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九州大学

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Nuclear Spin-Isospin Responses Studied by Nuclear Reactions: *A tribute to Munetake Ichimura*

Tomotsugu Wakasa

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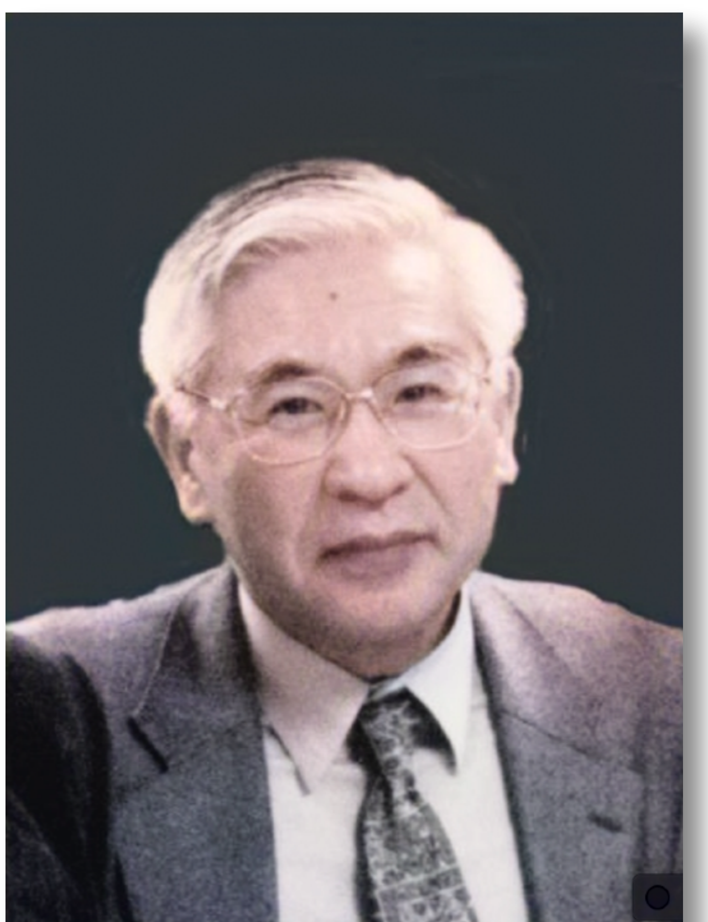
Kyushu University



Munetake Ichimura
1938 - 2020

Dedicated to Ichimura-san with deep gratitude

Ichimura-san and the spin-isospin problems

Ichimura-san made a significant contribution to nuclear physics, especially:

Solve the spin-isospin problems such as

- *Quenching* of Gamow-Teller strength
- *Enhancement* of spin-longitudinal π-mode

Give a unified understanding of spin-isospin responses in wide (q,ω) region

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Progress in Particle and Nuclear Physics 56 (2006) 446–531

Progress in Particle and Nuclear Physics

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Review

Spin–isospin responses via (p, n) and (n, p) reactions

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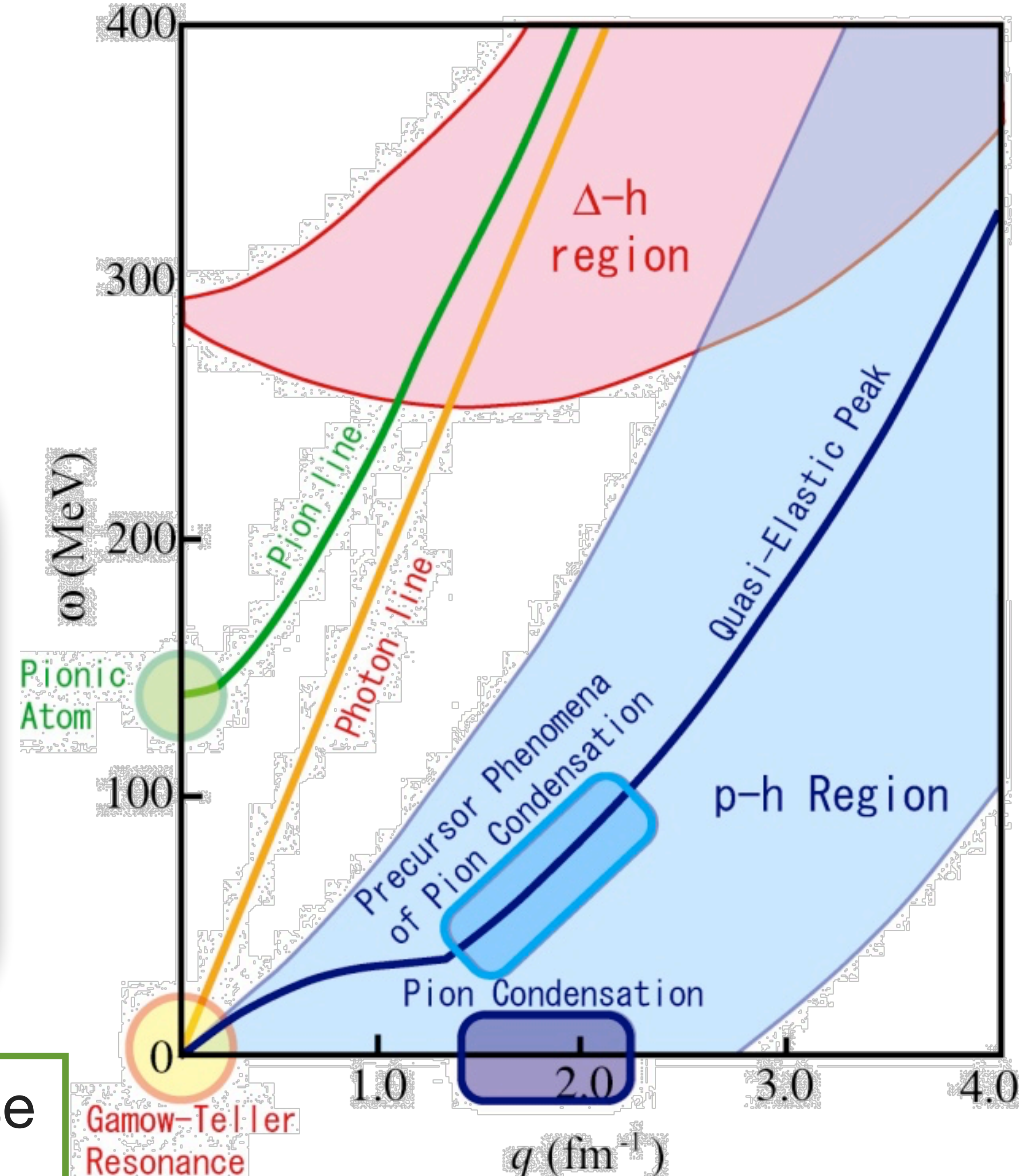


- GT and pionic spin-longitudinal response
- Recent progress for unstable nuclei

GT Response Function $R_{GT}(\omega)$

Gamow-Teller (GT) transition operator

- Nucleon (N) space

$$O_{\mathrm{GT}} = \boldsymbol{t}\boldsymbol{\sigma} = \frac{1}{2}\boldsymbol{\tau}\boldsymbol{\sigma}$$

- Extend to N+Δ space

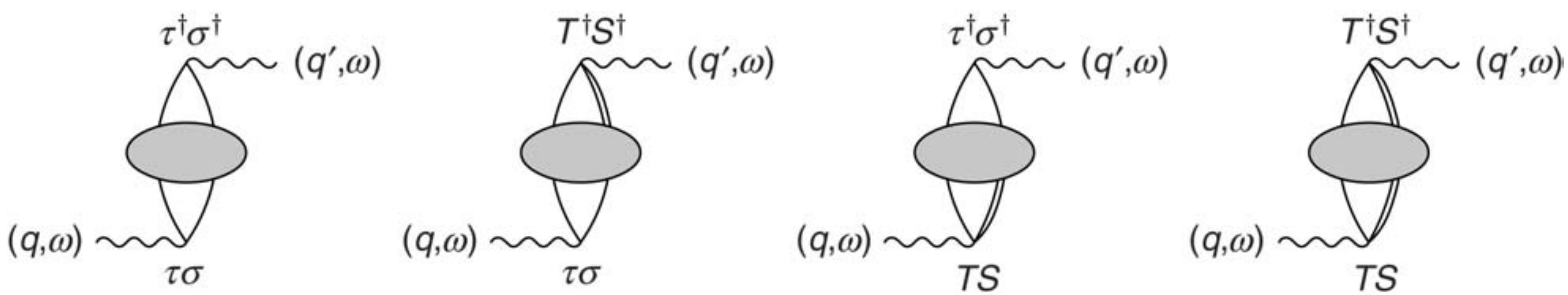
spin operator from N to Δ

$$O^{\pm}_{\mathrm{GT}} = \mp\frac{1}{\sqrt{2}}\sum_{k=1}^{A}\left\{\tau_{k,\pm1}\boldsymbol{\sigma}_k + \frac{g_A^{N\Delta}}{g_A}\left(T_{k,\pm1}S_k - T^{\dagger}_{k,\mp1}S^{\dagger}_k\right)\right\}$$

isospin operator from N to Δ

GT response function

$$R^{\pm}_{\mathrm{GT}}(\omega) = \sum_n \left|\langle\Psi_n|O^{\pm}_{\mathrm{GT}}|\Psi_0\rangle\right|^2 \delta(\omega - (\mathcal{E}_n - \mathcal{E}_0))$$



※ q=q'=0 and ω〜0 for GT transition

Pionic (Spin-Longitudinal) Response Function

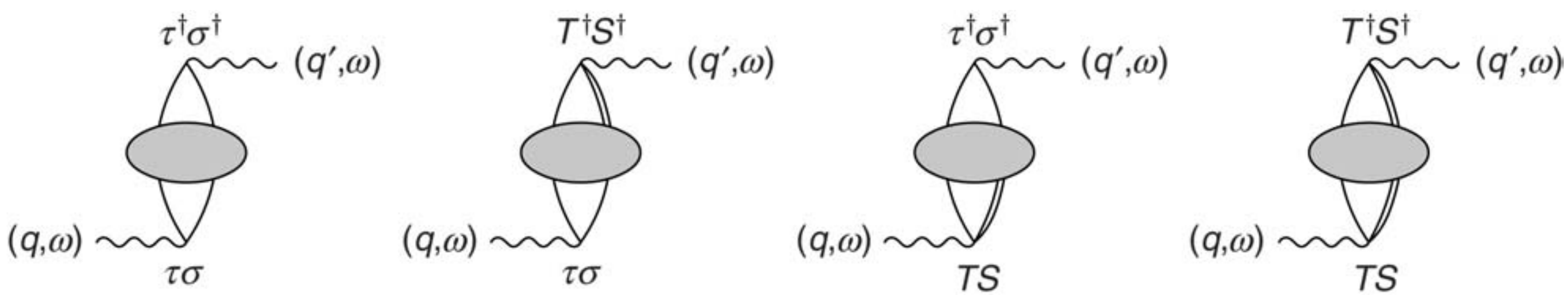
Isovector spin-longitudinal transition operator

$$O_L^\lambda(\boldsymbol{q}) = \sum_{k=1}^{A} \left\{ \tau_{k,\lambda}\boldsymbol{\sigma}_k \cdot \hat{\boldsymbol{q}} + \frac{f_{\pi N\Delta}}{f_{\pi NN}} \left(T_{k,\lambda}\boldsymbol{S}_k \cdot \hat{\boldsymbol{q}} + (-1)^\lambda T^\dagger_{k,-\lambda}\boldsymbol{S}^\dagger_k \cdot \hat{\boldsymbol{q}} \right) \right\} e^{i\boldsymbol{q}\cdot\boldsymbol{r}_k}$$

Isovector spin-longitudinal response function

$$R_L^\lambda(q,\omega) = \sum_n \left| \langle \Psi_n | O_L^\lambda(\boldsymbol{q}) | \Psi_0 \rangle \right|^2 \delta(\omega - (\mathcal{E}_n - \mathcal{E}_0))$$

- Representing πNN and πNΔ coupling

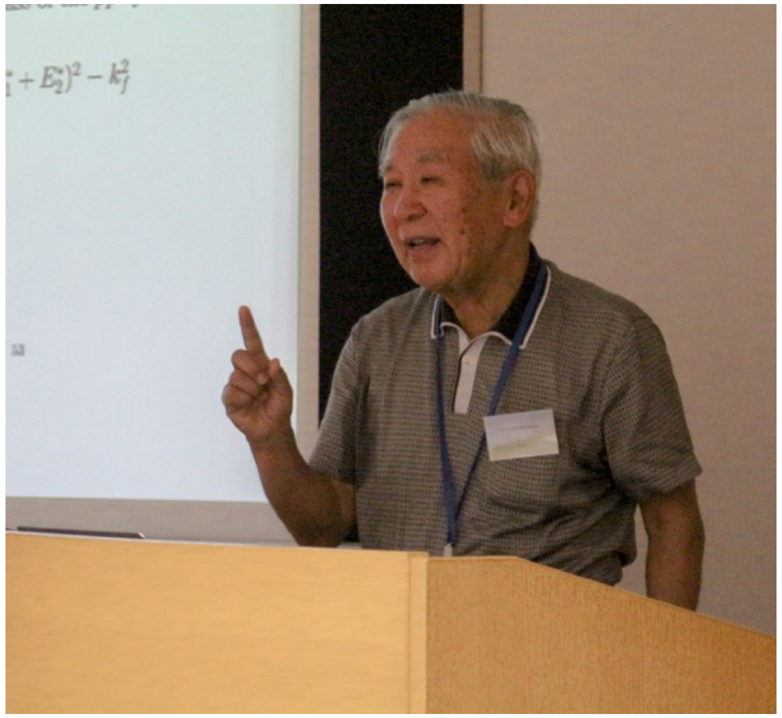


※ *$q \sim q' \sim 1.7\ \mathrm{fm}^{-1}$ and $\omega \sim q^2/2m_N$ for quasi-elastic scattering*

Contrastive Phenomena

Why Ichimura-san and we are especially interested in R_{GT} and R_L ?

