Gamow-Teller and Spin-Dipole Transitions Studied by $^{12}C(p,n)^{12}N$ Polarization Measurements

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(RCNP E256 and E317 Collaborations)

Contents

- Gamow-Teller $^{12}N(1^{+})$ excitation by $^{12}C(p,n)$
  - Pionic correlation effects at large momentum transfers
    - Precursor of pion condensation
  - Rho-mesonic correlation effects

- Spin-Dipole transitions by $^{12}C(p,n)^{12}N$
  - Spin-parity structure of SDR at 7 MeV
    - 2^{-} or 1^{-}
    - Tensor force effects (1^{-}: fragmented ?)
  - Search and indentify 0^{-} state
    - Clear evidence of 0^{-}

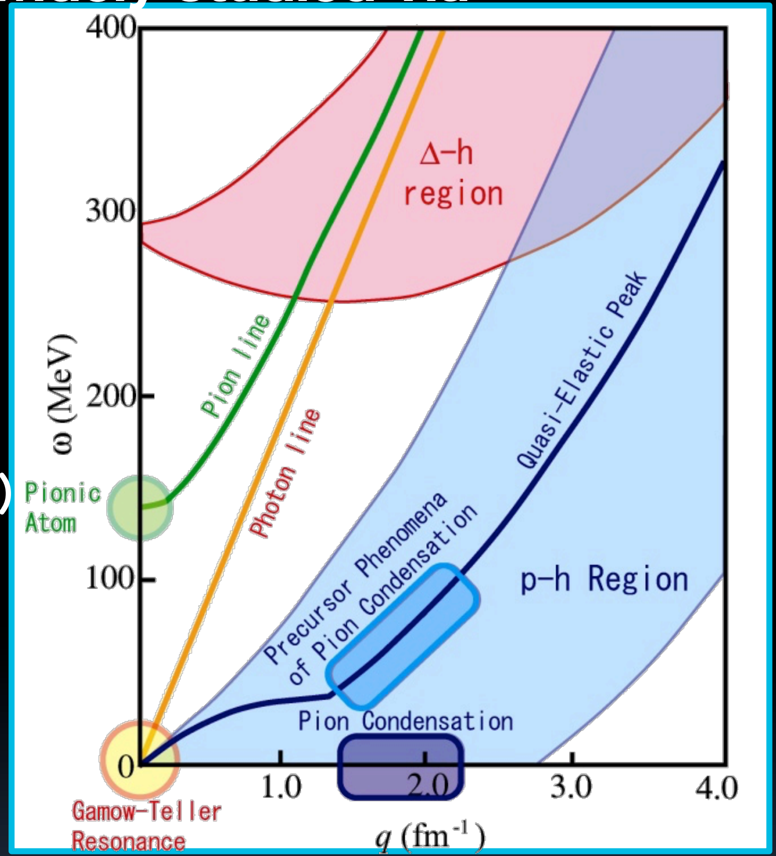
Emphasis on recent experimental data for polarization observables

Pionic Correlations in Gamow-Teller $^{12}C(p,n)^{12}N(1^+)$

Spin-Isospin Modes in Nuclei

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

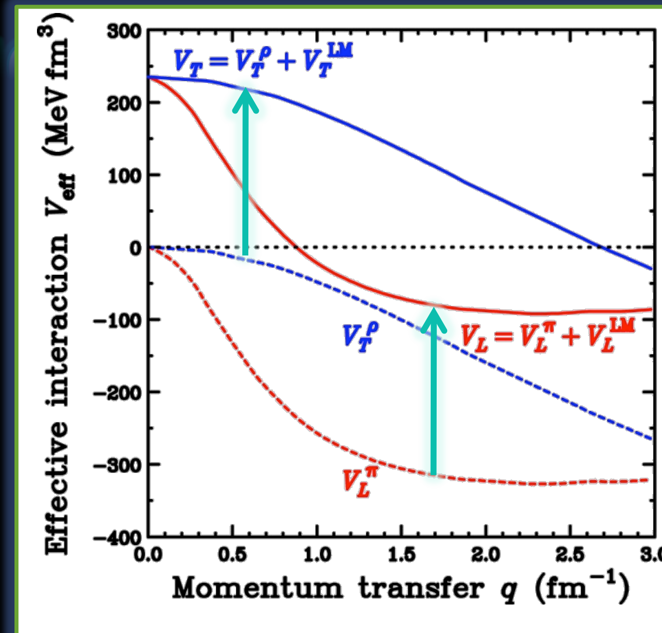
- **Spin-isospin responses have been widely studied via**
  - GT/M1 at q~0 and small ω
    - (p,n) , (^{3}He,t) , (p,p')
  - SDR at small q and small ω
    - (p,n) , (d,^{2}He)
  - QES at large q (1-2 fm^{-1}) and medium ω
    - (p,n)
  - Spin-longitudinal at wide q and small ω
    - (p,n), (p,p') (Dispersion matching)
  - Pionic atoms at small q and large ω (m_π)
    - (d,^{3}He), (p,^{2}He)



- **In progress**
  - GT at small q and medium ω
    - ICHOR/SHARAQ at RIBF by U-Tokyo

Goal: Understand spin-isospin responses in wide (q,ω) in a unified way
✓*Pionic and rho-mesonic correlations in nuclei*
✓*Tensor correlations in nuclei*

Nuclear Correlations and Δ Effects



- Effective Interaction

$$V_{\rm eff} = V_L + V_T$$

Longitudinal (π) Transverse (ρ)

