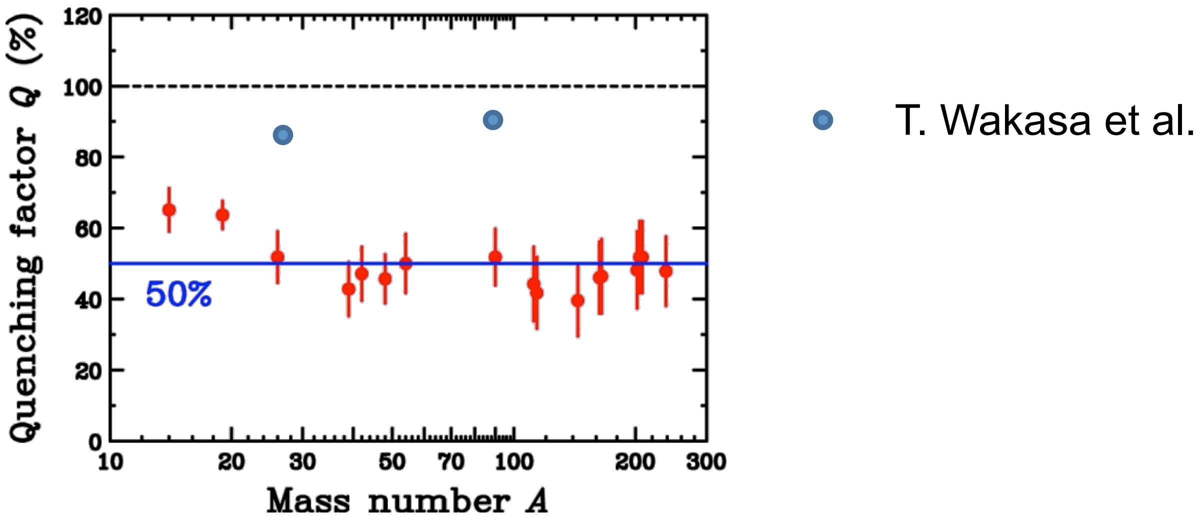
- Final Values (Up to 50 MeV of ^{90}Nb)
  - **Total GT strengths**
    - $S_{\beta^-} = 29.3 \pm 1.7(\mathrm{stat+MDA}) \pm 0.9(\mathrm{IVSM}) \pm 1.7(\hat{\sigma}_{\mathrm{GT}})$
    - $S_{\beta^+} = 2.9 \pm 0.6(\mathrm{stat+MDA}) \pm 0.3(\mathrm{IVSM}) \pm 0.2(\hat{\sigma}_{\mathrm{GT}})$
  - **GT sum rule**
    - $S_{\beta^-} - S_{\beta^+} = 26.4 \pm 1.6(\mathrm{stat+MDA}) \pm 0.7(\mathrm{IVSM}) \pm 1.5(\hat{\sigma}_{\mathrm{GT}})$
  - **Quenching Factor**
    - $Q = 0.86 \pm 0.05(\mathrm{stat+MDA}) \pm 0.02(\mathrm{IVSM}) \pm 0.05(\hat{\sigma}_{\mathrm{GT}})$
      $= 0.86 \pm 0.07(\text{quadratic sum of uncertainties})$
      - » Configuration mixing (2p2h) plays major role
      - » Δh^{-1} coupling plays minor role

New empirical sum rule values

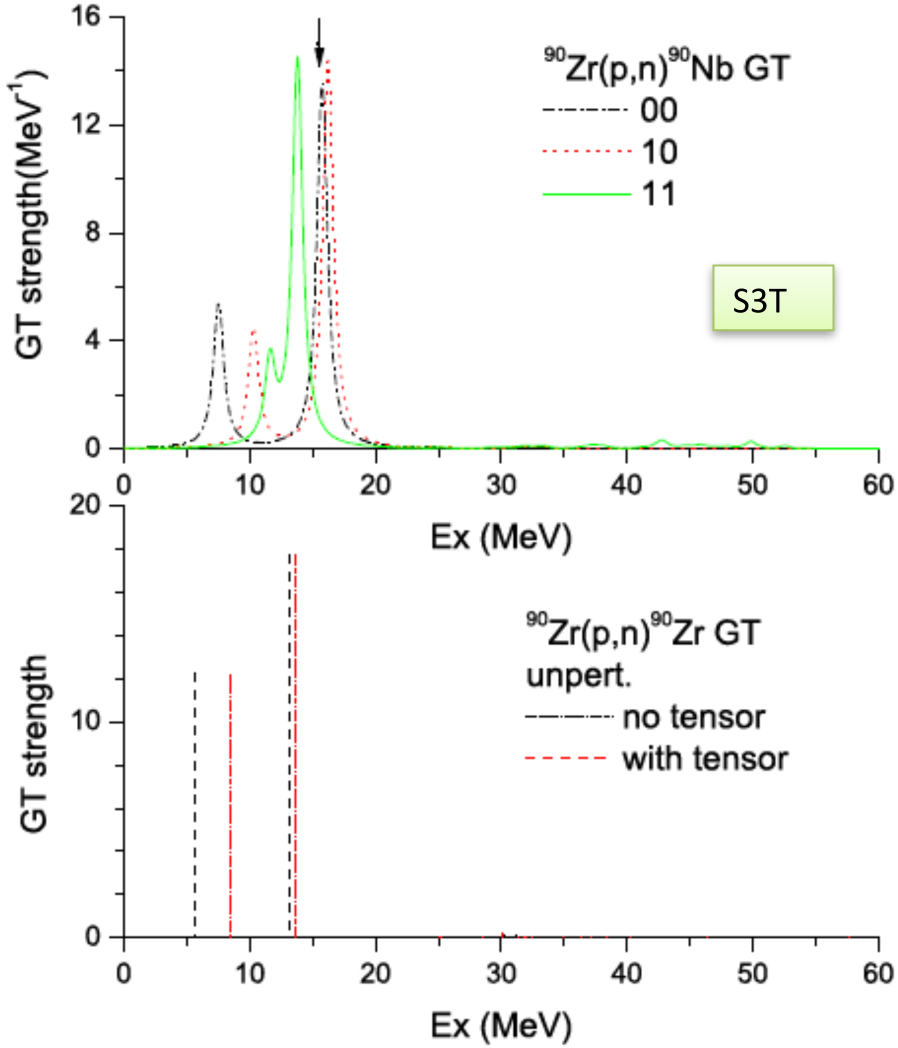
+strength 20<Ex<50MeV

~30% of Ikeda sum rule was found in this energy region

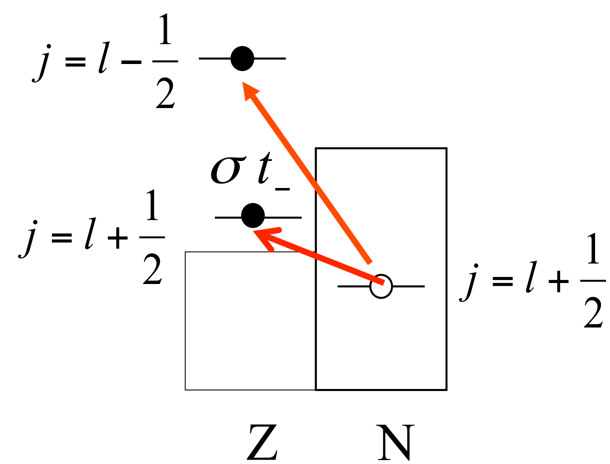
$$Q = \frac{S_-(p,n) - S_+(n,p)}{3(N-Z)}$$



The tensor force and charge-exchange excitations



Gamow-Teller $\lambda^{\pi} = 1^{+}$



The main peak is moved downward by the tensor force but the centroid is moved upwards !

C.L.Bai, HS, H.Q.Zhang, X.Z.Zhang, G.Colo and F.R.Xu, P.L.B675,28 (2009).
C.L.Bai, H.Q. Zhang, X.Z.Zhang, F,R,Xu, HS and G.Colo, PRC79, 041301(R) (2009).