- They show very contrastive phenomena



▷ *Quenching* of R_{GT}

$$\tau\sigma \quad : \quad q \simeq 0, \quad \omega < 50\,\mathrm{MeV}$$

- GT resonance (GTR) region

▷ *Enhancement* of R_L

$$\tau\sigma\cdot\hat{q} \quad : \quad q \simeq q_c \simeq 1.7\,\mathrm{fm}^{-1}, \quad \omega \simeq \frac{q^2}{2m_N}$$

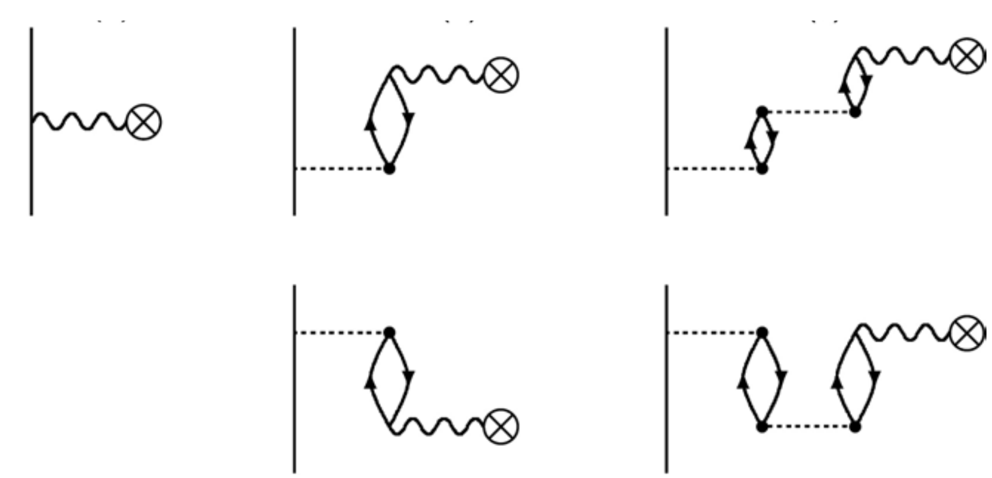
- Quasi-elastic scattering (QES) region

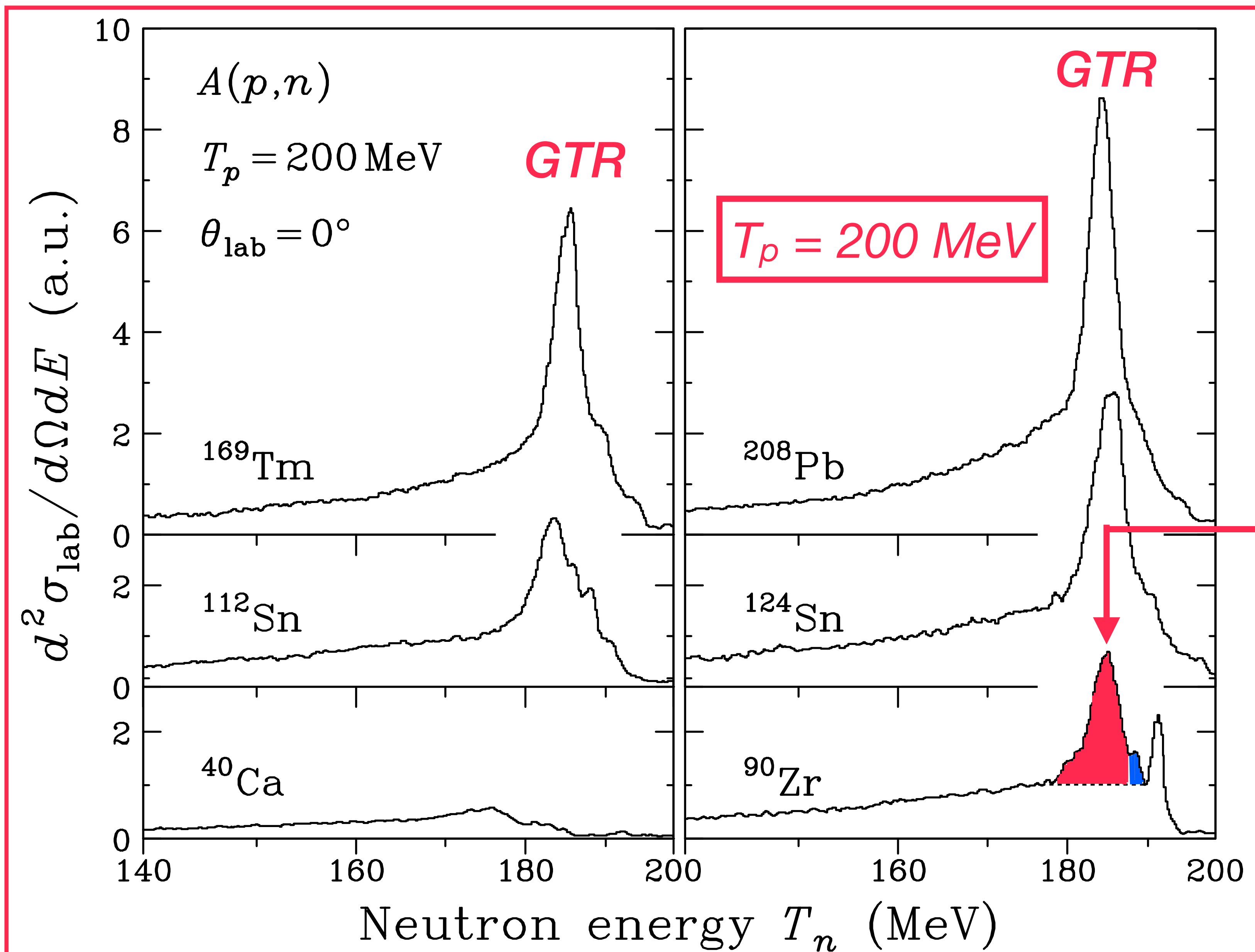
Quenching of GT Transition I

Delay of GT β- decays (1950s〜)

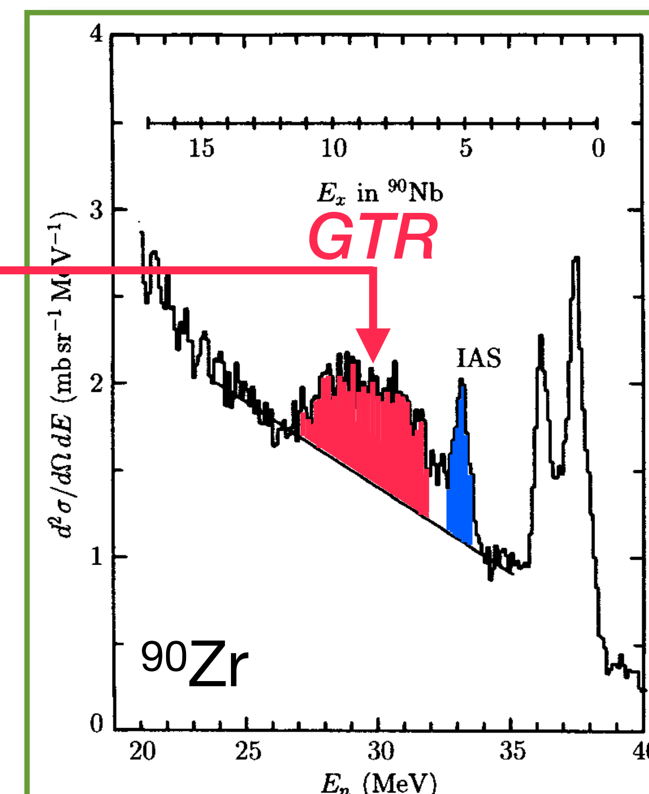
- Core polarization (first-order config. mixing)
- RPA-type additional terms
  - *Collective states such as IAS and GTR*

Impulse term | *Core polarization* | *RPA-type add. terms*





T_p = 45 MeV



C. Gaarde, Nucl. Phys. A 369, 258 (1981).

R.R.Doering et al., Phys. Rev. lett. 35, 1691 (1975).

Quenching of GT Transition II

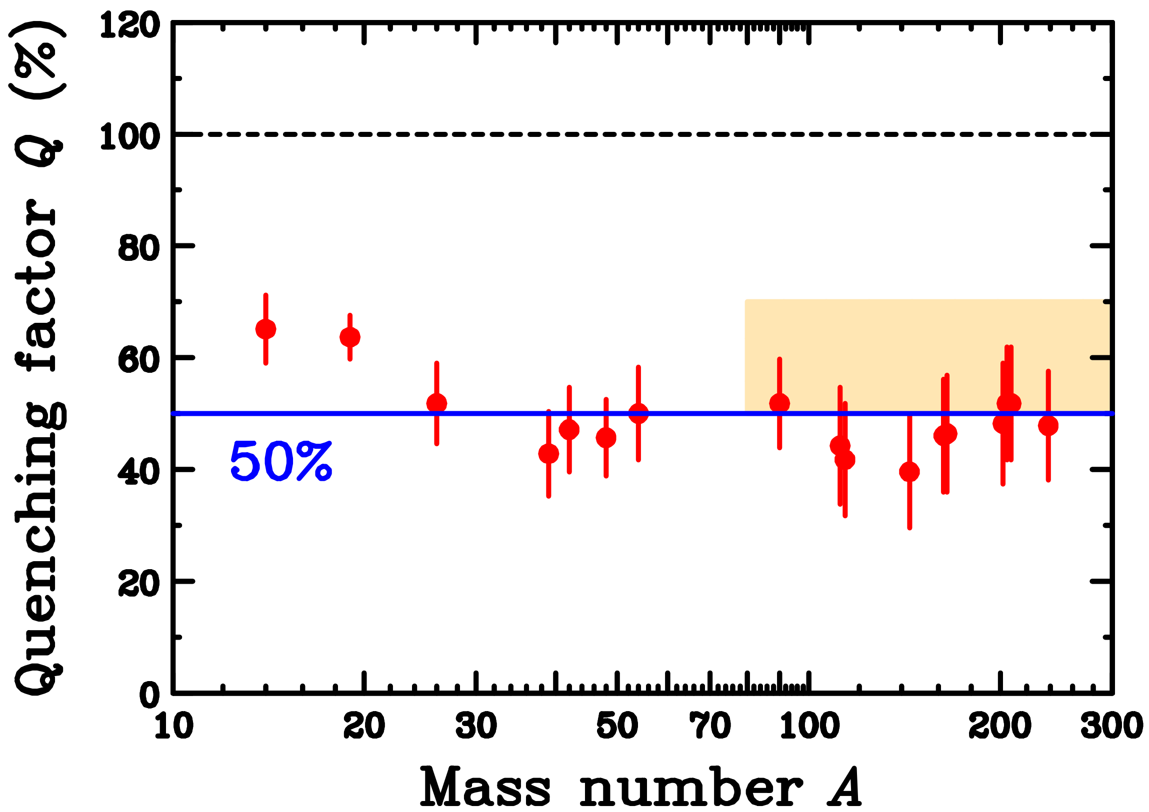
Extraction of R_{GT} (B(GT)) from (p,n) and (n,p) reactions

$$\frac{d^2\sigma_{\Delta L=0}(q,\omega)}{d\Omega d\omega} = \hat{\sigma}_{\rm GT} F(q,\omega) R^{\pm}_{\rm GT}(\omega)$$

GT total strength

$$S^{\pm}_{\rm GT}(\omega^{\pm}_{\rm top}) = \int^{\omega^{\pm}_{\rm top}} R^{\rm exp}_{\pm,{\rm GT}}(\omega) d\omega$$

C. Gaarde, Nucl. Phys. A 396, 127c (1983).



GT sum rule

$$S_{\beta-} - S_{\beta+} = 3(N-Z)$$

- *Model independent in the nucleon space*

GT quenching factor

$$Q = \frac{S^{-}_{\rm GT}(\omega^{-}_{\rm top}) - S^{+}_{\rm GT}(\omega^{+}_{\rm top})}{3(N-Z)}$$

- *If nucleus is made by nucleons, Q=1.*

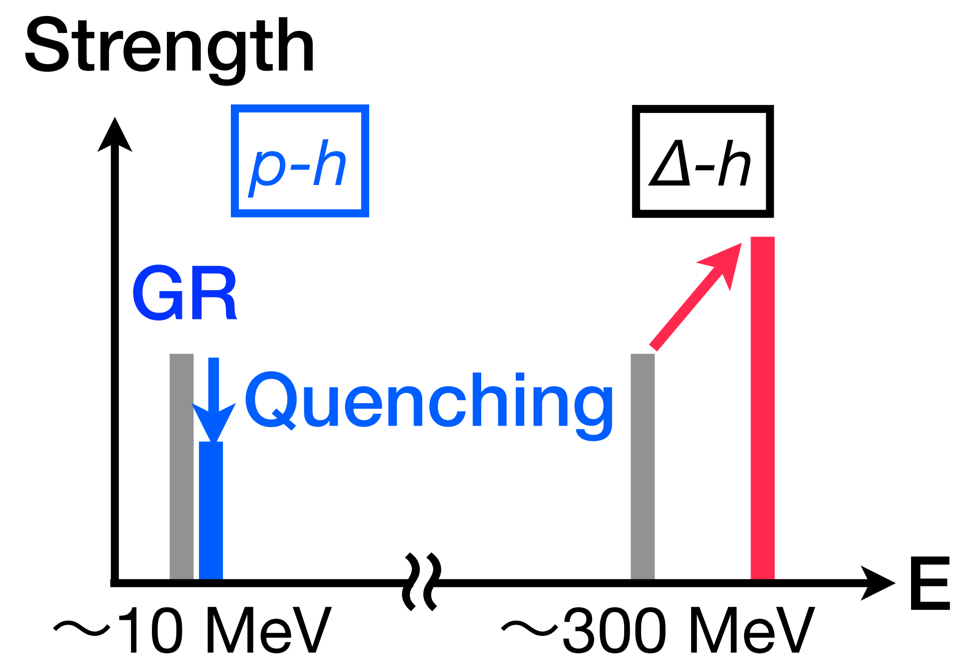
- Up to GTR (≦20 MeV), Q=0.5-0.6
- About 40% strength is missing

Origin of Quenching of Total GT Strength

Quark-degree (Δ-isobar) effect

Coupling between p-h and Δ-h is *large (strong repulsion)*

- Significant GT strengths move to Δ region (ω〜300 MeV)
- GTR strength is quenched



Configuration mixing effect

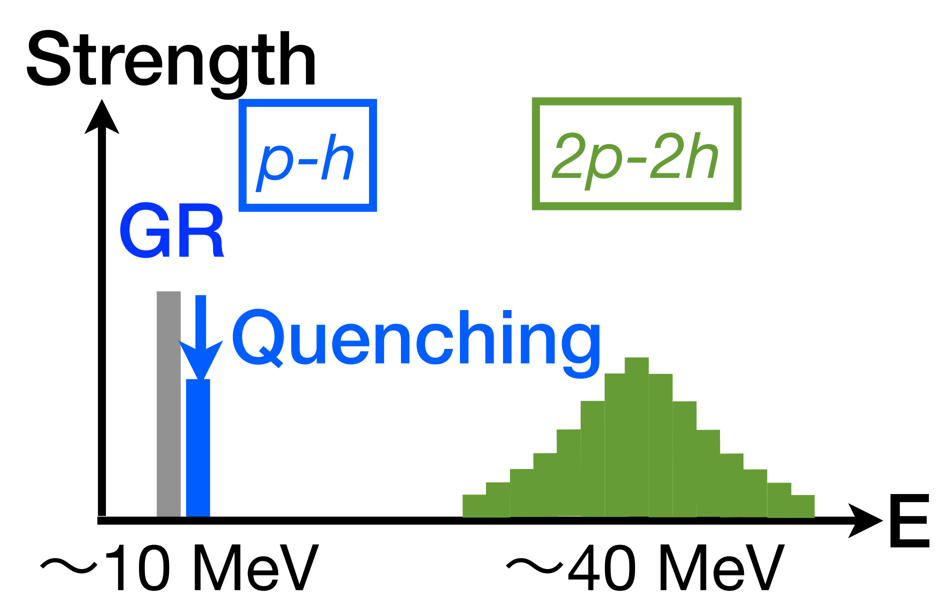
2nd-order config. mixing is ***effective for all nuclei***

- *M.Ichimura and K.Yazaki, NP 63, 401 (1965).*
- *H.A.Mavromatis, L.Zamick, G.E.Brown, NP 80, 545 (1966).*
- *K.Shimizu, M.Ichimura, A.Arima, NPA 226, 282 (1974).*
- *I.S.Towner, F.C.Khanna, PRL 42, 51 (1979).*
- *I.S.Towner, PR 155, 264 (1987).*
- *A.Arima et al., Adv. NP, 18, 1 (1987).*