- $\pi + \rho + g'$ model
  - Spin-longitudinal $V_L = V_L^\pi + V_L^{\rm LM}$
  - Spin-transverse $V_T = V_T^\rho + V_T^{\rm LM}$
- NN(p-h) effective Interaction

$$V_L(q,\omega) = \frac{f_{\pi NN}^2}{m_\pi^2}\left(\underbrace{\frac{q^2}{\omega^2 - q^2 - m_\pi^2}\Gamma_{\pi NN}^2}_{\pi\text{-exchange}} + \underbrace{g'_{NN}}_{\text{Short-range repulsion}}\right)(\tau_1\cdot\tau_2)(\sigma_1\cdot\hat{q})(\sigma_2\cdot\hat{q})$$

$$V_T(q,\omega) = \frac{f_{\pi NN}^2}{m_\pi^2}\left(\underbrace{C_\rho\frac{q^2}{\omega^2 - q^2 - m_\rho^2}\Gamma_{\rho NN}^2}_{\rho\text{-exchange}} + g'_{NN}\right)(\tau_1\cdot\tau_2)(\sigma_1\times\hat{q})(\sigma_2\times\hat{q})$$

- Extension to N+Δ system for LM interaction

$$V_{N\Delta}^{\rm LM} = \frac{f_{\pi NN} f_{\pi N\Delta}}{m_\pi^2} g'_{N\Delta}$$

^{90}Zr(p,n)^{90}Nb *(Gamow-Teller)*
$$g'_{NN} = 0.6 \pm 0.1$$
$$g'_{N\Delta} = 0.35 \pm 0.16$$

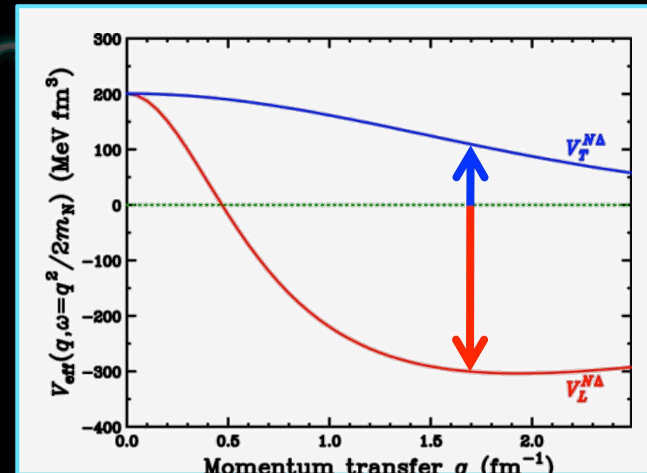
Pionic Enhancement in QES

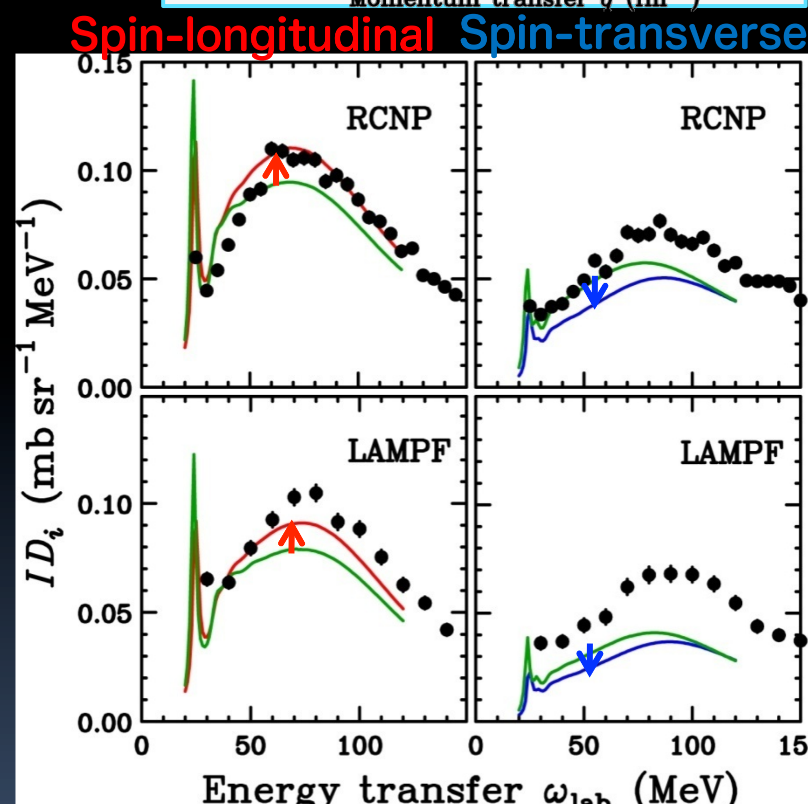
- Effective interaction at large q
  - Attractive spin-longitudinal V_L
    - Especially for NΔ with small $g'_{N\Delta}$
- Quasi-elastic scattering at large q
  - Spin-longitudinal (π) mode
    - **Enhancement** by attractive π-corr.
  - Spin-transverse (ρ) mode
    - **Quenching** by repulsive ρ-corr.
- RCNP/LAMPF data on ^{12}C at $q=1.7 fm^{-1}$
  - Spin-longitudinal mode
    - Exp. = RPA > Free (w/o corr.)

Pionic enhancement/correlations in nuclei

  - Spin-transverse mode
    - Exp. > Free > RPA

Attractive rho-mesonic correlations?





T.N.Taddeucci et al., PRL 73,3516(1994).
T.W. et al., PRC 59,3177(1999).