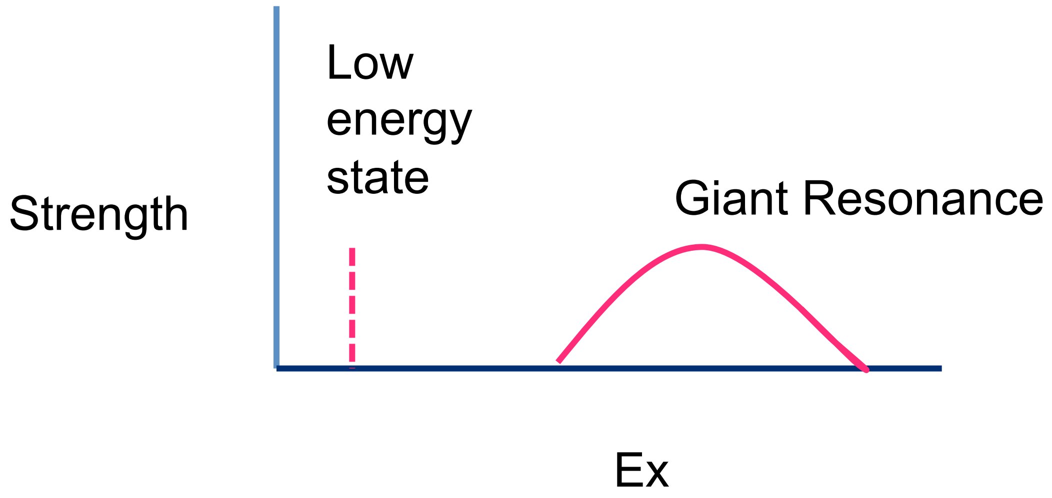
Energy-weighted (EW) and NEW sum rules

$$m(k) = \sum_i E^k{}_i \left| \left\langle i \middle| \hat{O}_\lambda \middle| 0 \right\rangle \right|^2$$

$$m(1) = \frac{1}{2} \left\langle 0 \middle| \left[\hat{O}_\lambda , \left[H, \hat{O}_\lambda \right] \right] \middle| 0 \right\rangle$$

$$\begin{aligned} m_-(0) - m_+(0) &= \sum_\nu \left(|\langle \nu | O_- | 0 \rangle|^2 - |\langle \nu | O_+ | 0 \rangle|^2 \right) \\ &= \langle 0 | \left[O_-, O_+ \right] | 0 \rangle, \end{aligned}$$ =3(N-Z)

GT (Ikeda) sum rule



Tensor correlations on Spin-Isospin mode

Effect of Tensor Correlations on Gamow-Teller States in ^{90}Zr and ^{208}Pb

C.L. Bai[1,2], H. Sagawa[3], H.Q. Zhang[1,2], X.Z. Zhang [2], G. Colò[4] and F.R. Xu[1]

$$
\begin{aligned}
V^T = & \frac{T}{2}\{[(\sigma_1\cdot \mathbf{k}')(\sigma_2\cdot \mathbf{k}') - \frac{1}{3}(\sigma_1\cdot\sigma_2)\mathbf{k}'^2]\delta(\mathbf{r}_1-\mathbf{r}_2) \\
& +\delta(\mathbf{r}_1-\mathbf{r}_2)\left[(\sigma_1\cdot\mathbf{k})(\sigma_2\cdot\mathbf{k}) - \tfrac{1}{3}(\sigma_1\cdot\sigma_2)\mathbf{k}^2\right]\} \\
& +\frac{U}{2}\{(\sigma_1\cdot\mathbf{k}')\,\delta(\mathbf{r}_1-\mathbf{r}_2)(\sigma_2\cdot\mathbf{k}) + (\sigma_2\cdot\mathbf{k}')\,\delta(\mathbf{r}_1-\mathbf{r}_2)(\sigma_1\cdot\mathbf{k}) \\
& -\tfrac{2}{3}\left[(\sigma_1\cdot\sigma_2)\mathbf{k}'\cdot\delta(\mathbf{r}_1-\mathbf{r}_2)\mathbf{k}\right]\}
\end{aligned}
$$

$$O_- = \sigma t_-$$
$$O_+ = \sigma t_+$$

$$
\begin{aligned}
m_-(0) - m_+(0) &= \sum_\nu \left(|\langle\nu|O_-|0\rangle|^2 - |\langle\nu|O_+|0\rangle|^2\right) \\
&= \langle 0|\,[O_-,O_+]\,|0\rangle, \quad =3(N-Z)
\end{aligned}
$$

$$
\begin{aligned}
m_-(1) + m_+(1) &= \sum_\nu \left(|\langle\nu|O_-|0\rangle| + |\langle\nu|O_+|0\rangle|^2\right)E_\nu \\
&= \langle 0|\,[O_+,[H,O_-]]\,|0\rangle,
\end{aligned}
$$

$$
\begin{aligned}
\Delta E_{GT} &= \frac{m_-(1)}{m_-(0)} \\
&\sim \frac{m_-(1)+m_+(1)}{m_-(0)-m_+(0)} \\
&= \frac{4\pi}{3(N-Z)}\int drr^2\left[-\left(\tfrac{5}{2}U+\tfrac{5}{2}T\right)J_nJ_p - \tfrac{5}{3}U(J_n^2+J_p^2)\right]
\end{aligned}
$$

S3+Tensor

	$m_-(1;\text{no tensor})$ MeV	$m_-(1;\text{with tensor})$ MeV	δE_{RPA} MeV	δE_{DC} MeV
^{90}Zr	271.45	338.68	2.241	2.276
^{208}Pb	1854.12	2000.76	1.111	1.118

	type of calculation	$m_-(0)$ 0-30MeV	$m_-(0)$ 30-60MeV	$m_-(1)$ 0-30 MeV	$m_-(1)$ 30-60 MeV	$m_-(1)$ total	$m_+(1)$ total
^{90}Zr	00	29.16	0.71	395	26.2	421.8	10.1
	10	29.16	0.79	444	22	466	11.1
	11	27.00	2.89	366.9	122	493.2	10.3
^{208}Pb	00	127.54	3.43	2080	124.5	2212.8	18.8
	10	127.38	3.68	2176	93	2269	21
	11	114.10	16.58	1658	694	2370	19.3

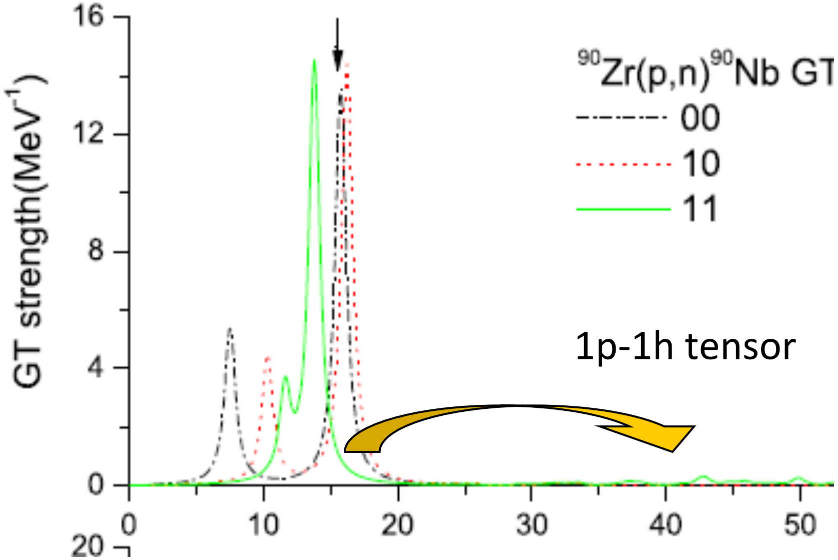
Energy-weighted sum rules

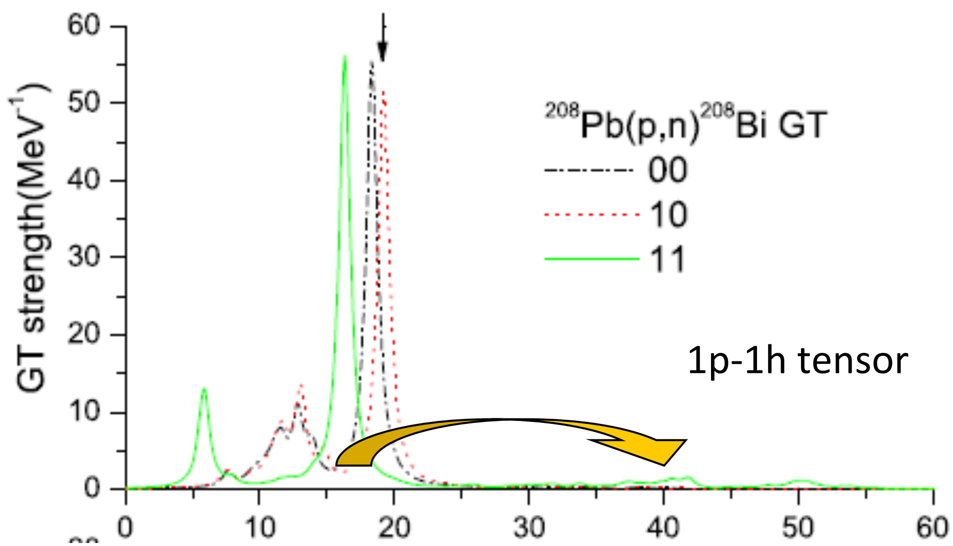
$$m(k) = \sum_i E^k{}_i \left| \langle i | \hat{O}_\lambda | 0 \rangle \right|^2$$