Coupling between p-h and Δ-h is *small (weak repulsion)*

- Strength-shift to Δ region is small
- GTR strength is quenched by configuration mixing

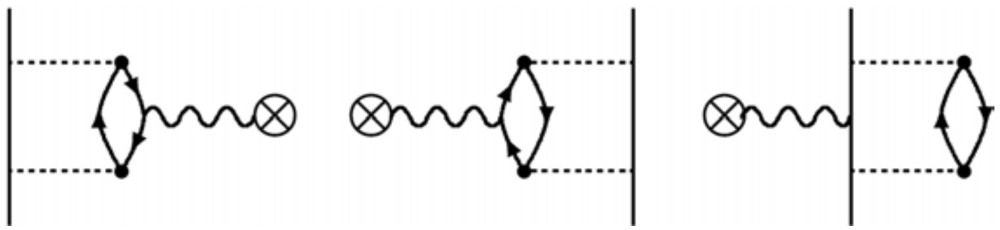
2nd-order configuration mixing

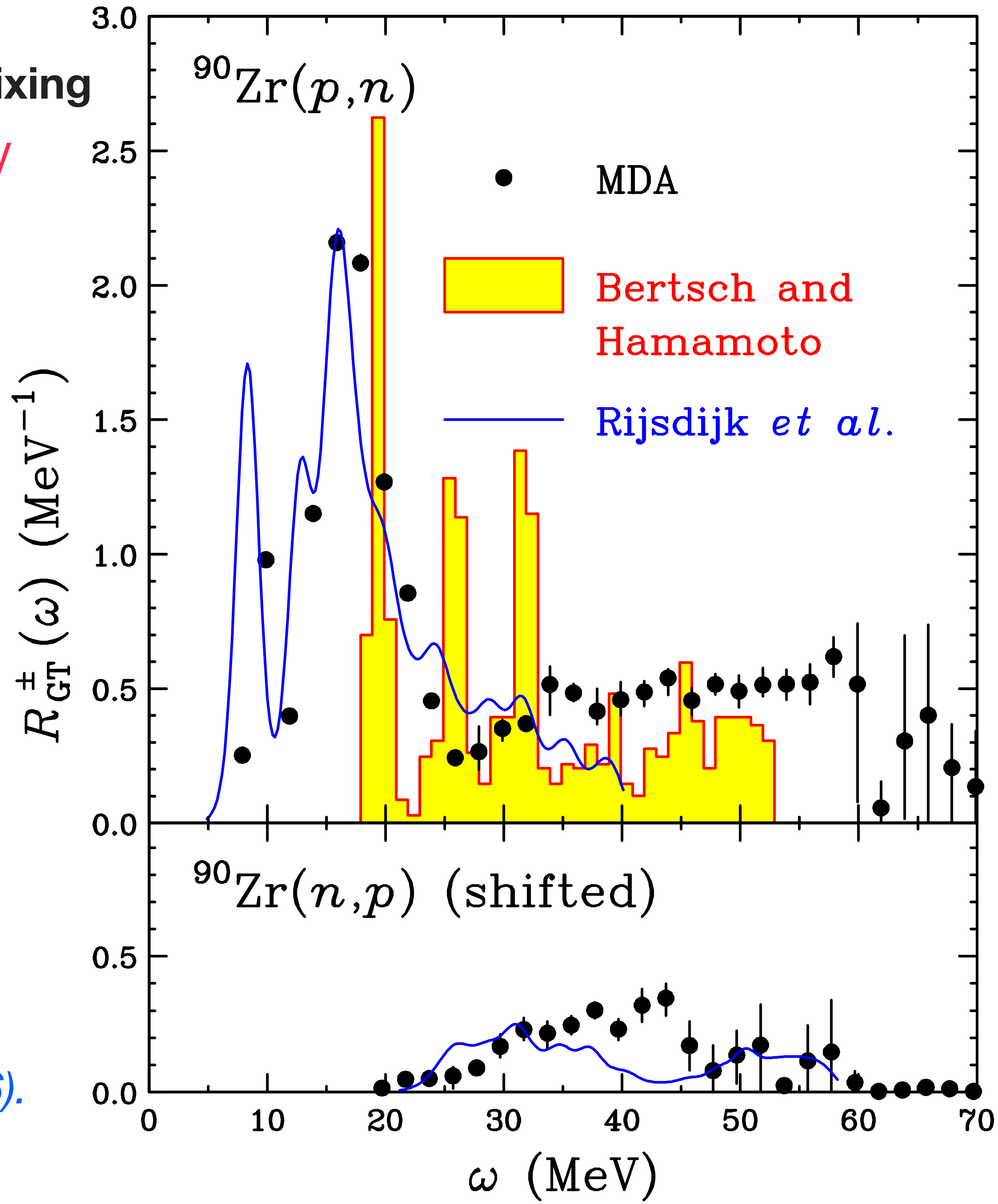


Dominance of Nuclear Configuration Mixing

Experimental results (MDA) support dominance of nuclear configuration mixing

- Significant GT strength up to 70 MeV





- TW et al., *Phys. Rev. C 55, 2909 (1997).*
- K. Yako, TW, et al., *Phys. Lett. B 615, 193 (2005).*
- **M. Ichimura**, H. Sakai, TW, *Prog. Part. Nuc. Phys. 56, 446 (2006).*

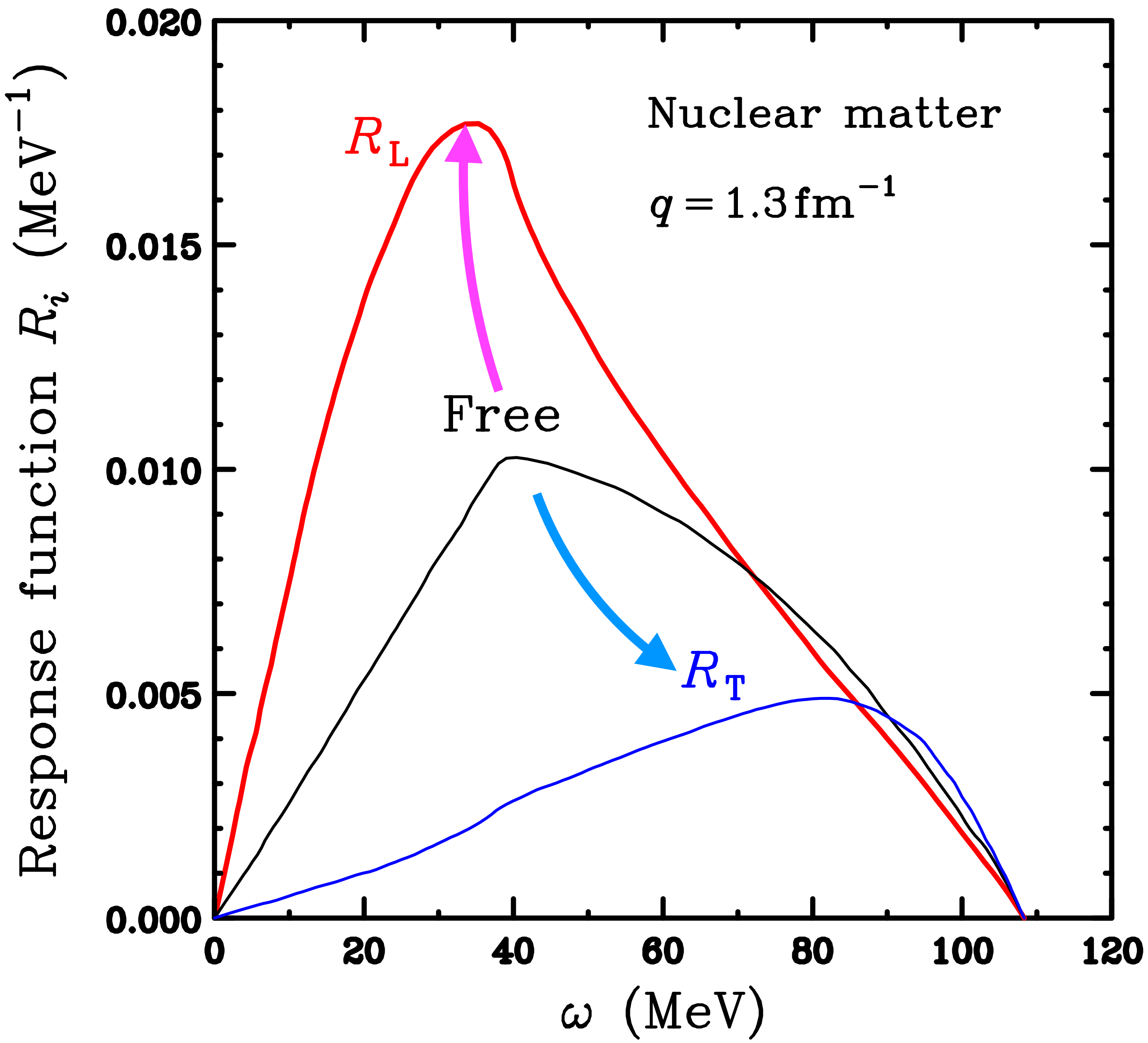
Enhancement of Pionic Response

A precursor phenomenon of pion condensation

Pionic (spin-longitudinal) response R_L : **Enhanced** and softened

Rho-mesonic (spin-transverse) response R_T : **Quenched** and hardened

- $R_L/R_T \gg 1$ → Good signature of pion condensation precursor phenomena



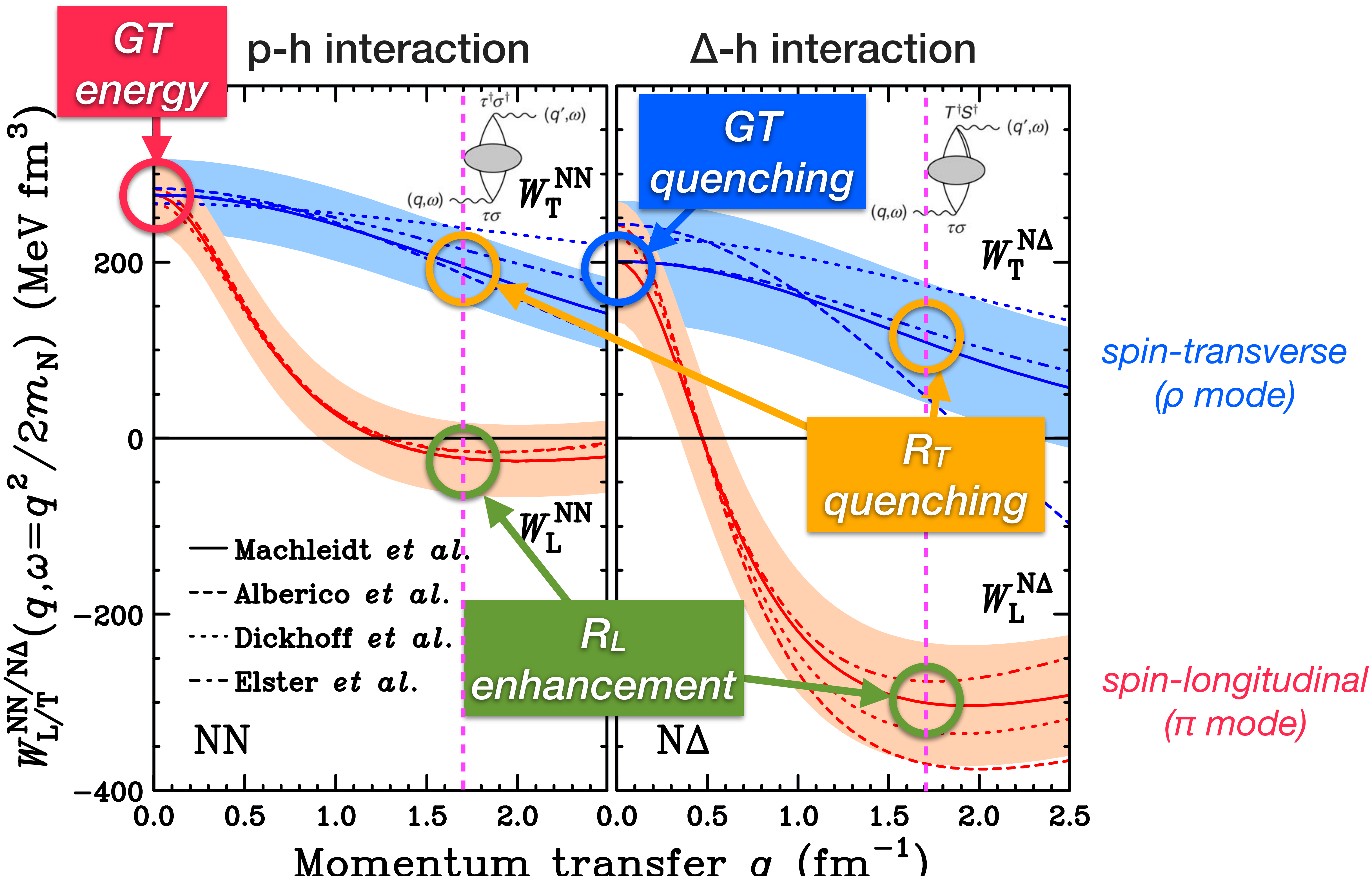
- Fermi gas model
- RPA include Δ
- π + ρ + g' interaction

W.M.Alberico, M. Ericson, and A. Molinari, Nucl. Phys. A 379, 429 (1982).

Origin of the Enhancement/Quenching

M. Ichimura, H. Sakai, TW, PPNP 56, 446 (2006).

Effective p-h and Δ-h interaction governed by OPEP develops pionic correlation.