New Experiments for Pionic Correlations

- **Results of quasi-elastic scattering**
  - Enhancement of spin-longitudinal OK
  - Quenching of spin-transverse NG
  - Is Enhancement really due to attractive pionic correlations ?
    - Spin-longitudinal/transverse modes were separated with D_{ij}
    - Simple reaction mechanism was assumed

  → More systematic data desired

- **New experiments at RCNP**
  - Measure D_{ij} of $^{12}C(p,n)^{12}N(1^+,T=1)$ ··· RCNP-E256
    - $q=0\sim2.0\ fm^{-1}$
    - Separation to spin-longitudinal/transverse modes can be checked by q-dependence

Research Center for Nuclear Physics Osaka University

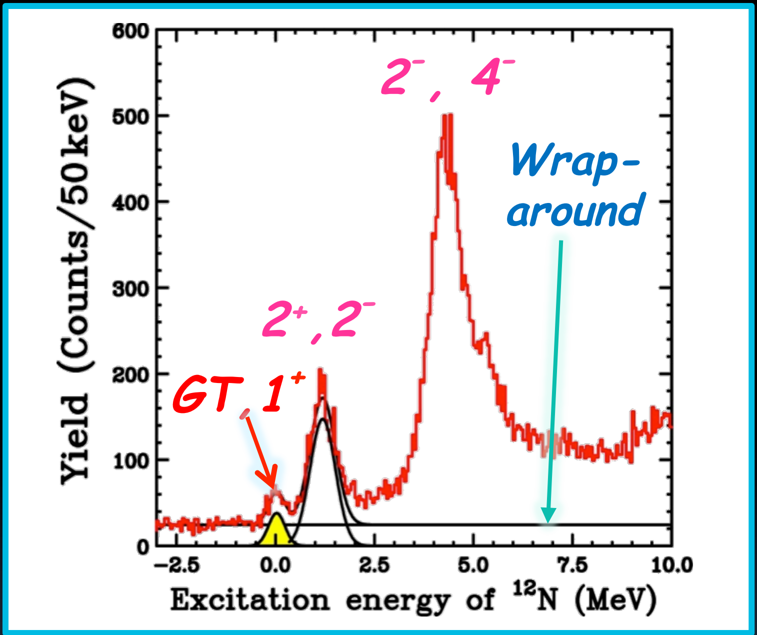
Thanks to M. Dozono

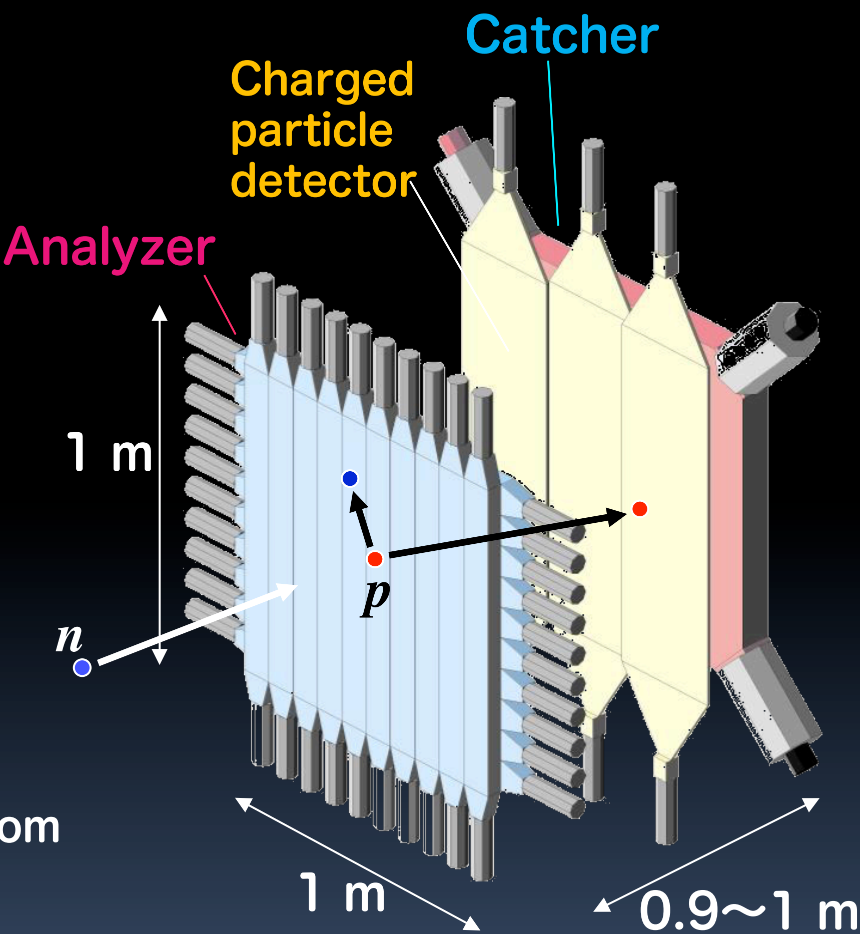
- 295 MeV Polarized protons
  - Predominantly excite GT and SDR
- Beam polarization
  - Control with 2-sets of solenoids
  - Measure with 2-sets of BLP by p-p
- Beam swinger
  - Cover q=0.1-2.0 fm^{-1}
- Neutron measurement
  - NPOL3 with 100 m TOF
  - Complete measurement of neutron polarization with NSR

Neutron Detector/Polarimeter NPOL3

T. W., Y. Hagihara et al., Nucl. Instrum. Methods Phys. Res. A 547 (2005) 569.

- **Setup**
  - *Analyzer* : 20sets of 1-dim. position-sensitive counters (hodoscopes)
  - *Catcher* : 2-dimensional position-sensitive counter
- **Neutron detector mode**
  - High energy resolution ~500 keV





- **Neutron polarimeter mode**
  - Neutron polarization is determined from asymmetry of *n* + *p* events
  - High performance FOM=1.0×10^{-4}