$$m(1) = \frac{1}{2} \langle 0 | [\hat{O}_\lambda, [H, \hat{O}_\lambda]] | 0 \rangle$$

$$m_-(0) - m_+(0) = 3(N-Z) = \begin{cases} 30 \text{ for } {}^{90}Zr \\ 132 \text{ for } {}^{208}Pb \end{cases}$$

About 10% of strength is moved by the tensor correlations to the energy region above 30 MeV.
Relevance for the GT quenching problem.





Multipole Expansion of Tensor Interactions

$$
\begin{aligned}
V^T = & \frac{T}{2}\{[(\sigma_1 \cdot \mathbf{k}')(\sigma_2 \cdot \mathbf{k}') - \frac{1}{3}(\sigma_1 \cdot \sigma_2)\mathbf{k}'^2]\delta(\mathbf{r}_1 - \mathbf{r}_2) \\
& + \delta(\mathbf{r}_1 - \mathbf{r}_2)[(\sigma_1 \cdot \mathbf{k})(\sigma_2 \cdot \mathbf{k}) - \frac{1}{3}(\sigma_1 \cdot \sigma_2)\mathbf{k}^2]\} \\
& + \frac{U}{2}\{(\sigma_1 \cdot \mathbf{k}')\delta(\mathbf{r}_1 - \mathbf{r}_2)(\sigma_2 \cdot \mathbf{k}) + (\sigma_2 \cdot \mathbf{k}')\delta(\mathbf{r}_1 - \mathbf{r}_2)(\sigma_1 \cdot \mathbf{k}) \\
& - \frac{2}{3}[(\sigma_1 \cdot \sigma_2)\mathbf{k}' \cdot \delta(\mathbf{r}_1 - \mathbf{r}_2)\mathbf{k}]\}
\end{aligned}
$$

$$
\delta(\vec{r}_1 - \vec{r}_2) = \sum_{lm} Y_{lm}(\hat{r}_1) Y^*_{lm}(\hat{r}_2) \frac{\delta(r_1 - r_2)}{r_1 r_2}
$$

$$
V^T \propto T_{(\lambda,\kappa)}\{[\sigma_1 \times [\nabla_1 \times Y_{l=1}(\hat{r}_1)]^{(\lambda)}\}^{(\kappa)}[\sigma_2 \times [\nabla_2 \times Y_{l=1}(\hat{r}_2)]^{(\lambda')}\}^{(\kappa)}\}^{(0)}\delta(r_1 - r_2)
$$

$1^+ \quad T_{(\lambda=\lambda'=2,\kappa=1)} \Rightarrow$ *repulsive*

$1^+ \quad T_{(\lambda=2,\lambda'=0,\kappa=1)} \Rightarrow$ strong mixing between Gamow-Teller and spin-quadrupole excitations!

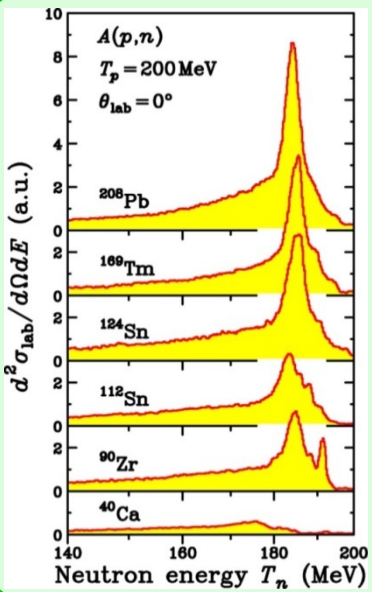
Spin-isospin physics: Gamow-Teller responses

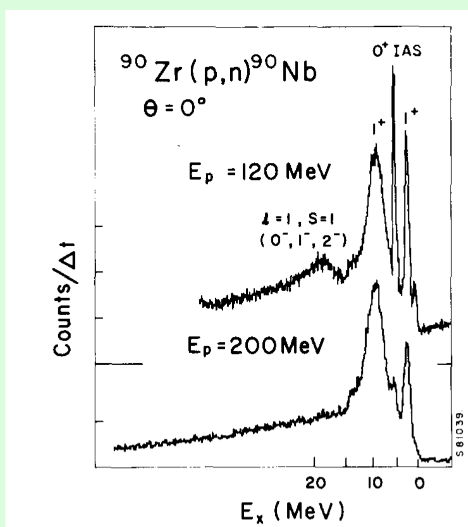
Summary of Last century

Courtesy of H. Sakai

- $\sigma\tau_{\pm}$ induces GT transition
- 1963 GT giant resonance predicted, Ikeda sum rule 3(N-Z)
  collectivity?
- ~1980 GT giant resonances established
- Strength quenched/missing: 50-60% of 3(N-Z) due to Δh or 2p2h ?
- 1997 ~90% of 3(N-Z) found
- Charge-exchange reactions on stable target nuclei
- CHEX reactions: (p,n)/(n,p) reactions at intermediate energy

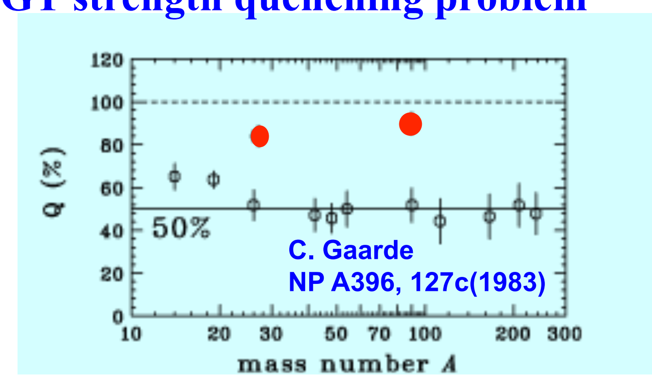
- C. Garrde, NPA396(1982)127c.





- Wakasa et al., PR C55, 2909 (1997)

GT strength quenching problem



- **Wakasa et al.,** PR C **55**, 2909 (1997)

Spin-isospin physics: Gamow-Teller responses

This century

- Unstable beams → extend the horizon of spin-isospin responses
- Charge-exchange reactions in inverse kinematics
- Innumerable possibilities are in front of us (H. Sakai)

Gamow-Teller giant resonance under extreme condition

1. Isospin : (N-Z)/A asymmetry
2. Spin-isospin correlations in N>>Z nuclei
3. Quenching of Spin-orbit interaction
4. Continuum coupling
5. ….