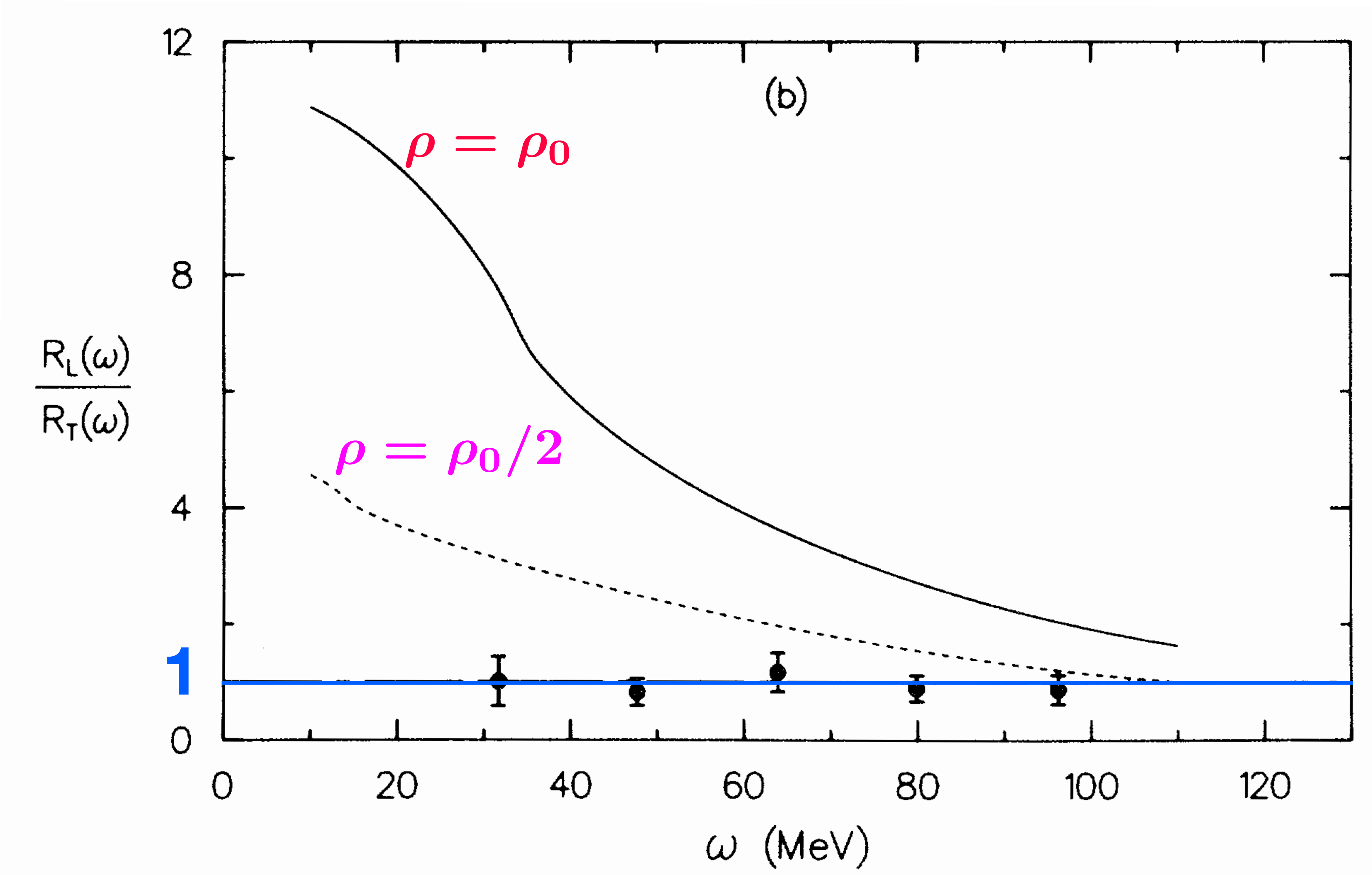
Experimental Spin-Response Ratio

Pb(p,p') at T_p=500 MeV and q=1.75 fm^{-1}

Measure polarization transfer D_{ij} → *Separate I (cross section) into ID_L and ID_T*

Use the *proportionality relation between ID_L (ID_T) and R_L (R_T)*

- $R_L/R_T \sim 1$ → **No evidence** of theoretically expected enhancement



T.A.Carey et al., Phys. Rev. Lett. 53, 144 (1984).

Issues raised by Prof. Ichimura

Prof. Ichimura raised the following issues regarding the "R_L/R_T ratio problem"

Q1 : Is the method used to extract R_L, R_T from D_{ij} reasonable?

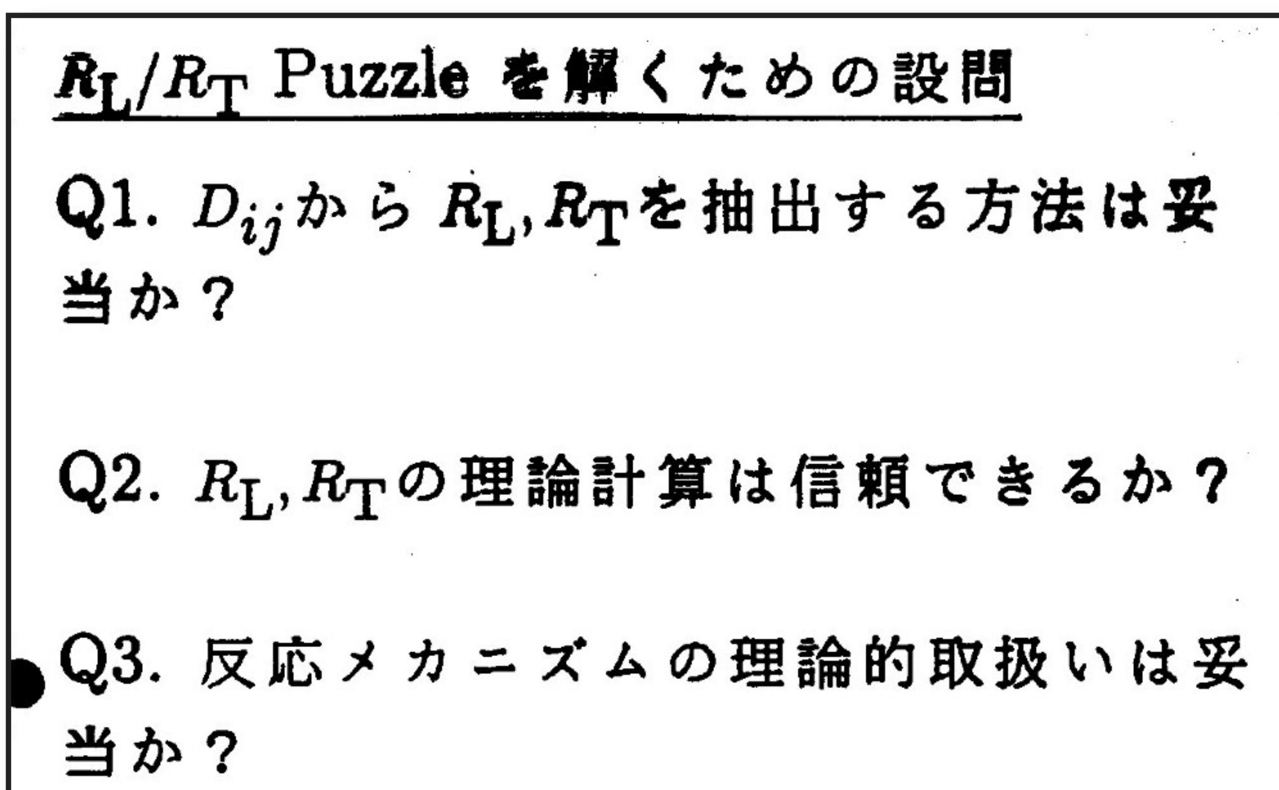
- Relation between the polarized cross sections and D_{ij}

Q2 : Are theoretical calculations of R_L and R_T reliable?

- Fermi gas model calculations

Q3 : Is the theoretical treatment of the reaction mechanism reasonable?

- Proportionality between the polarization cross sections and the corresponding response functions



R_L/R_T Puzzle を解くための設問

Q1. D_{ij}から R_L, R_Tを抽出する方法は妥当か？

Q2. R_L, R_Tの理論計算は信頼できるか？

Q3. 反応メカニズムの理論的取扱いは妥当か？

Original slide by Prof. Ichimura in the RCNP workshop (1992).

Q1 : Is the method used to extract R_L, R_T from D_{ij} reasonable?

M. Ichimura and K.Kawahigashi, Phys. Rev. C 45, 1822 (1992).

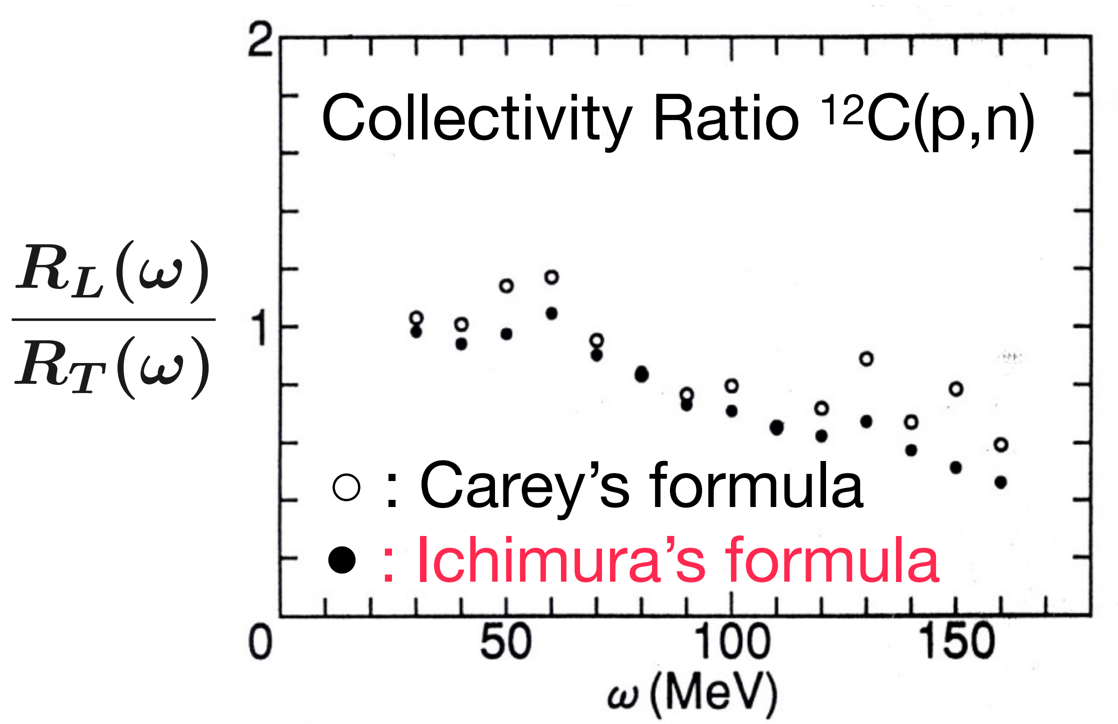
Carey's formula

- *spin-longitudinal (π) :* $ID_q = \frac{I}{4}\left[1 - D_{NN} + (D_{SS'} - D_{LL'})\sec\theta_{\rm lab}\right] \propto R_L$
- *spin-transverse (ρ) :* $ID_p = \frac{I}{4}\left[1 - D_{NN} - (D_{SS'} - D_{LL'})\sec\theta_{\rm lab}\right] \propto R_T$

This formula is adequate ***only for NN scattering*** (NOT for NA scattering)

Ichimura's correct formula

- $ID_q = \frac{I}{4}\left[1 - D_{NN} + (D_{SS'} - D_{LL'})\cos(2\theta_p - \theta_{\rm lab} - \Omega) - (D_{LS'} + D_{SL'})\sin(2\theta_p - \theta_{\rm lab} - \Omega)\right]$
- $ID_p = \frac{I}{4}\left[1 - D_{NN} - (D_{SS'} - D_{LL'})\cos(2\theta_p - \theta_{\rm lab} - \Omega) + (D_{LS'} + D_{SL'})\sin(2\theta_p - \theta_{\rm lab} - \Omega)\right]$



Now we can separate the cross section into spin-longitudinal and spin-transverse modes correctly **based on Ichimura's formula.**

↓

Use of the correct formula further reduces the collectivity ratio.

Q2 : Are theoretical calculations of R_L and R_T reliable?

M. Ichimura, K.Kawahigashi, T.S.Jorgensoen and C.Gaarde. Phys. Rev. C 39, 1446 (1989).

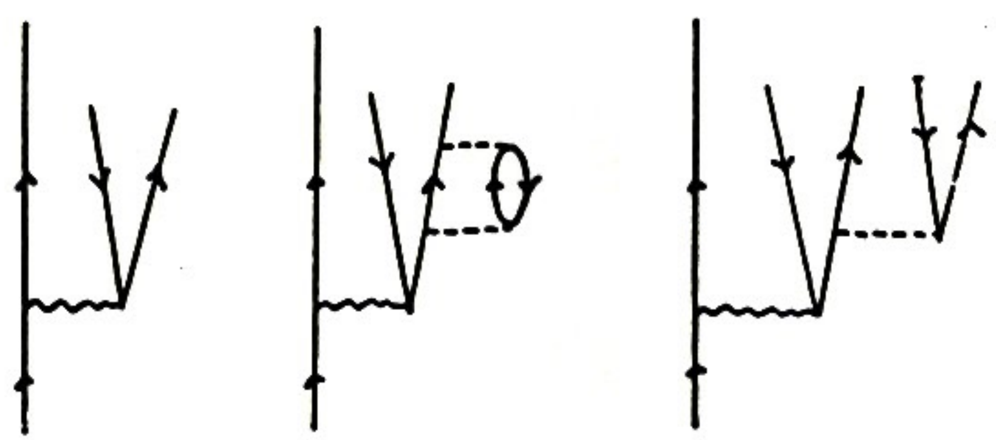
Refinement of the calculation of the response function

Finiteness of the nucleus

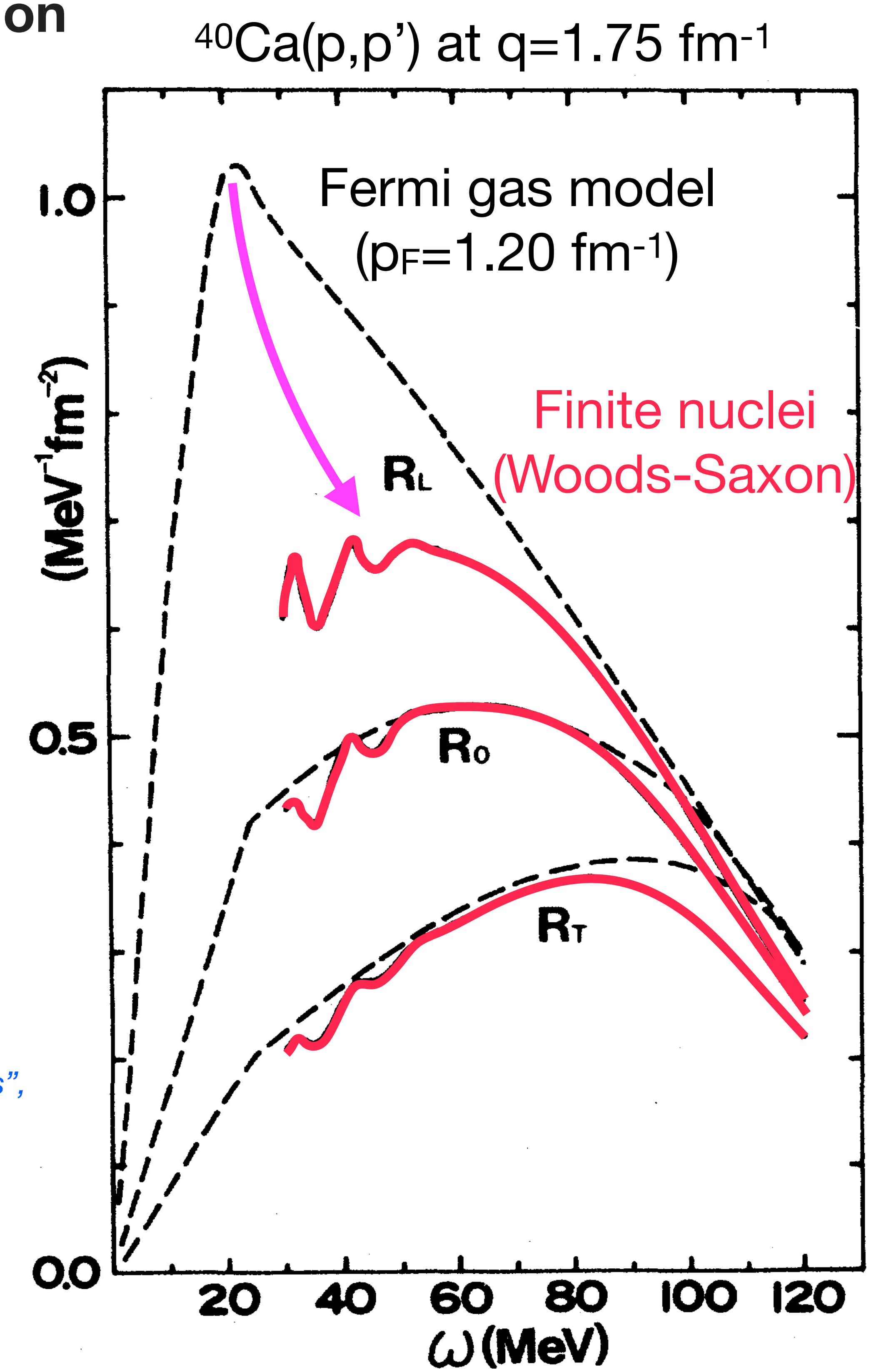
- Fermi gas (infinite nuclear matter)
  → Woods-Saxon shell model (finite nuclei)

Spreading width

- Complex Woods-Saxon :
  Distortion, absorption of knocked-out nucleon & two-nucleon knock-out, etc.