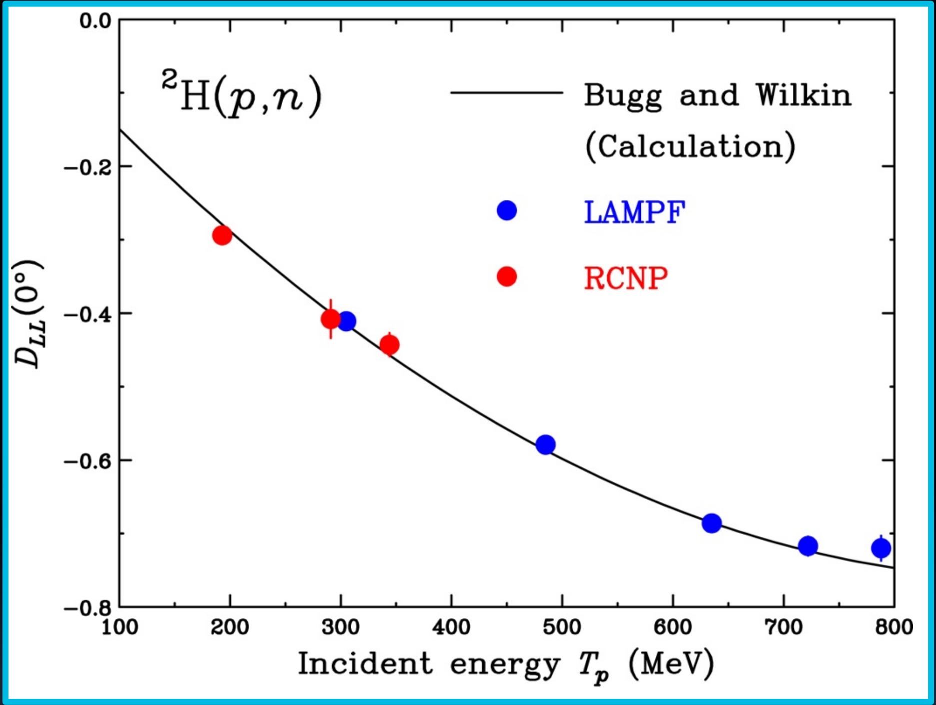
Accuracy of Polarization Data

T.W., E.Ihara et al., PRC 77, 054611 (2008).

- $^2H(p,n)^2He$ at 0deg.
  - Reliable theoretical calculations
  - Reliable experimental data

Benchmark reaction
⇒ accuracy of polarization data

- Theoretical calculations
  - Including deuteron D-state
  - Including p-p FSI (^2He)
- LAMPF data
  - Consistent with calculations
  - Calculations are reliable
- RCNP data
  - Consistent with LAMPF data and calculations

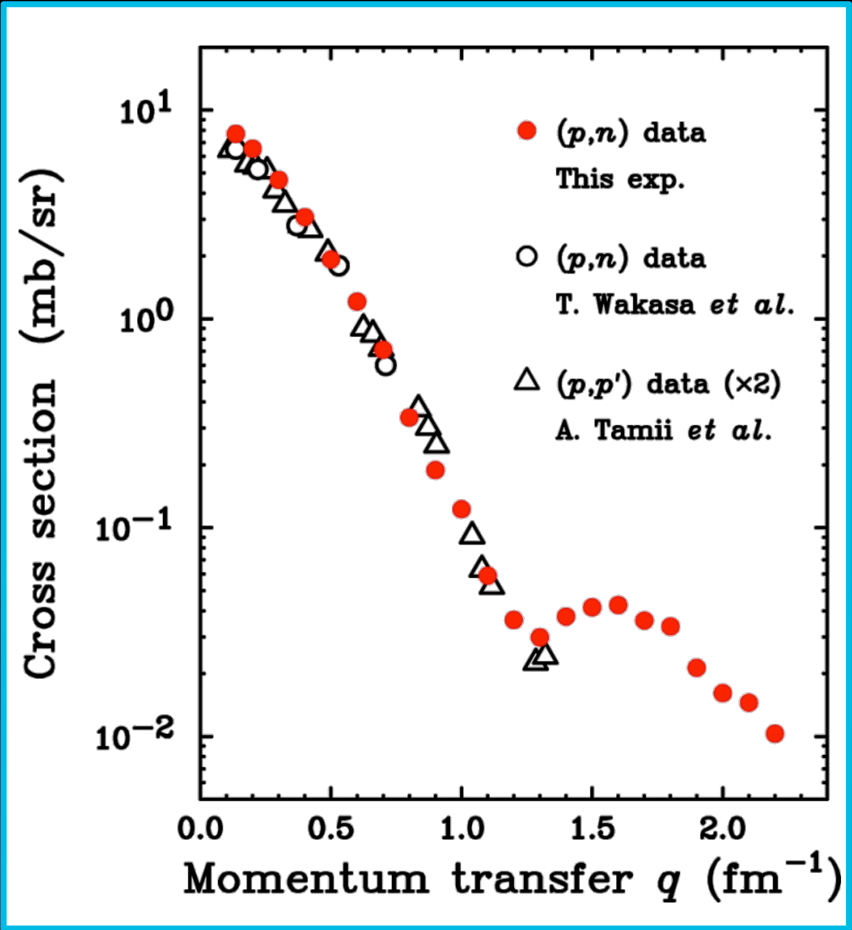


Our polarization data are reliable and accurate within 3%

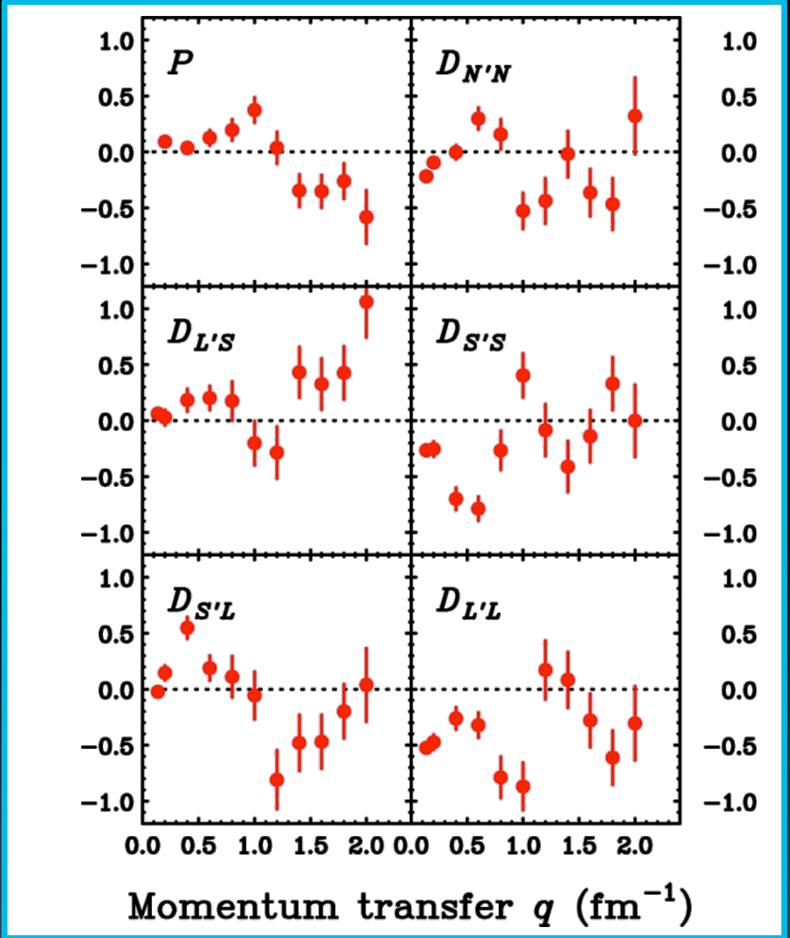
D.V. Bugg and C. Wilkin, NPA 467,575(1987)
M.W.McNaughton et al., PRC 45,2564(1992)