Recent observations at (N-Z)/A extreme

Gamow-Teller Giant Resonances in very light neutron rich nuclei, ^{8}He & ^{12}Be

Spin-isospin correlations in schematic model(H. Sakai)

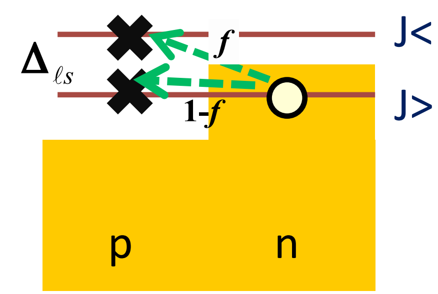
- **GTGR (IAS) induced by *ph* residual interaction:**

$$V_{12} = \kappa_{\sigma\tau}\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \quad (\kappa_\tau \vec{\tau}_1\vec{\tau}_2)$$

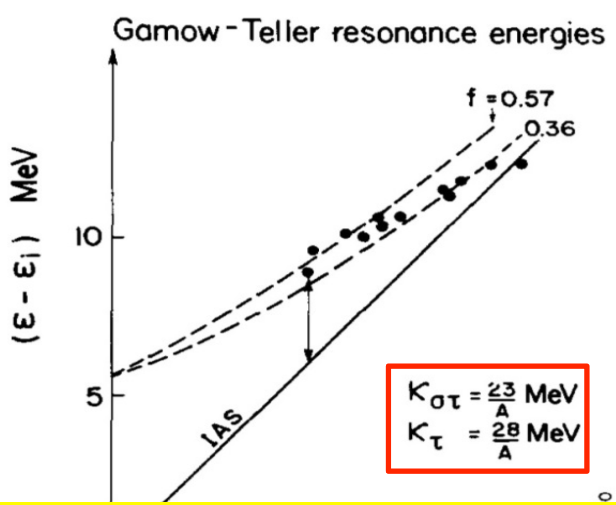
- **Dispersion relation for the collective state(GTGR)**

$$\frac{\left|\langle j_>^{-1} j_> |\sigma\tau| 0\rangle\right|^2 2(N-Z)(1-f)}{\varepsilon_i - \varepsilon} + \frac{\left|\langle j_>^{-1} j_< |\sigma\tau| 0\rangle\right|^2 2(N-Z) f}{\varepsilon_i + \Delta_{\ell s} - \varepsilon} = \frac{1}{\kappa_{\sigma\tau}}$$

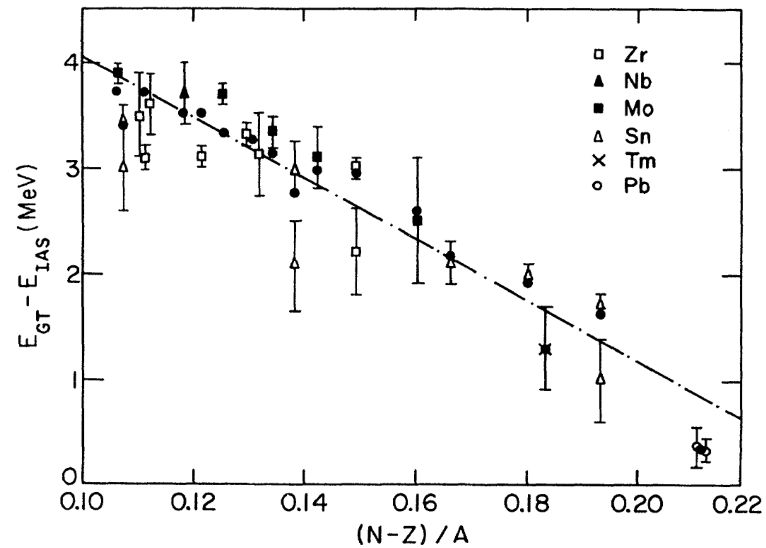
two p-h configurations for GT



- **C. Garrde, NPA396(1982)127c.**



- **Nakayama et al.,PLB114(1982)217**



$$E_{GT} - E_{IAS} = \Delta_{\ell s} + 2\frac{(\kappa_{GT} - \kappa_F)}{A}(N-Z)$$

$$(\kappa_F - \kappa_{GT})A = 9.25 \text{ MeV}$$

one-p-h configuration for GT

Data:
(N-Z)/A < 0.21 was missing in 20th century
$E_{GT} - E_{IAS} > 0$

- **Nakayama, Pio Galeao and Krmpotic, PLB114(1982)217**

One degenerate-p-h configuration for both IAS and GT

$$E_{sym} = V_1 \frac{t \cdot T_0}{A}$$

Unperturbed $j_>^{\nu} \to j_<^{\pi}$ energy for dispersion equation.
GT: spin-orbit + symmetry energy + Coulomb energy

Fermi(IAS): symmetry energy + Coulomb energy

$$\Delta\varepsilon_{ls} - V_1 \frac{T_0}{A} + \Delta E_{Coul}$$

$$+ \quad V_{12} = \kappa_{\sigma\tau} \vec{\sigma}_1 \vec{\sigma}_2 \vec{\tau}_1 \vec{\tau}_2 \quad (\kappa_\tau \vec{\tau}_1 \vec{\tau}_2)$$

IAS energy

$$\omega_{IAS} = T_0 (4\kappa_\tau - V_1 / A) \Delta E_{Coul}$$

GT energy

$$\omega_{GT} = \Delta\varepsilon_{ls} + T_0 (4\kappa_{\sigma\tau} - V_1 / A) + \Delta E_{Coul}$$

self-consistent condition

$$\kappa_\tau = V_1 / 4A$$

$$\omega_{IAS} = \Delta E_{Coul}$$

$$\omega_{GT} - \omega_{IAS} = \Delta\varepsilon_{ls} + T_0 (4\kappa_{\sigma\tau} - 4\kappa_\tau)$$

$$= 26 / A^{1/3} - 37 T_0 / A$$

$$\kappa_{\sigma\tau} - \kappa_\tau = -9.25 / A \text{ MeV}$$

$$\Delta\varepsilon_{ls} = 26 / A^{1/3} \text{ MeV}$$

(a) spin-obit and residual interaction (one-level)

$$\omega_{GT} - \omega_{IAS} = \Delta\varepsilon_{ls} + T_0(4\kappa_{\sigma\tau} - 4\kappa_{\tau})$$
$$= 26 / A^{1/3} - 37T_0 / A$$

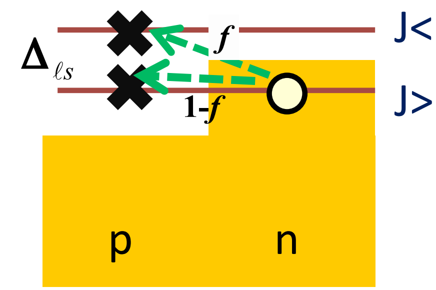
(b) Nakayama fitting eq.

$$\omega_{GT} - \omega_{IAS} = 7.0 - 57.8T_0 / A$$

	^{90}Zr	^{208}Pb	^{12}Be	^{22}C	^{8}He
T_z	5	22	2	5	2
(N-Z)/A	0.11	0.21	0.333	0.455	0.5
(a) (MeV)	3.75	0.48	5.19	0.87	3.75
(b) (MeV)	3.79	0.89	-2.63	- 6.14	-7.45
exp.	3.6	0.4	-1.2		-2.5

- **GTGR (IAS) induced by *ph* residual interaction:**

$$V_{12} = \kappa_{\sigma\tau}\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \quad (\kappa_{\tau}\vec{\tau}_1\vec{\tau}_2)$$

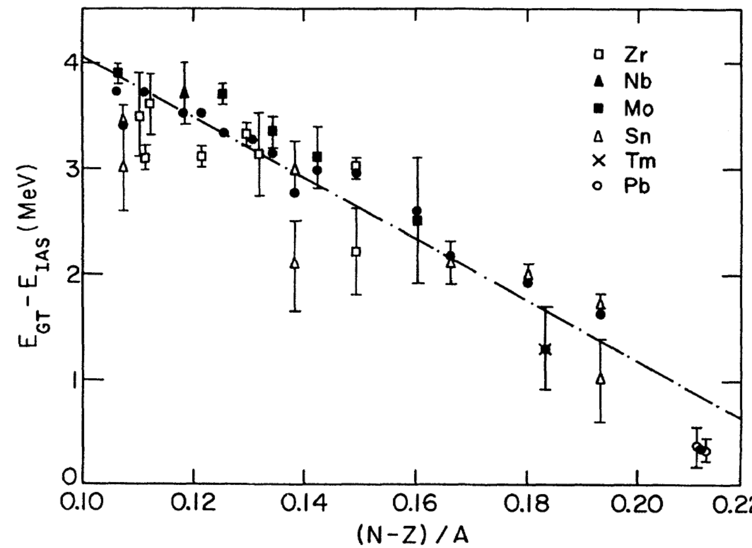


- **Dispersion relation for the collective state(GTGR)**

$$\frac{\left|\langle j_>^{-1} j_> | \sigma\tau_- | 0\rangle\right|^2}{\varepsilon_i - \varepsilon} + \frac{\left|\langle j_>^{-1} j_< | \sigma\tau_- | 0\rangle\right|^2}{\varepsilon_i + \Delta_{\ell s} - \varepsilon} = -\frac{1}{\kappa_{\sigma\tau}}$$