M. Ichimura,
"Spin Observables in Quasifree Scatterings",
RCNP Workshop (1992).



The very large enhancement in R_L at low ω is *the artifact in the Fermi gas model*.

Q3 : Is the theoretical treatment of the reaction mechanism reasonable?

M. Ichimura, K.Kawahigashi, T.S.Jorgensoen and C.Gaarde. Phys. Rev. C 39, 1446 (1989).

Basic idea to deduce R_L/R_T experimentally

PWIA with Glauber-like approximation

- Distortion effects with effective nucleon number $\mathcal{N}_{L/T}$

spin-longitudinal $ID_q^{NA} \simeq ID_q^{NN}\,\mathcal{N}_L\,R_L(q,\omega)$

spin-transverse $ID_p^{NA} \simeq ID_p^{NN}\,\mathcal{N}_T\,R_T(q,\omega)$

ID_q^{NN}/ID_p^{NN} can be obtained from *Nd* data

$$\rightarrow \frac{R_L(q,\omega)}{R_T(q,\omega)} = \left(\frac{ID_q^{NA}}{ID_p^{NA}}\right) \Big/ \left(\frac{ID_q^{Nd}}{ID_p^{Nd}}\right)$$

DWIA analysis by Ichimura-san

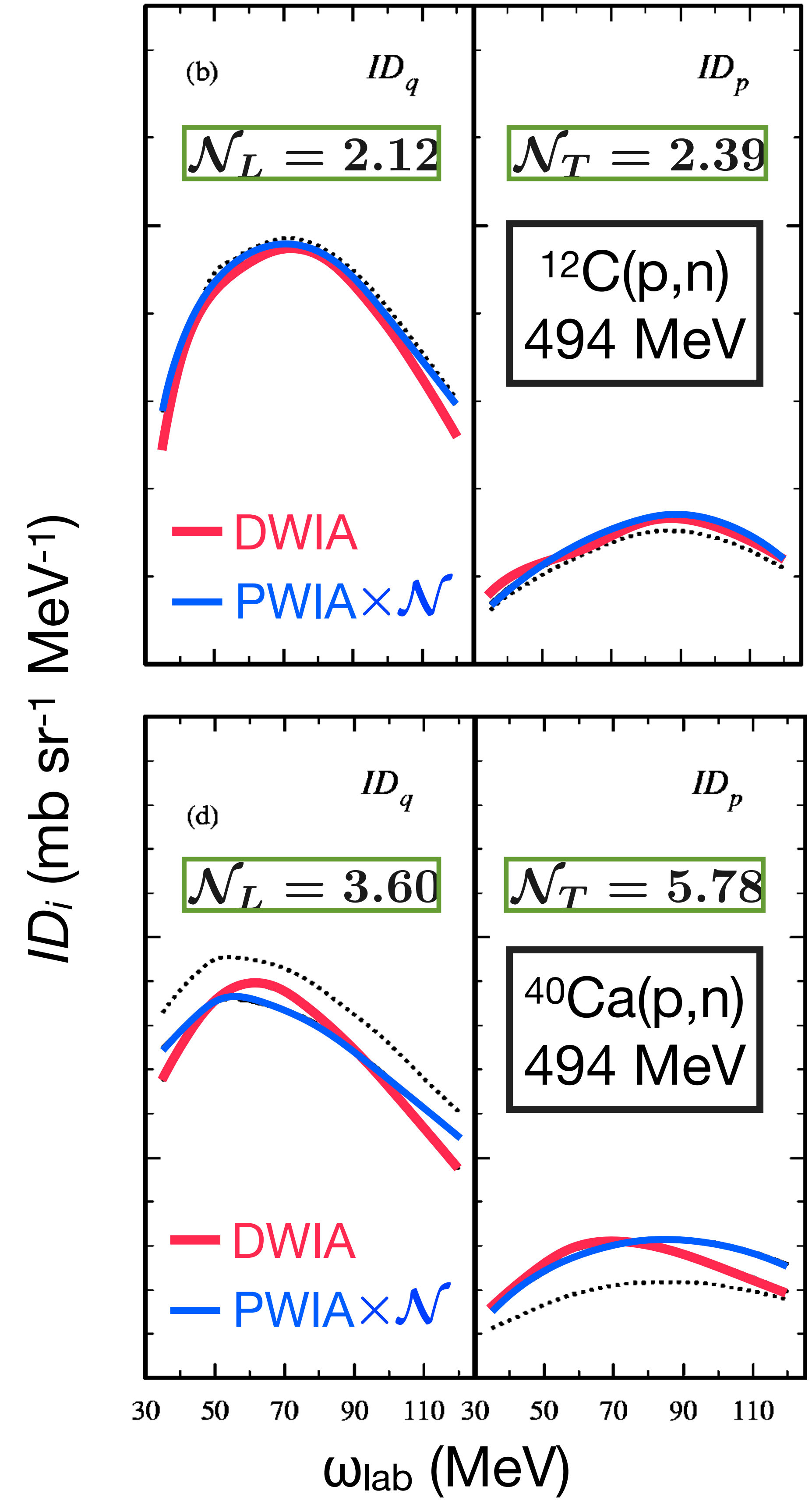
PWIA+Glauber approx. works well for ^{12}C

- $\mathcal{N}_L < \mathcal{N}_T$

PWIA+Glauber approx. is *inappropriate* for ^{40}Ca

- Significant distortion effects affect spectrum shape
- $\mathcal{N}_L \ll \mathcal{N}_T$

Exp. ID_i should be compared with DWIA calc.



Unified Analysis

Analyzed

- GTGR spectrum
- GT quenching factor Q
- Spin-longitudinal (pionic) ID_q spectrum

by the *common* method

Continuum RPA

- Δ isobar is included
- Woods-Saxon type mean field
- Local effective mass
- Spreading widths

DWIA + Two-step processes

- Fermi motion
- Off-shell effect, etc.

PHYSICAL REVIEW C **72**, 067303 (2005)

Unified analysis of spin isospin responses of nuclei

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(Received 8 October 2004; published 30 December 2005)

PHYSICAL REVIEW C, VOLUME 63, 044609

Distorted wave impulse approximation analysis for spin observables in nucleon quasielastic scattering and enhancement of the spin longitudinal response

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(Received 27 July 2000; published 23 March 2001)

PHYSICAL REVIEW C **69**, 054609 (2004)

Pionic enhancement in quasielastic $(\vec{p},\vec{n})$ reactions at 345 MeV

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(Received 14 January 2004; published 25 May 2004)

Effective Interaction

Key parameters of the *unified/common* analysis

- π + ρ + g' model

spin-longitudinal (π)

$$V_{\mathrm{eff}}(\boldsymbol{q},\omega) = V_\pi(\boldsymbol{q},\omega) + V_\rho(\boldsymbol{q},\omega) + V_{\mathrm{LM}}$$

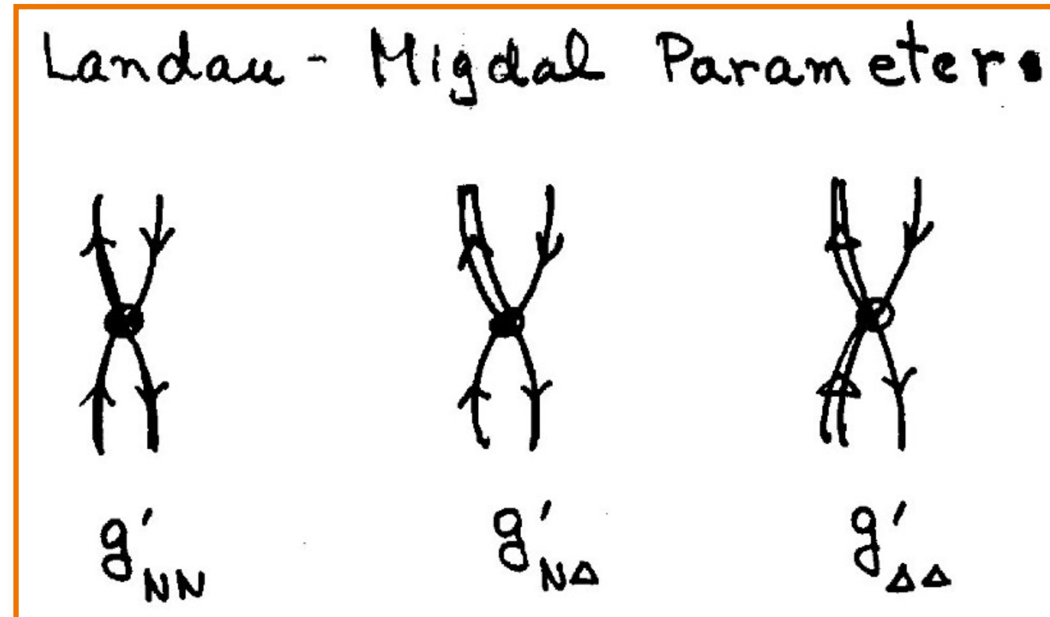
spin-transverse (ρ)

- Landau-Migdal (LM) parameters

$$V_{\mathrm{LM}} = \frac{f^2_{\pi NN}}{m^2_\pi}\Bigg\{\boxed{g'_{NN}}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)$$

$$+\frac{f_{\pi N\Delta}}{f_{\pi NN}}\boxed{g'_{N\Delta}}\left[\Big((\boldsymbol{\tau}_1\cdot\boldsymbol{T}_2)(\boldsymbol{\sigma}_1\cdot\boldsymbol{S}_2)+(\boldsymbol{\tau}_1\cdot\boldsymbol{T}^\dagger_2)(\boldsymbol{\sigma}_1\cdot\boldsymbol{S}^\dagger_2)\Big)+(1\leftrightarrow 2)\right]$$

$$+\left(\frac{f_{\pi\Delta\Delta}}{f_{\pi NN}}\right)^2\boxed{g'_{\Delta\Delta}}\left[\Big((\boldsymbol{T}_1\cdot\boldsymbol{T}_2)(\boldsymbol{S}_1\cdot\boldsymbol{S}_2)+(\boldsymbol{T}_1\cdot\boldsymbol{T}^\dagger_2)(\boldsymbol{S}_1\cdot\boldsymbol{S}^\dagger_2)\Big)+\mathrm{h.c.}\right]\Bigg\}\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)$$



A copy of Prof. Ichimura's handwritten slides

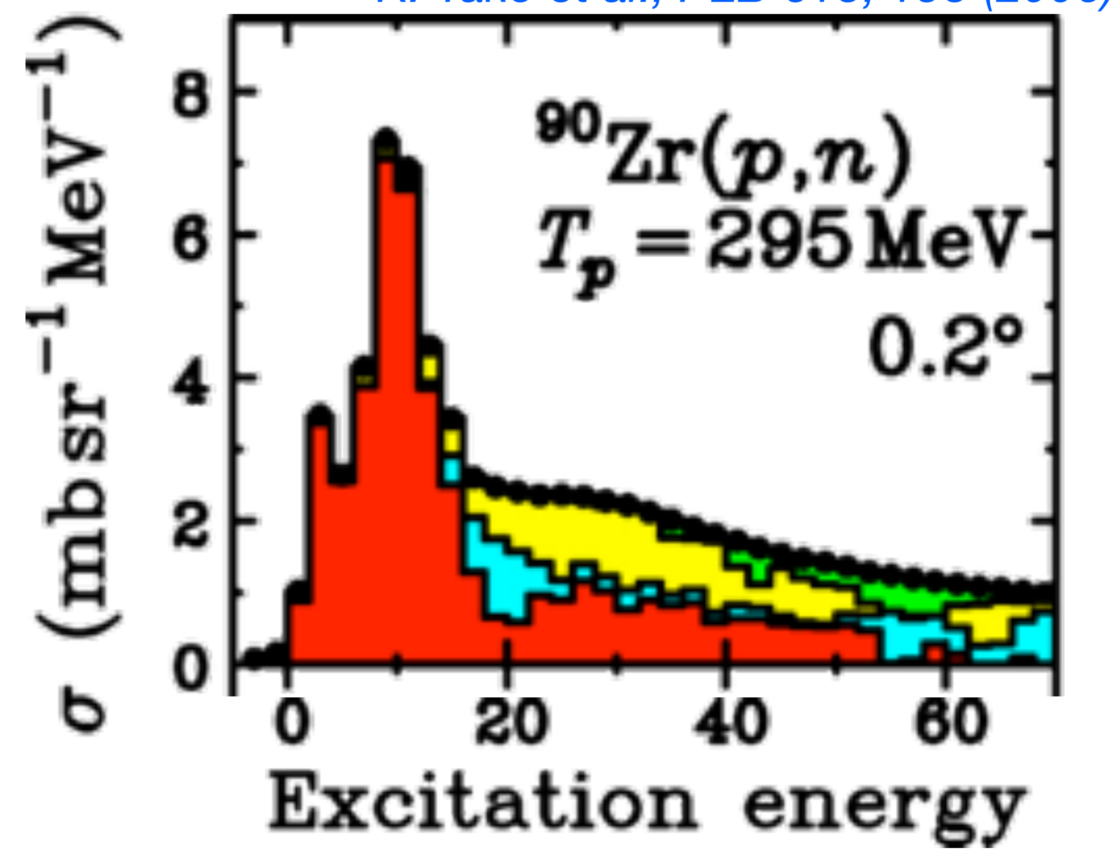
※ *g'ΔΔ is fixed to be 0.5 because its dependence is known to be small.*