Results ~ *I* and D_{ij} ~

- **Cross section *I***
  - Smooth angular distribution over wide *q*-region $q = 0.1 \sim 2.2\ \mathrm{fm}^{-1}$
  - Consistent with previous data



- **Polarization transfers D_{ij}**
  - First complete measurement for wide q



Pionic Enhancement in $^{12}C(p,n)^{12}N(1^+,T=1)$

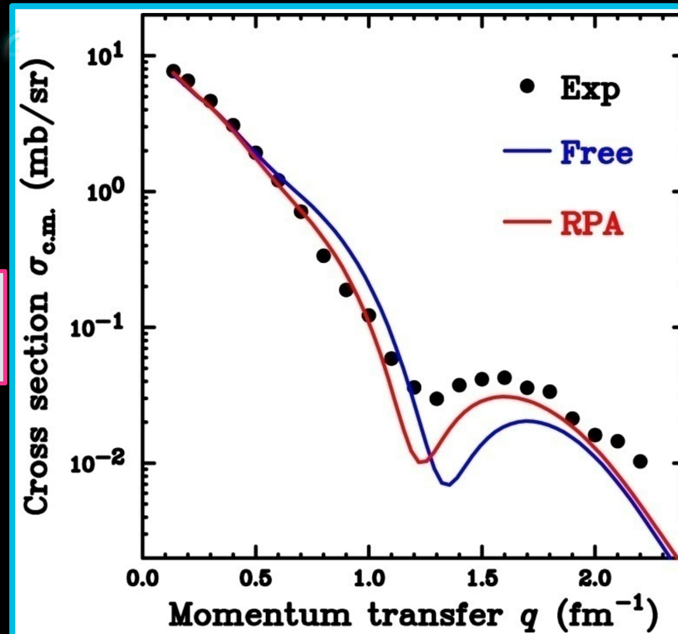
M.Dozono, T.W., et al., PLB 656(2007)38.

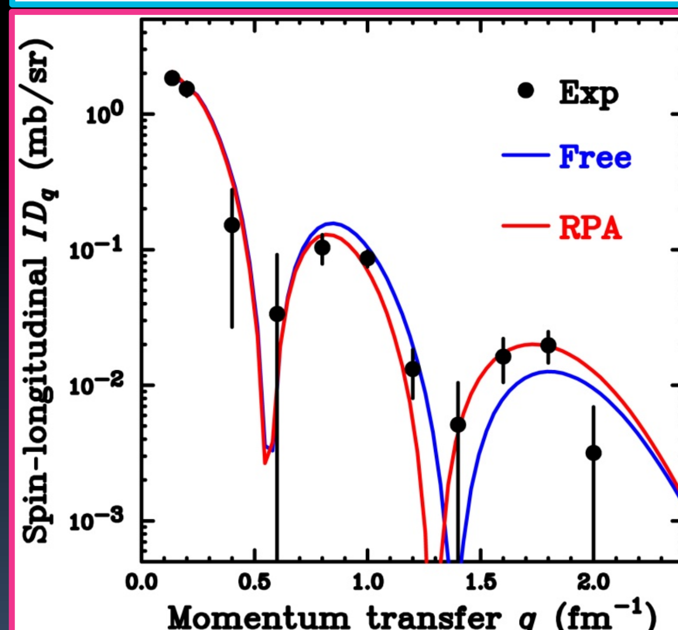
- Polarized cross section
  - $ID_q = KN\,|E|^2\,R_q$
  - $ID_p = KN\,|F|^2\,R_p$

Separation of π/ρ-mode with PTO is reliable

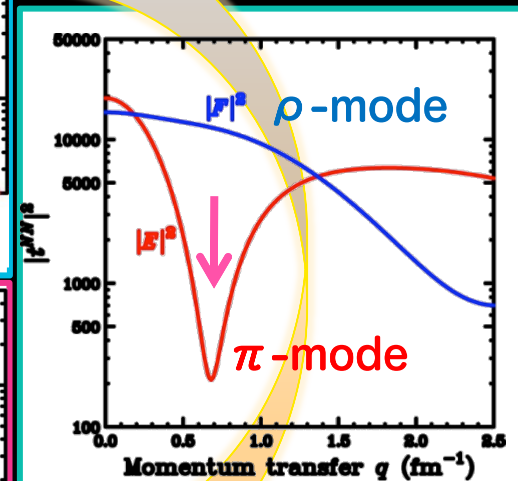
- Comparison with Free
  - Significant enhancement
- Comparison with RPA
  - g's are the same as those in QES
    - Parameter-free
  - Predict enhancement of the 3rd peak

This data ALSO supports pionic enhancement
⇒ What about ρ-mode?