two p-h configurations for GT

- **Nakayama et al.,PLB114(1982)217**

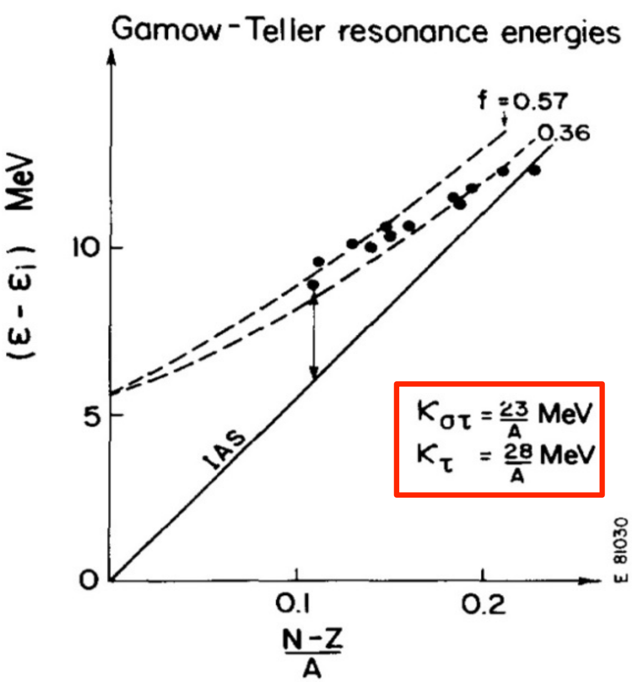


---- $E_{GT} - E_F = 7.0 - 57.8\, T_0\, A^{-1}$

• $E_{GT} - E_F = 26\, A^{-1/3} - 37\, T_0\, A^{-1}$

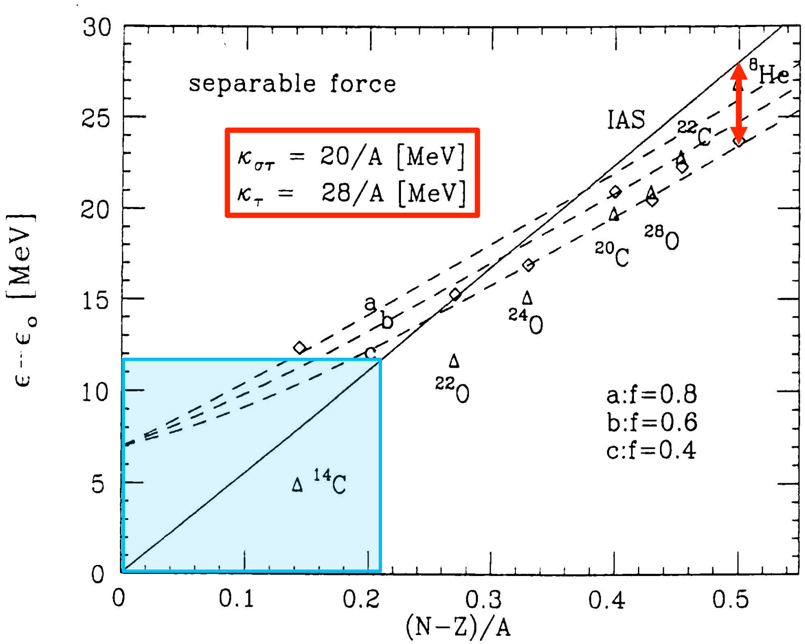
one-p-h configuration for GT

- **C. Garrde, NPA396(1982)127c.**



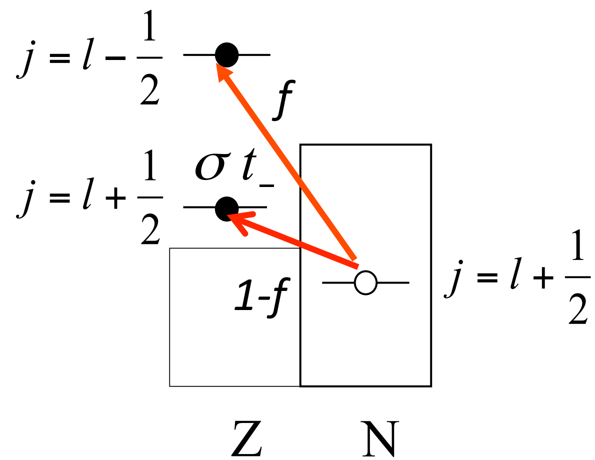
- **Predicted in 1993 by Sagawa-Hamamoto-Ishihara, PLB303,215**

Hartree-Fock + RPA (TDA) calculation with（BKN+spin-orbit (^{16}O))



- Relatively large $E_{GT} - E_{IAS} < 0$
- 8He : $E_{GT} - E_{IAS}$ = - 4.5 MeV (f=0.44)

Gamow-Teller



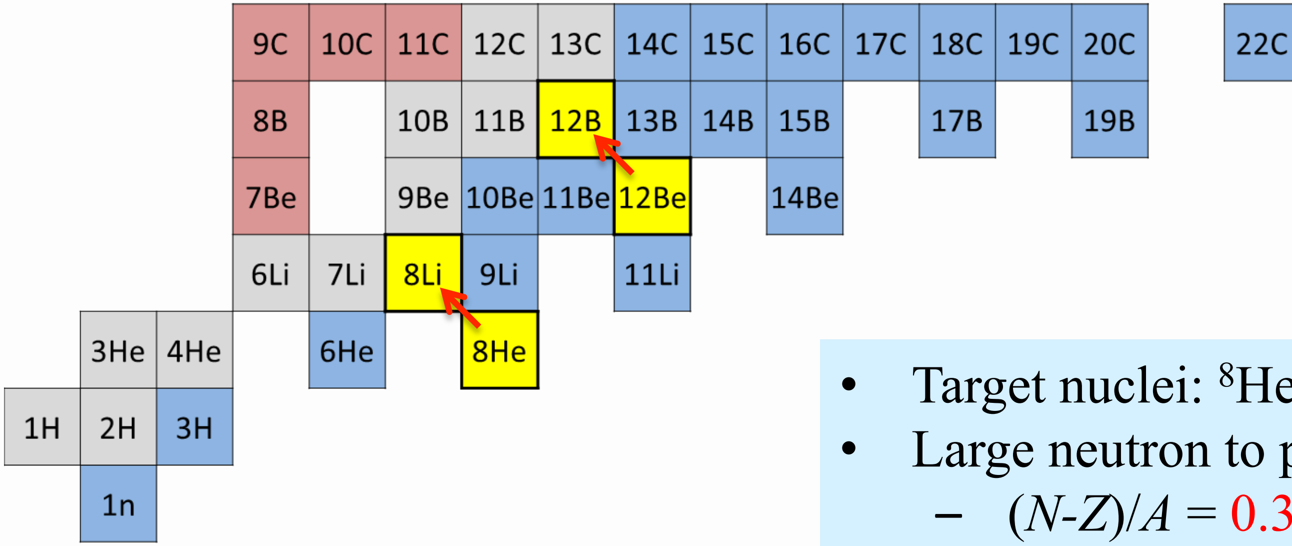
$$f = \frac{B(\mathrm{GT} j_> \to j_<)}{B(\mathrm{GT} j_> \to j_<) + B(\mathrm{GT} j_> \to j_>)} = 4/9 = 0.44 \qquad l = 1$$