GTGR Spectrum

K. Yako et al., PLB 615, 193 (2006).

Experiment: $^{90}Zr(p,n)^{90}Nb$ at 295 MeV

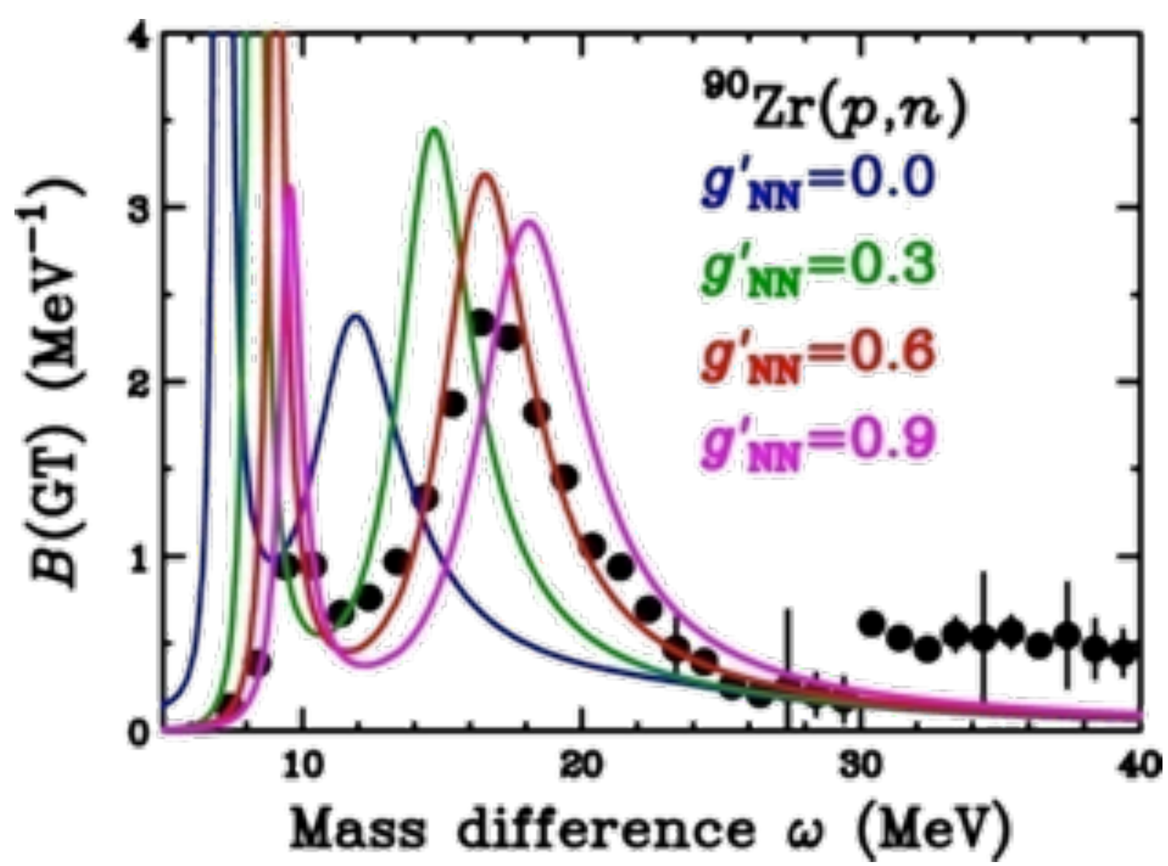
- Prominent GTGR peak
- GT (L=0) contribution is extracted by MDA
- GT strength, B(GT), is deduced with proportionality ansatz



Comparison with theory

- GTGR peak position
  - Strongly depends on g'_{NN}

    $g'_{NN} = 0.6 \pm 0.1$
  - Weak $g'_{N\Delta}$ dependence



GT Quenching Factor Q

GT quenching factor Q

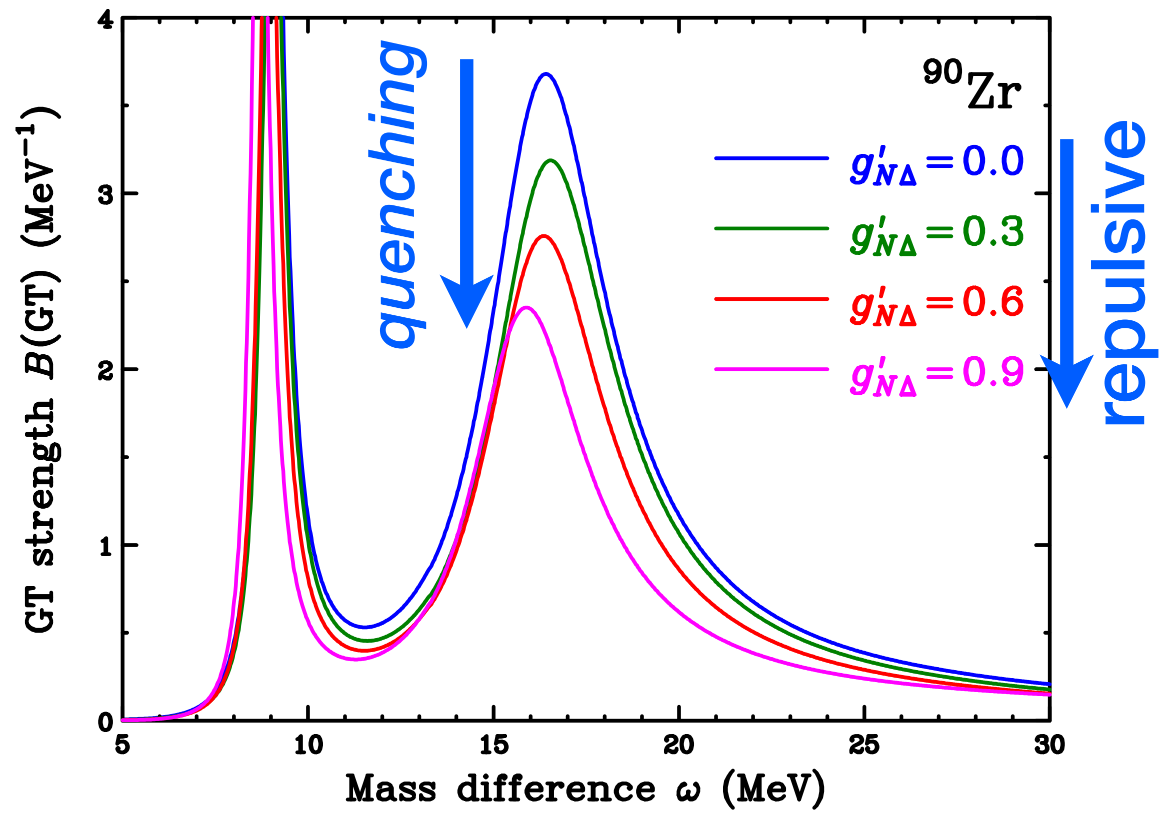
- Q = 0.86 ± 0.07 ← from MD analysis
  - 2p2h effects are dominant

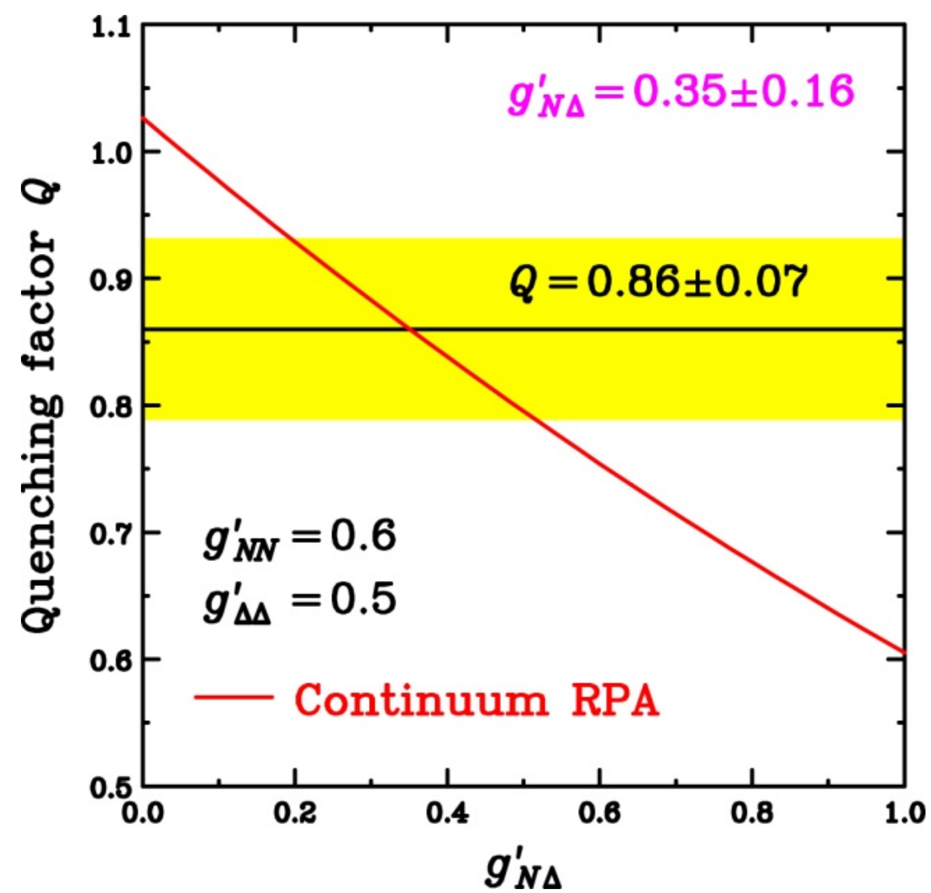
Q evaluated in RPA

- Determine the coupling to Δ
- Larger $g'_{N\Delta}$ → Stronger coupling
  - Strength becomes small (quenched)
    [Strength moves to Δ region]
- Q strongly depends on $g'_{N\Delta}$

  $g'_{N\Delta} = 0.35 \pm 0.16$

  - Weak g'_{NN} dependence





Spin-Longitudinal (Pionic) ID_q Enhancement

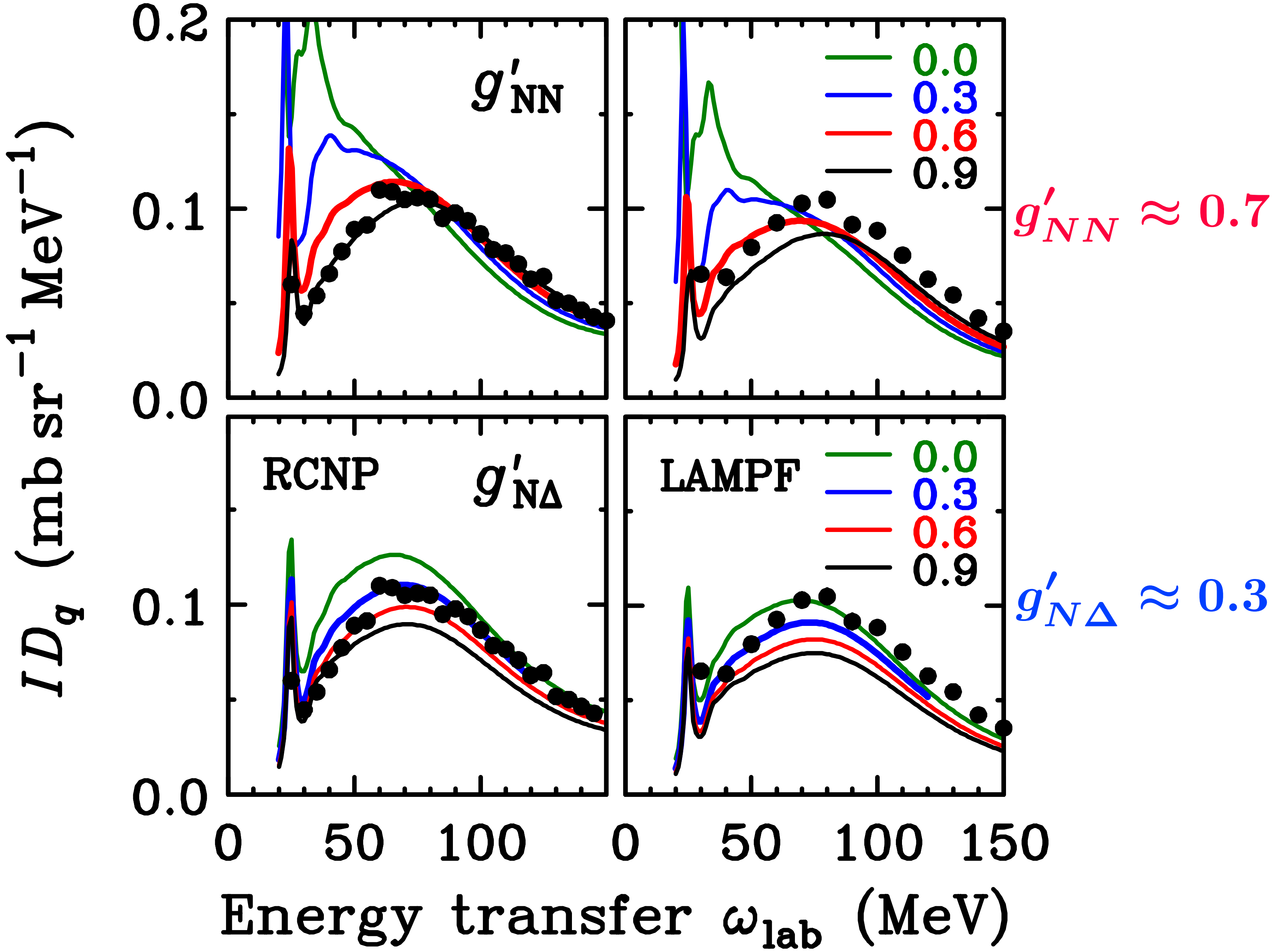
M. Ichimura, H. Sakai, TW, PPNP 56, 446 (2006).

Experiment (q = 1.7 fm^{-1})

- ^{12}C(p,n) at RCNP
  - T_p=346 MeV and θ=22°
- ^{12}C(p,n) at LAMPF
  - T_p=494 MeV and θ=18°

Comparison with theory

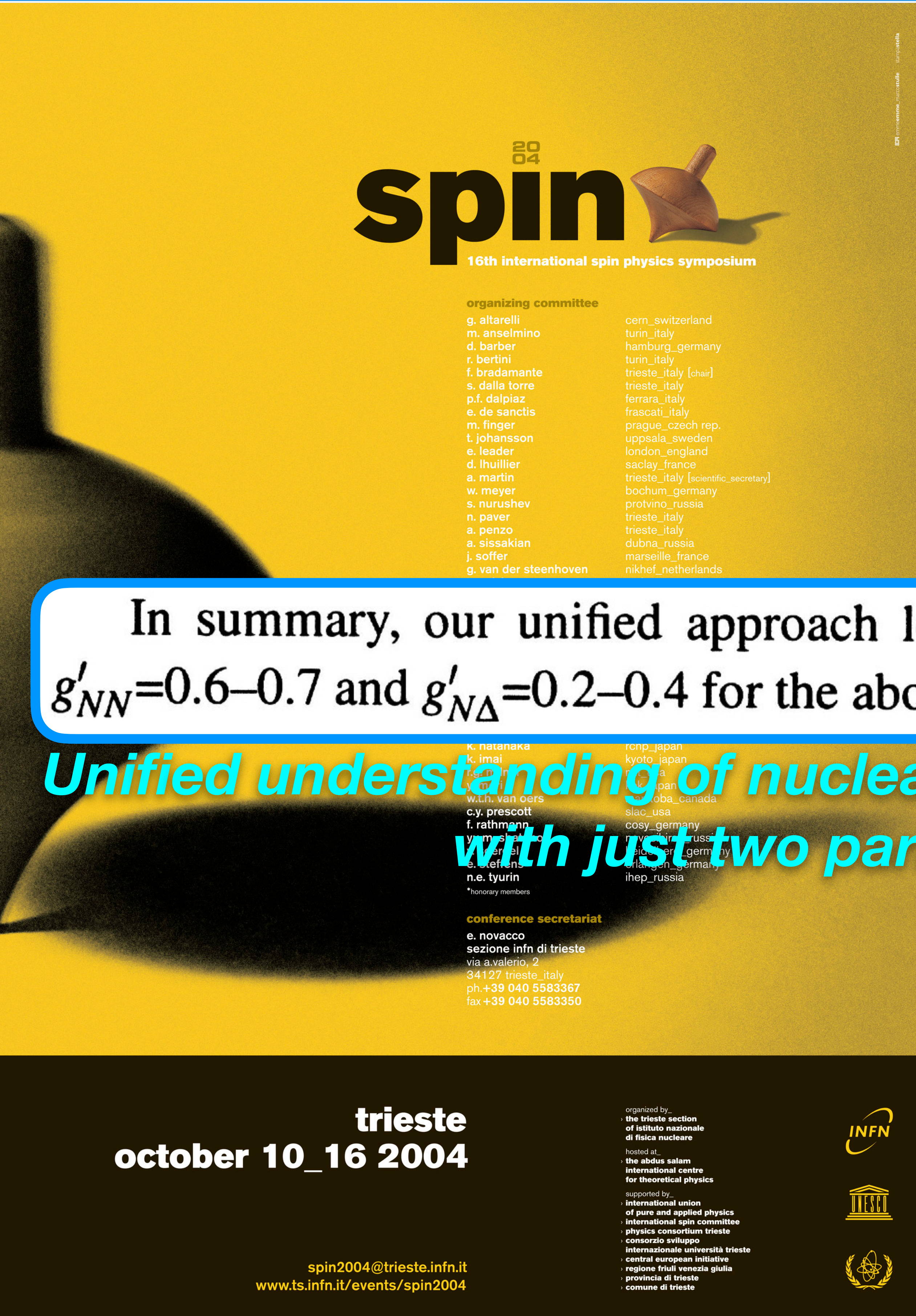
- DWIA + two-step
- QES peak depends on g'_{NN}
  - g'_{NN} = 0.6-0.7
- Enhancement depends on $g'_{N\Delta}$
  - $g'_{N\Delta}$ = 0.2-0.4



$$\boxed{g'_{NN} \approx 0.7, \quad g'_{N\Delta} \approx 0.3} \longleftrightarrow \boxed{g'_{NN} = 0.6 \pm 0.1, \quad g'_{N\Delta} = 0.35 \pm 0.16}$$