Extract Spin-longitudinal (π) with PTO



Nuclear Correlations in $^{12}C(p,n)^{12}N(1^+)$

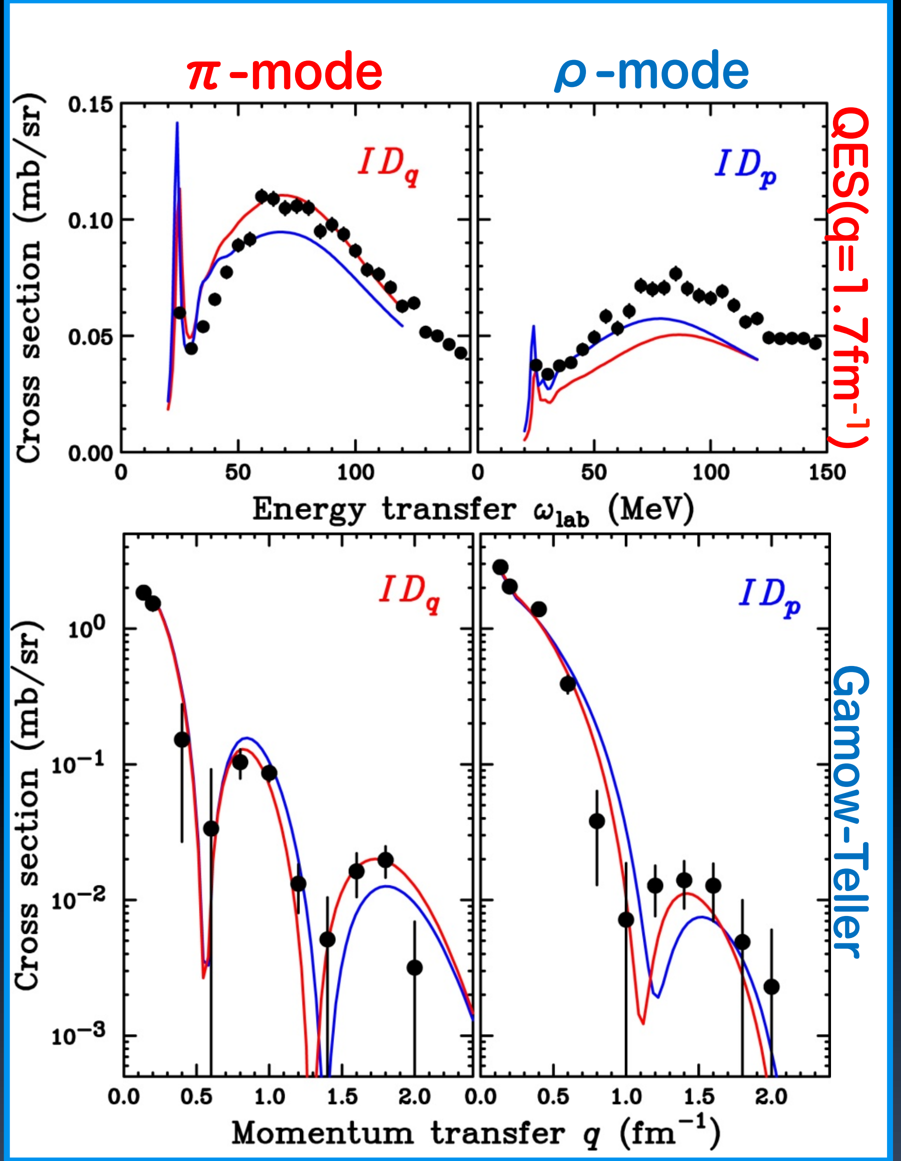
- Theoretical prediction
  - Blue : w/o correlations
  - Red : w/ correlations
    - B(GT) is normalized at q=0
      → g' effects have been excluded for the GT case
- π-mode
  - At large q
    - Exp. = RPA > Free(w/o corr.)

Attractive π-corr. at large q

- ρ-mode
  - At large q
    - Exp. > RPA > Free(w/o corr.)

Suggest attractive ρ-corr. at large q

> ➢ Spin-transverse in (e,e') ?
> ➢ Systematic understanding ?



Short-Range Tensor Correlations

- **Spin-transverse (e,e') response**
  - Enhancement from RPA
    - Higher-order (2p2h) effects
    - MEC (Negligible in some calculations)
- **Different g' for π and ρ-modes**

$$g'_\pi(\sigma_1\cdot\hat{q})(\sigma_2\cdot\hat{q}) + g'_\rho(\sigma_1\times\hat{q})(\sigma_2\times\hat{q})$$

Longitudinal (π) — Transverse (ρ)

$$= [g' - 2h'](\sigma_1\cdot\hat{q})(\sigma_2\cdot\hat{q}) + [g' + h'](\sigma_1\times\hat{q})(\sigma_2\times\hat{q})$$