$$= 8/15 = 0.53 \qquad l = 2$$

$$= 12/21 = 0.57 \qquad l = 3$$

$$= 16/27 = 0.59 \qquad l = 4$$

GT responses in very neutron rich light nuclei

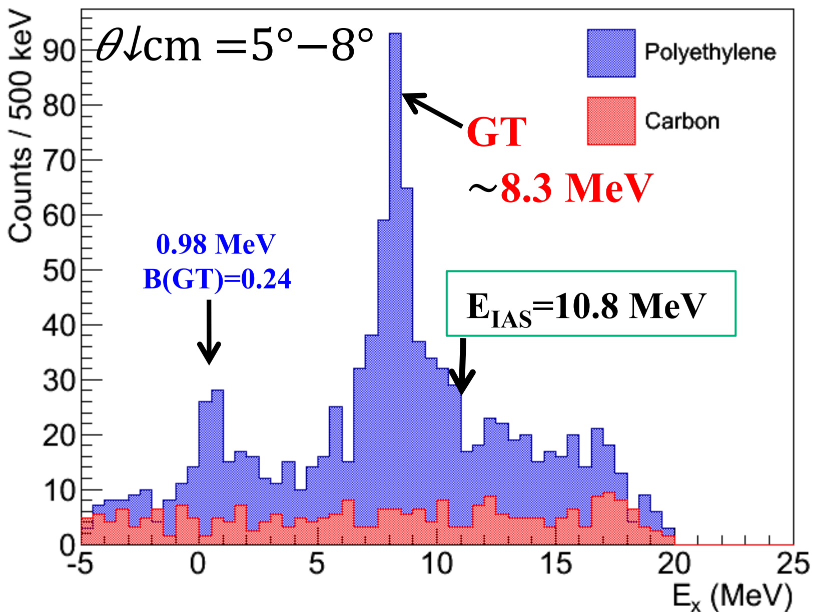


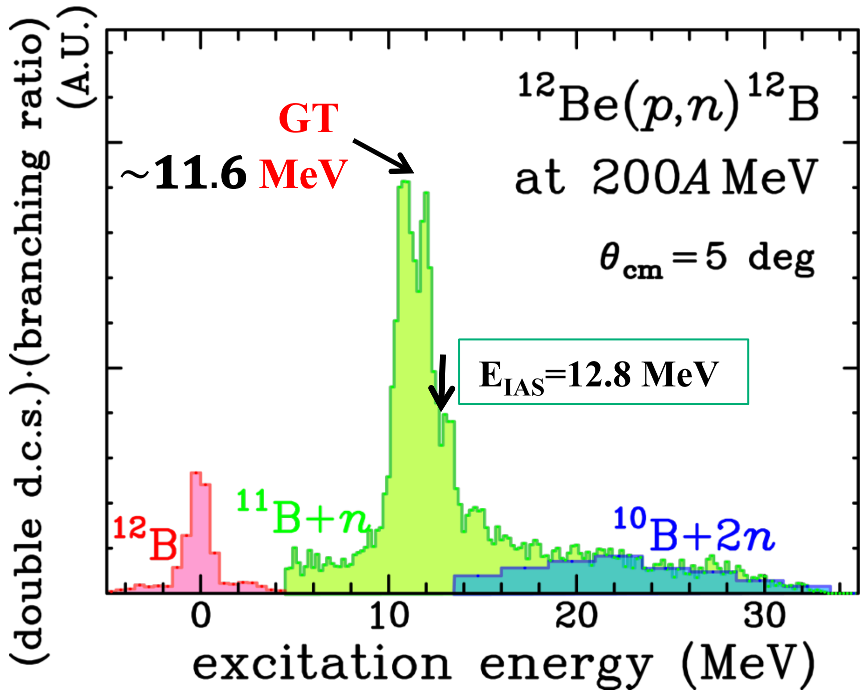
- Target nuclei: ^{8}He and ^{12}Be
- Large neutron to proton ratio
  - $(N\text{-}Z)/A$ = 0.33(^{12}Be), 0.5(^{8}He)
- (p,n) reaction in inverse kinematics
- ^{8}He(p,n) by Kobayashi *et al.*,
- ^{12}Be(p,n) by Yako *et al.*,

- Schematic model
  - ^{8}He : N=8 closed and f=0.44
  - ^{12}Be: N=8 not closed(deformed)
    40% admixture of 2*s*-orbit into 1*p*-shell
    → $E_{GT} - E_{IAS}$?

Experimental Results

- ^{8}He(p,n) at 200 MeV/u (Kobayashi)
- ^{12}Be(p,n) at 200 MeV/u (Yako)





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

$E_{GT} - E_{IAS} = -1.2 \pm 0.4$ MeV

p-shell dominance for ^{8}He
Deformation or 2p-2h state mixing in the ground state in ^{12}Be

<u>mixing of 2s1d configurations</u>

SFO’ interaction (2s1/2 s.p.e. is lowered to obtain B(GT:12Be->12B(g.s.)):

large 2hw excitation components in the ground state

$|^{12}Be\rangle = 0.55|p^8\rangle + 0.82|p^6(sd)^2\rangle$

Occupation probabilities of neutrons (# of particles)

p-orbits	4.61
s-orbit	0.68
d-orbit	0.71

spin-orbit splitting

$$\Delta\varepsilon_{ls} = -20\boldsymbol{l}\cdot\boldsymbol{s}A^{-2/3}$$

TABLE I: Calculated $E_{\rm GT} - E_{\rm IAS}$ values for $\kappa_{\sigma\tau} = \frac{21}{A}$, $\frac{22}{A}$ and $\frac{23}{A}$ MeV with several assumed neutron-orbit configurations for ^{8}He and ^{12}Be together with experimental values. For comparison purpose, the results for ^{208}Pb is also given. In all calculations, $\kappa_{\tau} = \frac{28}{A}$ MeV is assumed.

	$\Delta E = E_{\rm GT} - E_{\rm IAS}$ (MeV)			
$\kappa_{\sigma\tau}$ (MeV)	$\frac{21}{A}$	$\frac{22}{A}$	$\frac{23}{A}$	adopted ν configuration
^{8}He	-3.01	-2.03	-1.16	$(1p_{3/2})^4$
	Exp. -2.5 ± 0.5 [10]			
^{12}Be	-2.20	-1.58	-0.95	$(1p_{3/2})^4(1p_{1/2})^2$
	$+0.96$	$+1.75$	$+2.55$	$(1p_{3/2})^4(2s_{1/2})^2$
	$+0.09$	$+0.73$	$+1.37$	$(1p_{3/2})^4(2d_{5/2})^2$
	-1.55	-0.91	-0.26	SFO configuration [20]
	$-1.73.$	-1.10	-0.46	WBP' configuration [22]
	Exp. -1.2 ± 0.4 [11]			
^{208}Pb	-0.29	$+0.10$	$+0.50$	
	Exp. $+0.4\pm0.2$ [7]			