$q \simeq 1.7\,\mathrm{fm}^{-1}$ $\qquad$ $q = 0\,\mathrm{fm}^{-1}$

Ichimura-san's summary in SPIN2004

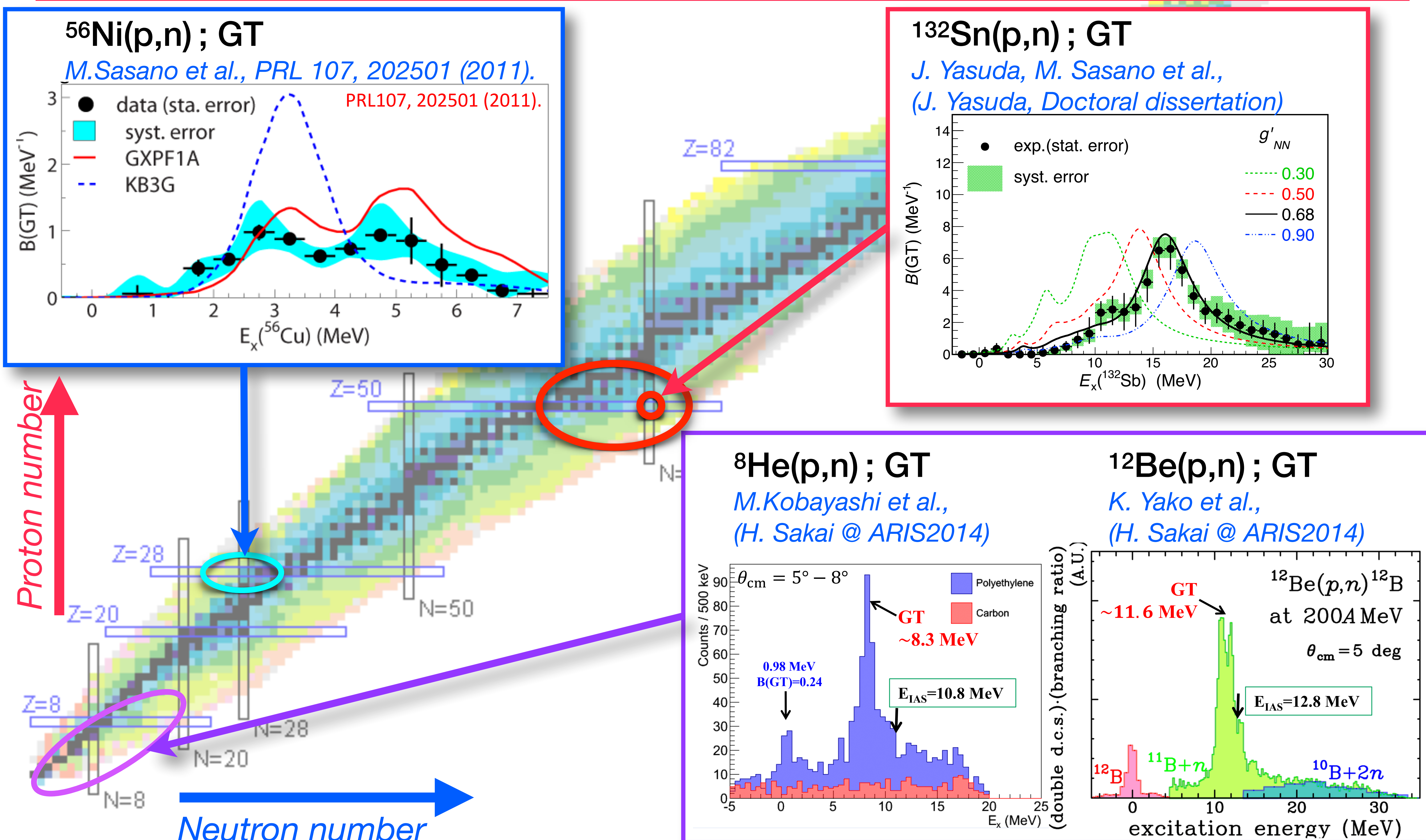


In summary, our unified approach leads to a common set of the LM parameters, g'_{NN}=0.6–0.7 and $g'_{N\Delta}$=0.2–0.4 for the above contrasting phenomena.

Unified understanding of nuclear spin responses in wide (q,ω) region with just two parameters, g'_{NN} and $g'_{N\Delta}$

Spin-isospin responses for unstable nuclei

・*Isospin dependence*
・*Skin/halo effect (Femi-level diff.)*
} *on resonance/residual int. will be known.*



B(GT) and Landau-Migdal parameter g'$_{NN}$ in ^{132}Sn

J. Yasuda, M. Sasano, TW et al., Phys. Rev. Lett. 121, 132501 (2018).

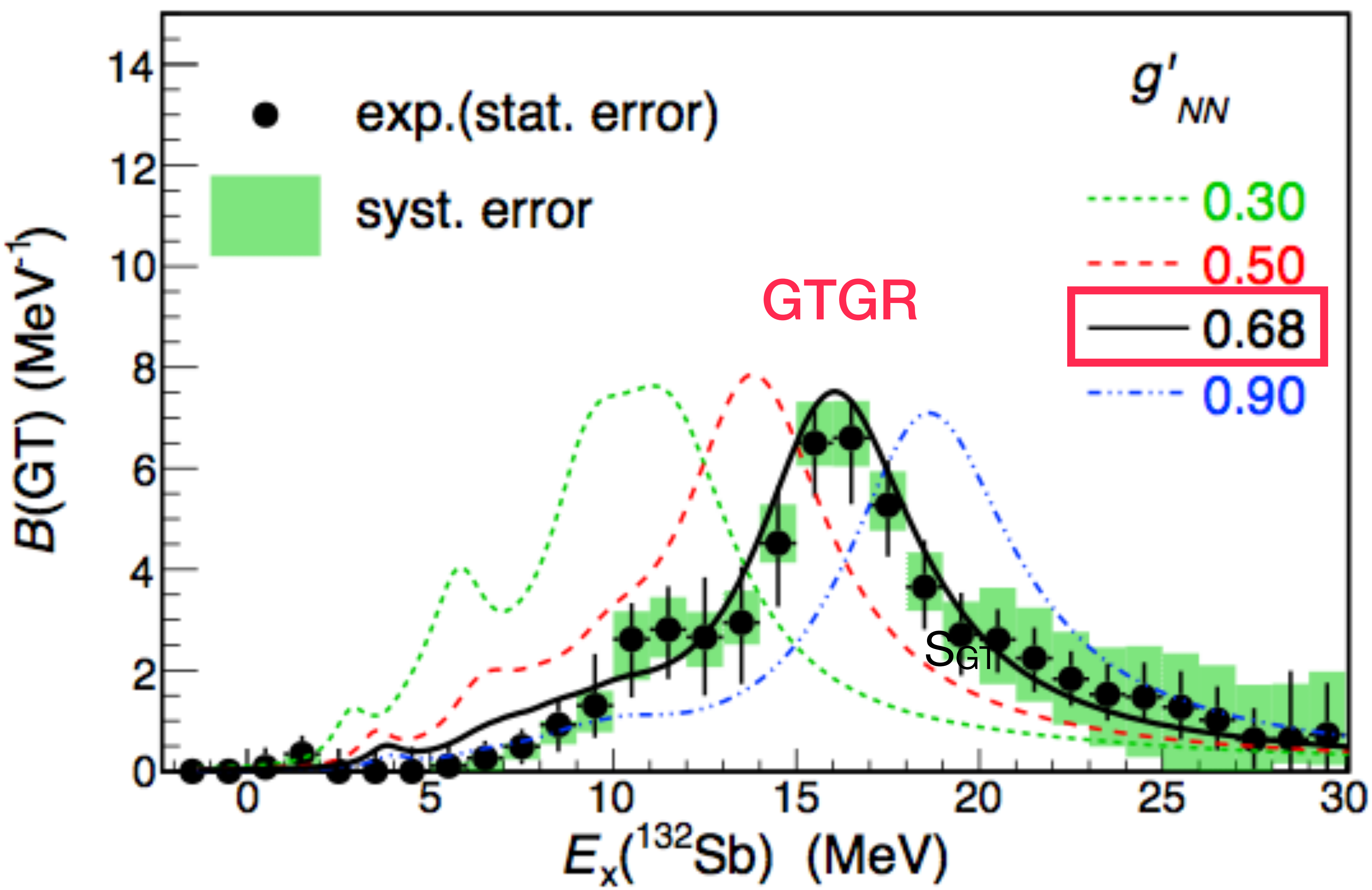
GT giant resonance (GTGR) is observed for ^{132}Sn (doubly-magic unstable nuclei)

GTGR peak is sensitive to g'$_{NN}$

- Ratio of the bump to the main peak is also sensitive to g'$_{NN}$

$$g'_{NN} = 0.68 \pm 0.07$$

※ g'$_{NN}$ is constant for isospin asymmetry (N-Z)/A of 0.11(^{90}Zr) to 0.24(^{132}Sn)