$$= g'\sigma_1\cdot\sigma_2 + h' S_{12}(q)$$

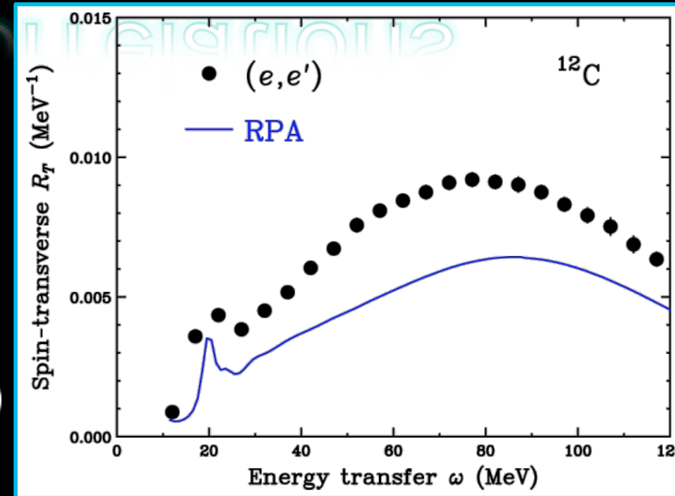
Central — Short-range tensor

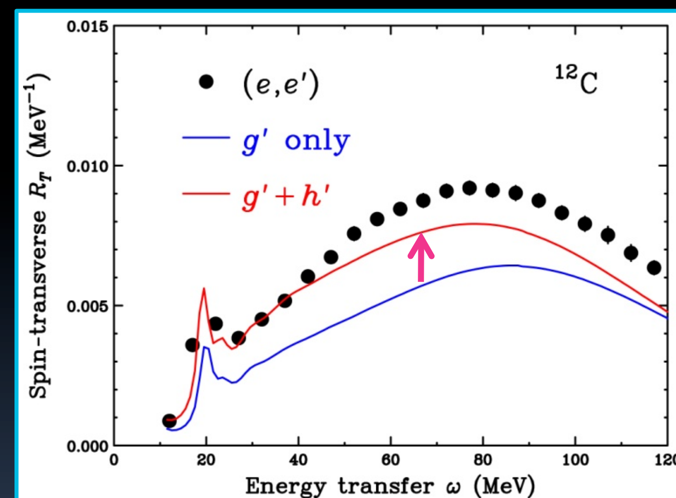
- **Short-range tensor h'**

  Spin-Longitudinal (π) $g'_\pi = g' + 2h'$

  Spin-Transverse (ρ) $g'_\rho = g' - h'$

  - h' effects are limited at large q
  - h' effects are attractive for ρ-mode





Reasonably reproduce (e,e') response
with short-range tensor h'
(Under-estimation at large ω would be 2p2h effets)

C.J.Horowitz et al., PRC 50,2540(1994).
M.Ichimura et al.,PPNP 56,446(2006).

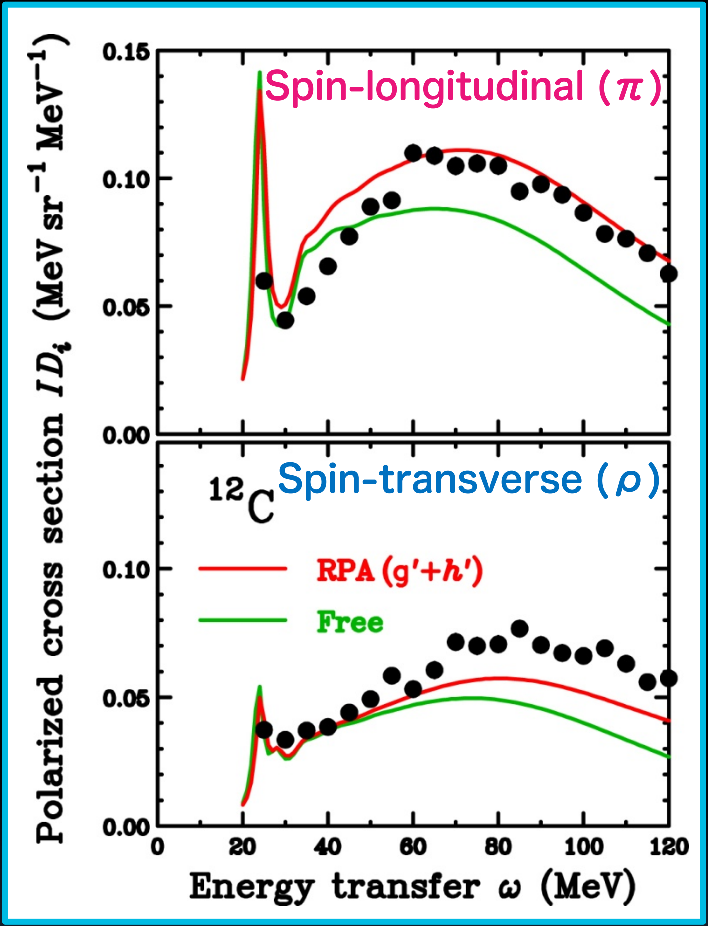
DWIA with Short-Range Tensor Correlations

- Short-range tensor h'
  - Determined by (e,e') response
    - Include Higher-order (2p2h)
  - Parameter-free calc.
- Spin-longitudinal (π) mode
  - g' values are adjusted within errors
    - $g'_{NN}=0.6\rightarrow0.5$
    - $g'_{N\Delta}=0.35\rightarrow0.2$

π + g' (less repulsive)+ h'(repulsive)
→ Net attractive effects for π-mode
→ Enhancement of π-mode

- Spin-transverse (ρ) mode

ρ +g'(less repulsive) + h'(attractive)
→ Repulsive effects by g' are cancelled by h'
→ Weak enhancement of ρ-mode



Short-range tensor correlations can provide better description for QES at large q
✓ Discrepancy at large ω (Higher-order effects not included by h'?)
✓ h' treatment for higher-order effects is reasonable ?
✓Calculations for $^{12}C(p,n)^{12}N(1^+,GT)$ are now in progress

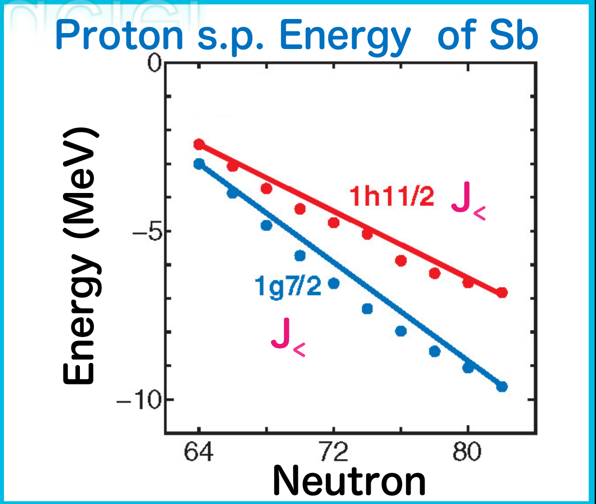
Spin-Dipole Transitions in $^{12}C(p,n)^{12}N$