RPA model

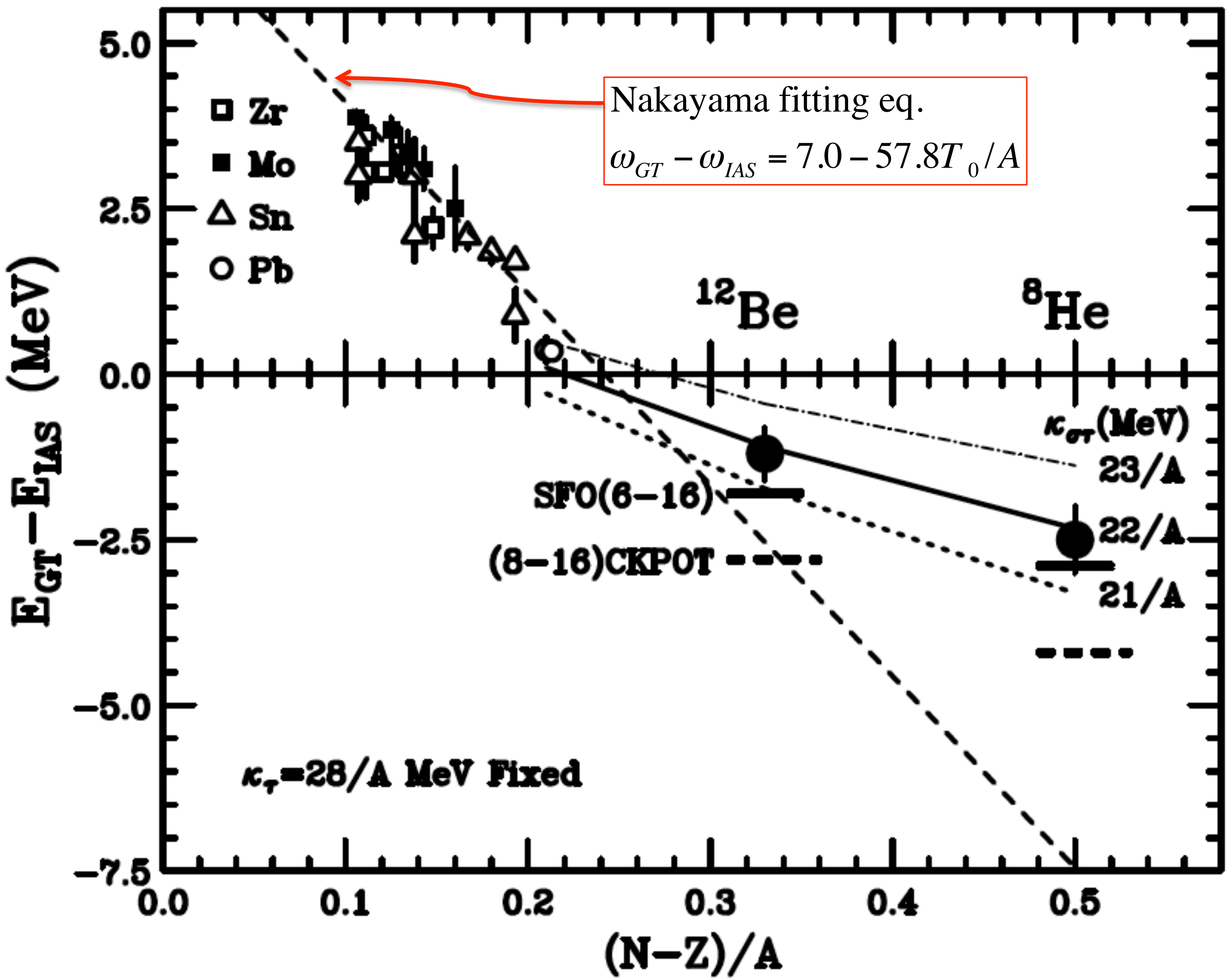
Shell model + Nakayama (b)+ SHI

TABLE II: Calculated results of excitation energies of GT and IAS and B(GT) values in ^{8}Li ^{12}B . The $E_{\rm IAS}$ values for ^{8}Li and ^{12}B are taken from [15] and [16], respectively.

^{8}Li	$E_{\rm GT}$ (MeV)	$E_{\rm IAS}$ (MeV)	ΔE (MeV)	B(GT)
(8-16)POT	7.5	11.7	−4.2	10.7
(6-16)2BME	8.3	11.1	−2.8	9.7
SFO	7.8	12.1	−4.3	8.8
WBT'	5.9	10.8	−4.9	5.6
SFO(6-16)	8.2	11.1	−2.9	8.3
Eq.(5)[9]	—	—	−7.5	—
SHI[2]	9.0	13.7	−4.7	9.4
^{8}He(β^-)[23]	∼9	10.8	−1.8	∼3.1
(p,n) exp.[10, 12]	8.3±0.5	10.8	−2.5±0.5	(8 ± 4)

Shell model + Nakayama (b)

^{12}B	E_{GT} (MeV)	E_{IAS} (MeV)	ΔE(MeV)	B(GT)
(8-16)POT	11.0	13.8	−2.8	9.3
(6-16)2BME	12.3	14.4	−2.1	7.4
SFO	11.6	13.8	−2.2	8.9
WBT'	9.5	13.2	−3.7	6.4
SFO(6-16)	12.5	14.3	−1.8	8.5
Eq.(5)[9]	—	—	−2.5	—
(p,n) exp.[11]	11.5±0.4	12.7	−1.2±0.4	(10 ± 2)

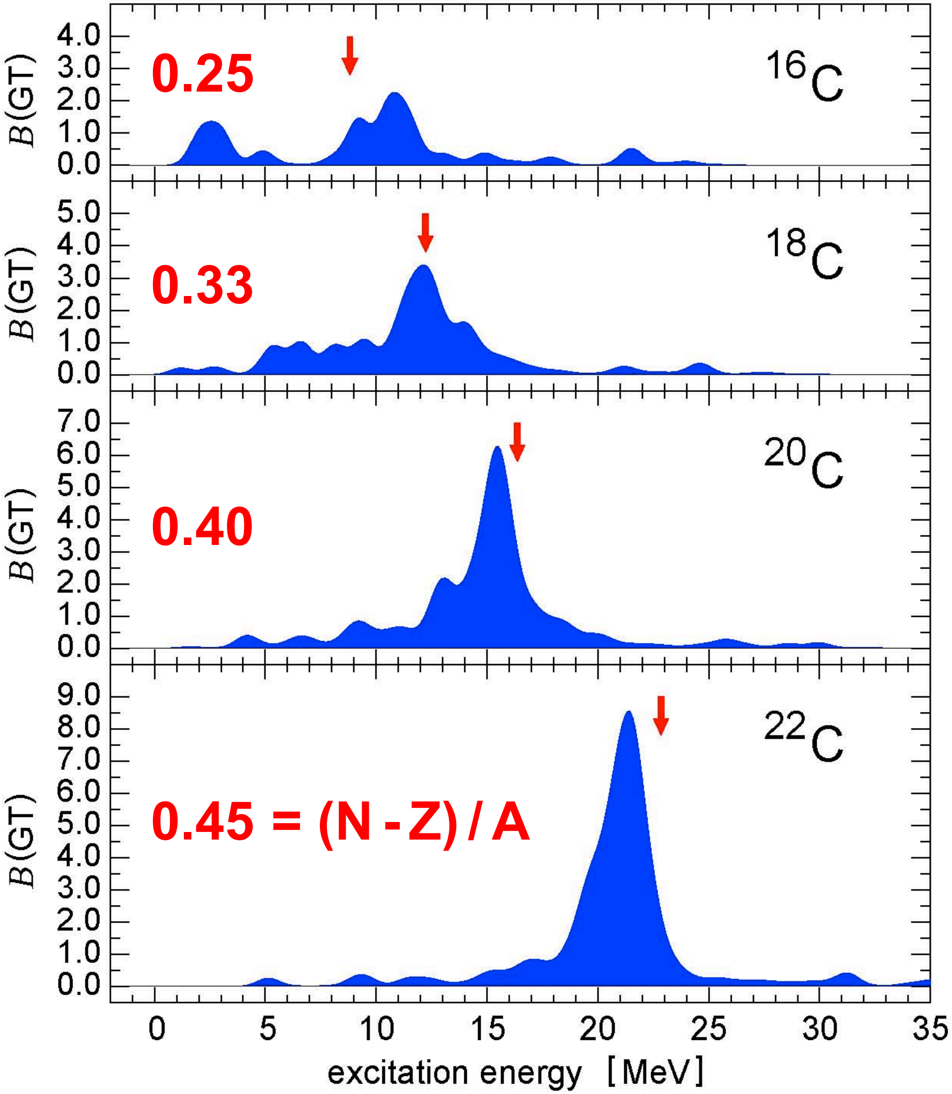


Nakayama fitting eq.
$\omega_{GT} - \omega_{IAS} = 7.0 - 57.8T_0/A$
Zr
Mo
Sn
Pb
^{12}Be
^{8}He
$\kappa_{\sigma\tau}$(MeV)
23/A
22/A
21/A
SFO(6−16)
(8−16)CKPOT
κ_τ=28/A MeV Fixed
5.0
2.5
0.0
−2.5
−5.0
−7.5
0.0
0.1
0.2
0.3
0.4
0.5
$E_{GT}-E_{IAS}$ (MeV)
(N−Z)/A

Future Perspectives for next few years

To establish firmly the collectivity in very neutron rich light nuclei, the measurements of GTGR as well as IAS in the neutron drip line nuclei such as ^{14}Be ($(N-Z)/A$=0.429) , ^{20,22}C ($(N-Z)/A$=0.400, 0.455) and ^{24}O ($(N-Z)/A$=0.333) are of highly desired.