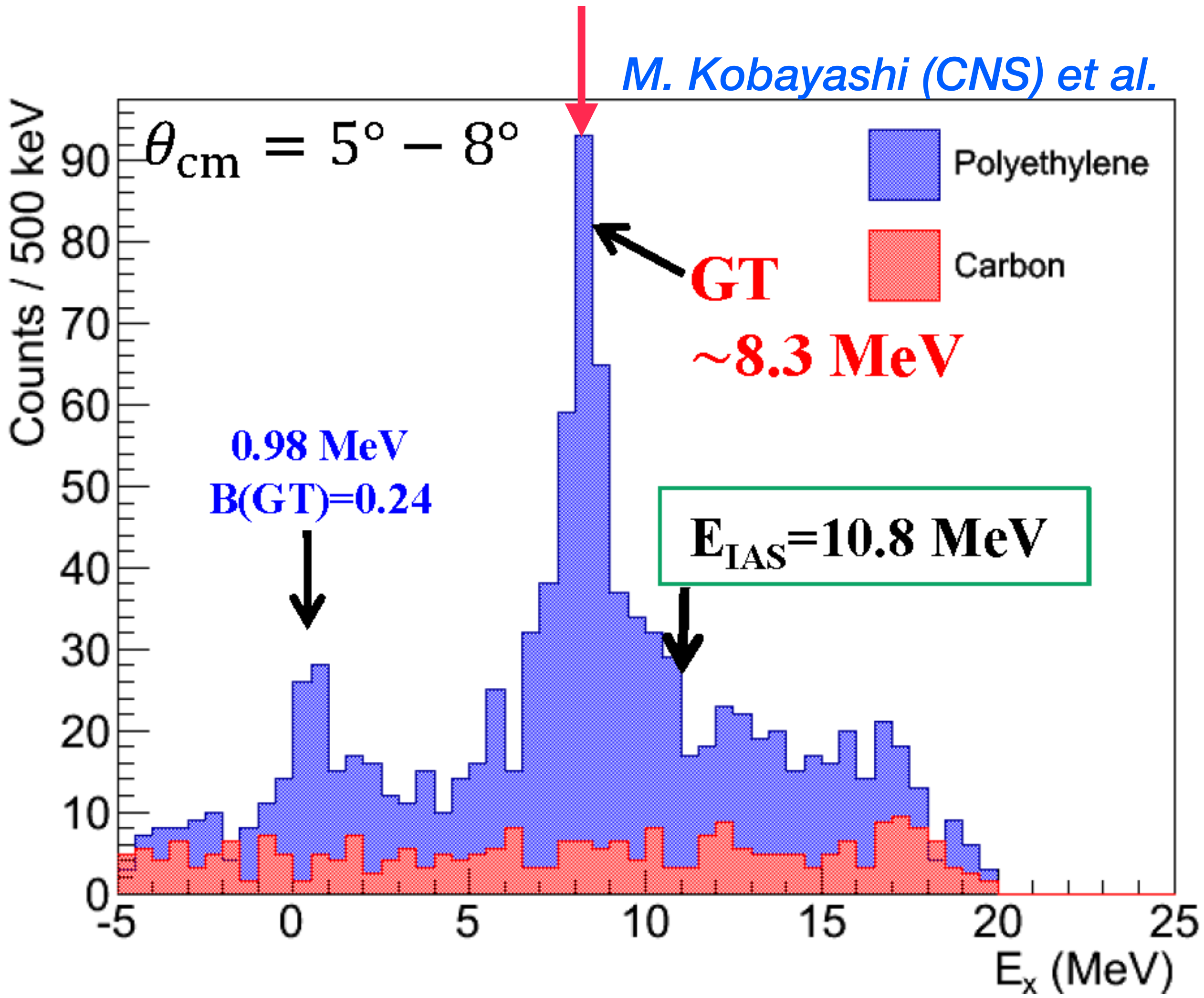


Experimental results

Gamow-Teller resonances have been *successfully observed* for ^{8}He and ^{12}Be

^{8}He(p,n) at 200 MeV/A

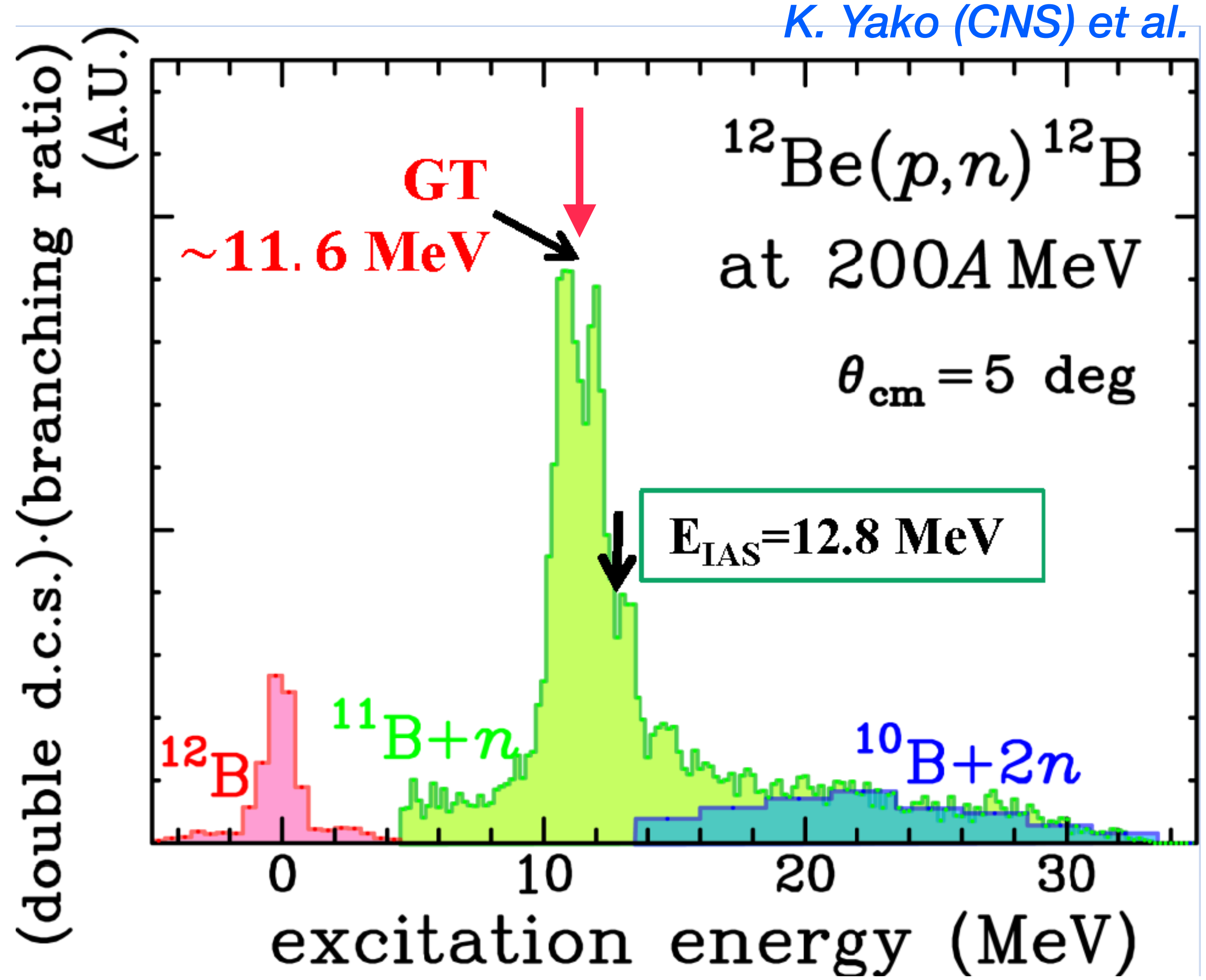
M. Kobayashi (CNS) et al.



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

^{12}Be(p,n) at 200 MeV/A

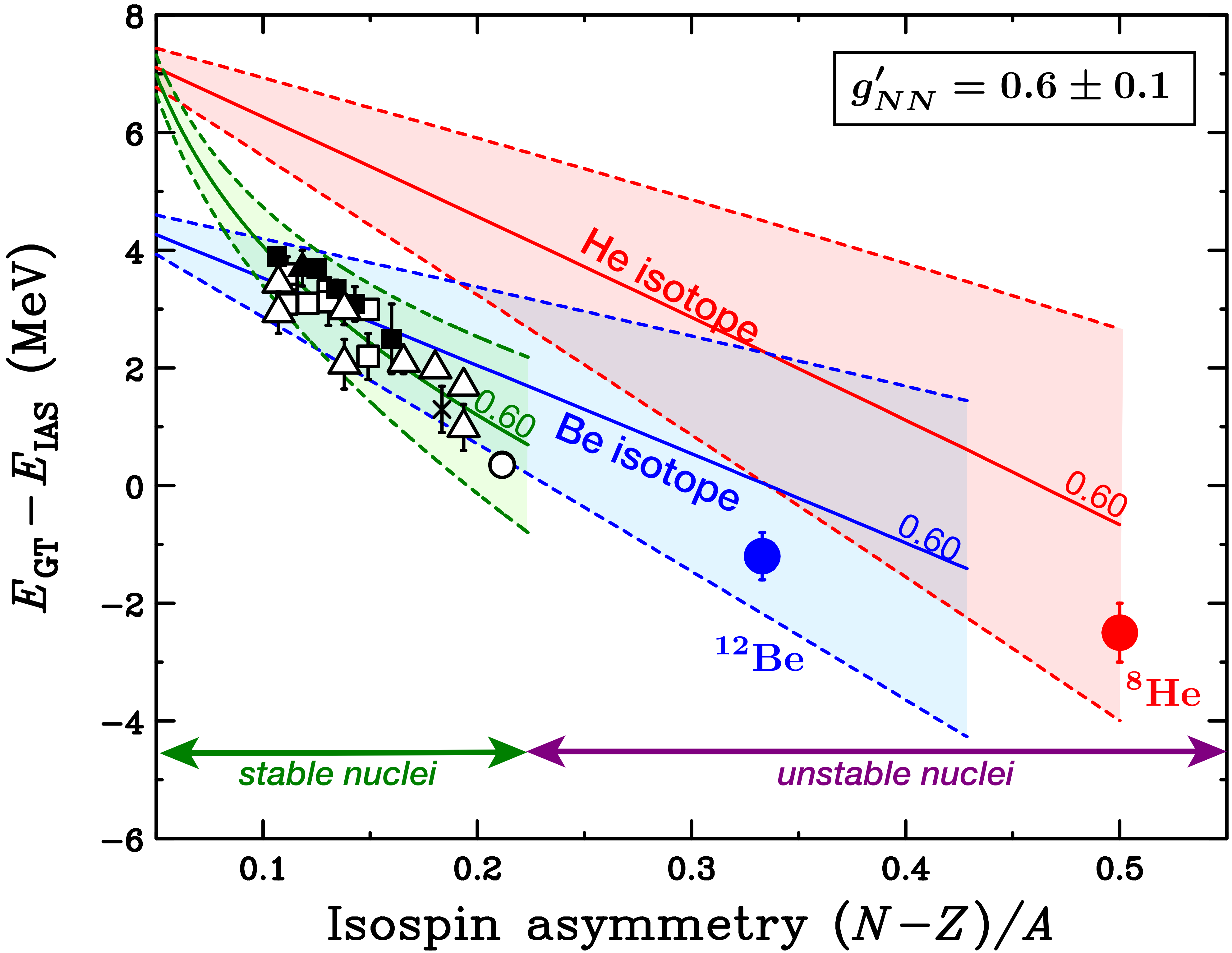
K. Yako (CNS) et al.



$E_{GT} - E_{IAS} = -1.2 \pm 0.5$ MeV

M. Kobayashi et al., JPS Conf. Proc. 1, 013034 (2014).
courtesy of K. Yako

Collectivity in (N-Z)/A > 0.21; Very neutron-rich nuclei



Data are consistent with predictions employing g'$_{NN}$=0.6±0.1

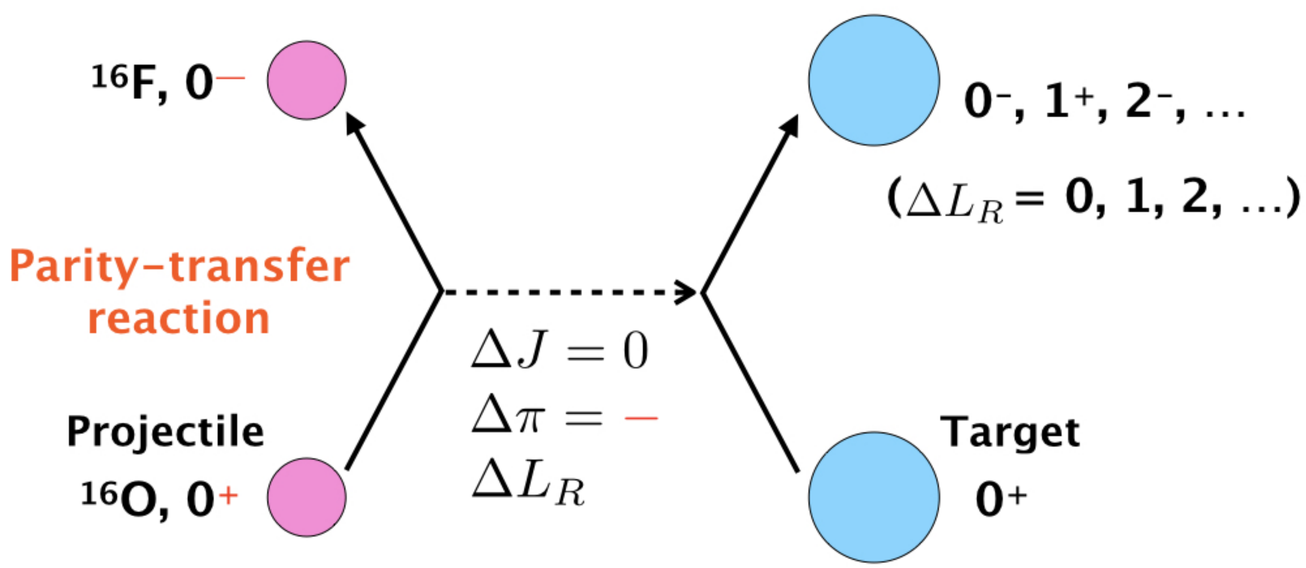
→ Suggests the constancy of residual interaction for up to (N-Z)/A=0.5 (very neutron-rich)

NEW reaction probe for pionic 0- state

courtesy of M. Dozono

Parity-transfer (^{16}O,^{16}F) reaction

- ^{16}O(g.s., 0^+) → ^{16}F(g.s., 0^-)
- Selective probe for pionic 0^- state



Different pattern depending on J^π

- NOT reproduced in PWBA
- Distortion effects are crucial

The parity-transfer (^{16}O, $^{16}F(0^-, g.s.)$) reaction as a probe of isovector 0^- states in nuclei

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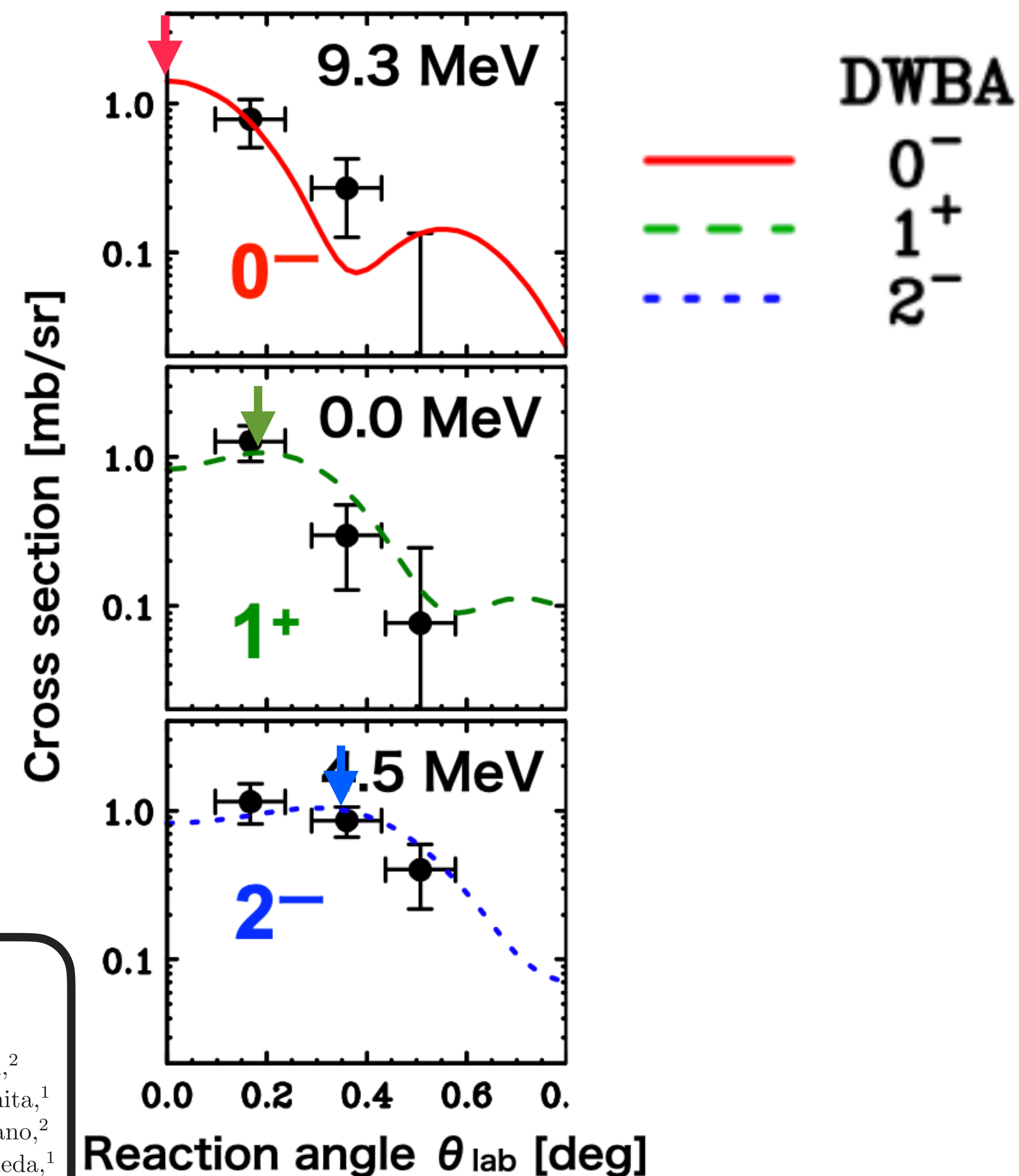
^{12}C(^{16}O,^{16}F) exp. @RIBF



Ichimura-san's legacy will live on

Ichimura-san's work laid the grounds for

- *the unified understanding of spin-isospin responses*
- *the analysis of experimental data using his computer codes*
  - CRDW : DWIA calculation
  - RESPQ : Spin-isospin response calculation

Computer Programs

CRDW

by M.Ichimura

CRDW is the abbreviation for Continuum RPA + DWIA. This is a computer program, which perform a DWIA calculation for the nucleon induced inelastic and charge exchange reactions to continuum final states as well as discrete states.

- Manual (PDF/259kb)
- Formalism (PDF/211kb)
- Source codes (243kb)

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RESPQ

by M.Ichimura

RESPQ is a computer program, which calculate the isovector spin-scalar, and spin-vector response functions of nuclei as a function of the transferred momentum q and energy ω including Δ isobar degrees of freedom.

- Manual (PDF/262kb)
- Source codes (65kb)