Calculation for C isotopes



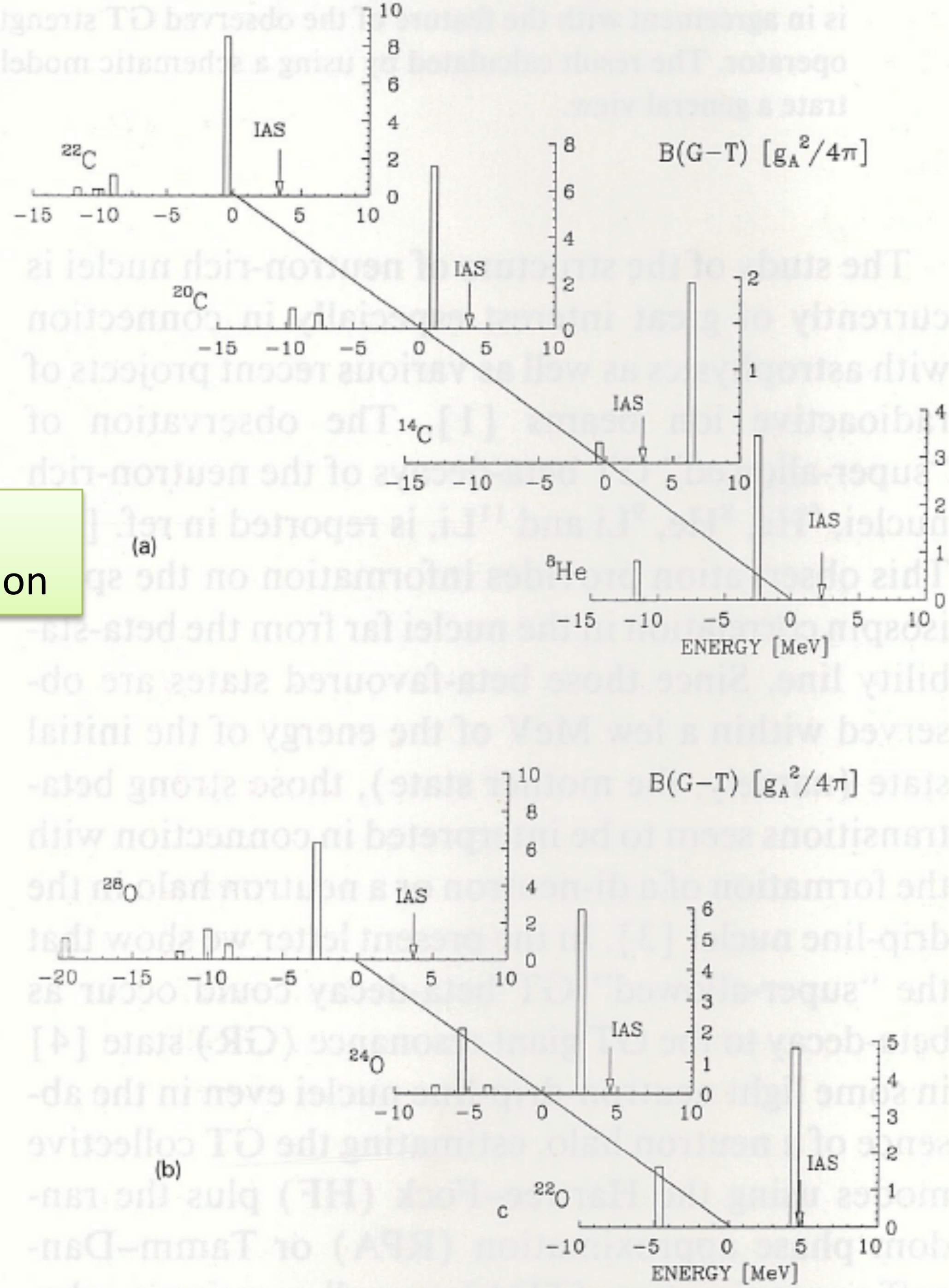
psd shell model

PSDWPT interaction
with the sd-shell part
replaced by USDB
no excitation
from *p*-shell to *sd*-shell

As the neutron number increases, the GT strength
(1) shifts to high energy region,
(2) concentrates to the giant resonance, and
the peak energy of the strength
(3) becomes lower than the IAS.

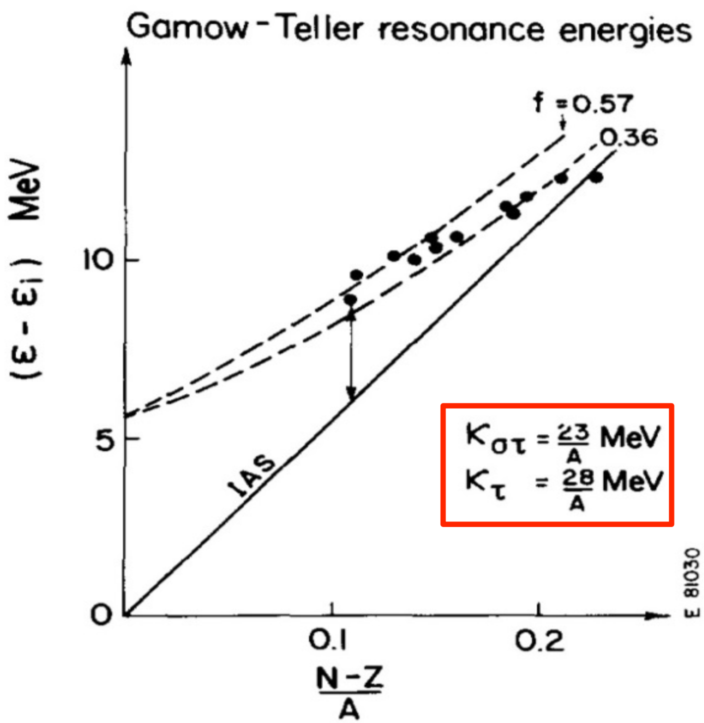
Calculated by Muto (TIT)

HF＋TDA
with BKN interaction

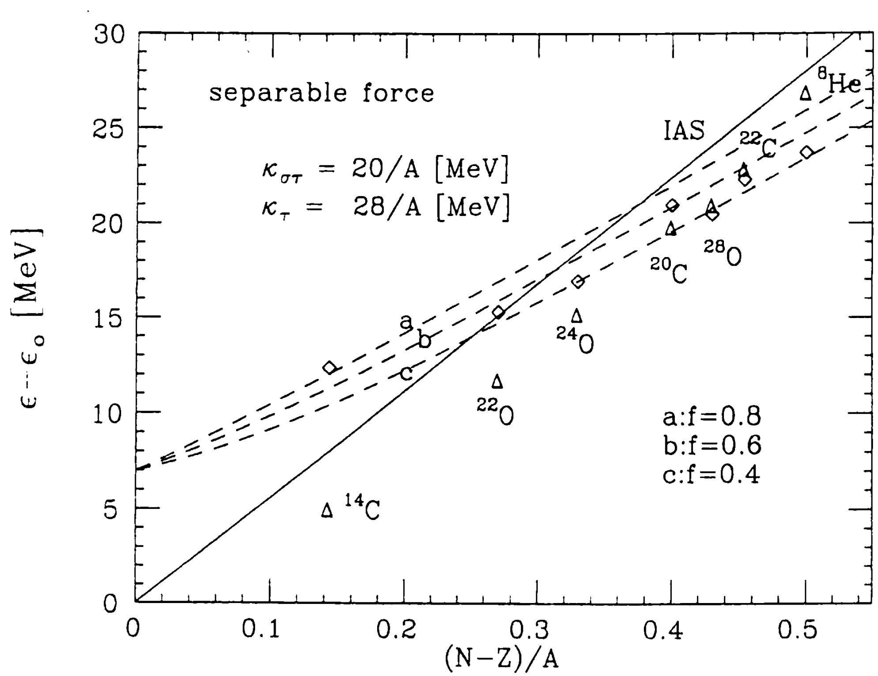


Observed systematics and prediction

- **C. Garrde, NPA396(1982)127c.**



H. Sagawa, I. Hamamoto and M. Ishihara, Phys. Lett. 303B (1993) 215
Hartree-Fock + RPA (TDA) calculation



GT giant resonance would appear below IAS with large portion of the sum rule in neutron-rich nuclei.

Future Perspectives for next few years

To establish firmly the collectivity in very neutron rich light nuclei, the measurements of GTGR as well as IAS in the neutron drip line nuclei such as ^{14}Be ($(N-Z)/A$=0.429) , ^{20,22}C ($(N-Z)/A$=0.400, 0.455) and ^{24}O ($(N-Z)/A$=0.333) are of highly desired.

1. Collectivity is enhanced by N>>Z (GT sum rule) ?
2. What happens on spin-orbit splitting due to the existence of more neutrons ?
3. Coupling to the continuum?
4. Deformation vs. 2hw and 4hw mixings?
5. RPA or shell model (IAS: self consistency is important)