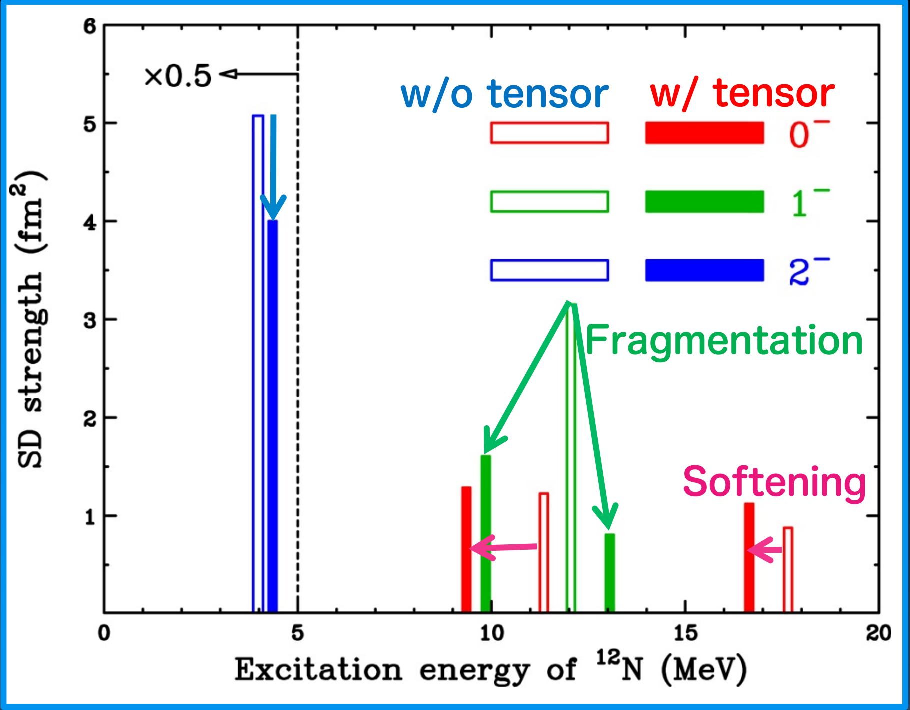
Tensor Force Effects in Nuclei

T.Otsuka et al.,PRL 95,232502(2005).

- Tensor force
  - NN int. is originally due to meson exchange
  - Tensor force is a manifestation of meson exchange
- Shell-structure due to tensor force
  - Due to tensor correlations, excess neutrons ($j_>$)
    - Pull-up proton-orbit with $j_>$
    - Pull-down proton-orbit with $j_<$
  - Experimental data for Sb are well reproduced
- Tensor force effects on SD
  - Attractive effects for $J^\pi=0^-,2^-$
  - Repulsive effects for $J^\pi=1^-$

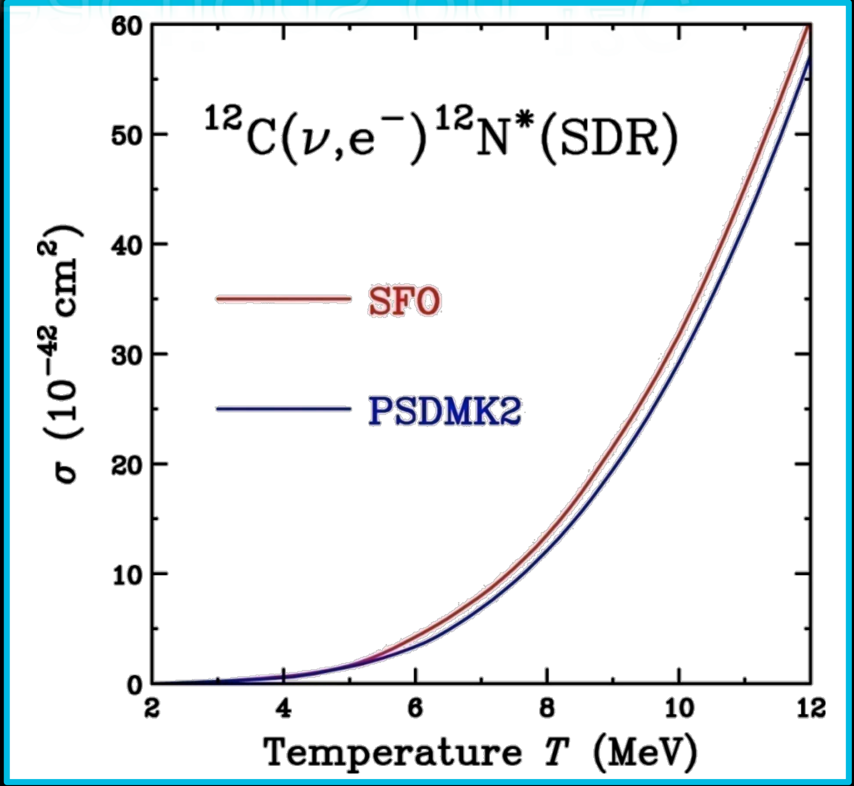
✓1^- strengths are fragmented
✓0^- strength is concentrated at 9 MeV





Neutrino-Induced Reactions on ^{12}C

T.Suzuki et al.,PPNP 59,486(2007).



- ^4He, ^{12}C, ^{16}O
  - Major stellar burning shells
  - Neutrinos will pass and excite
- SD excitations by neutrinos
  - $^{12}C(\nu,e^-)^{12}N^*(SDR)$
    - $^{12}N^*(SDR) \rightarrow {}^{11}C+p$
    - $^{12}N^*(SDR) \rightarrow {}^{11}N+n$
  - $^{12}C(\nu,\nu')^{12}C^*(SDR)$
    - $^{12}C^*(SDR) \rightarrow {}^{11}B+p$
    - $^{12}C^*(SDR) \rightarrow {}^{11}C+n$
  - Decay p/n contribute to nucleosynthesis
- Theoretical predictions
  - SD excitations are “enhanced” for SFO compared with PSDMK2

Detailed “experimental” information on SD distributions are important

J^π Components of SDR in ^{12}N

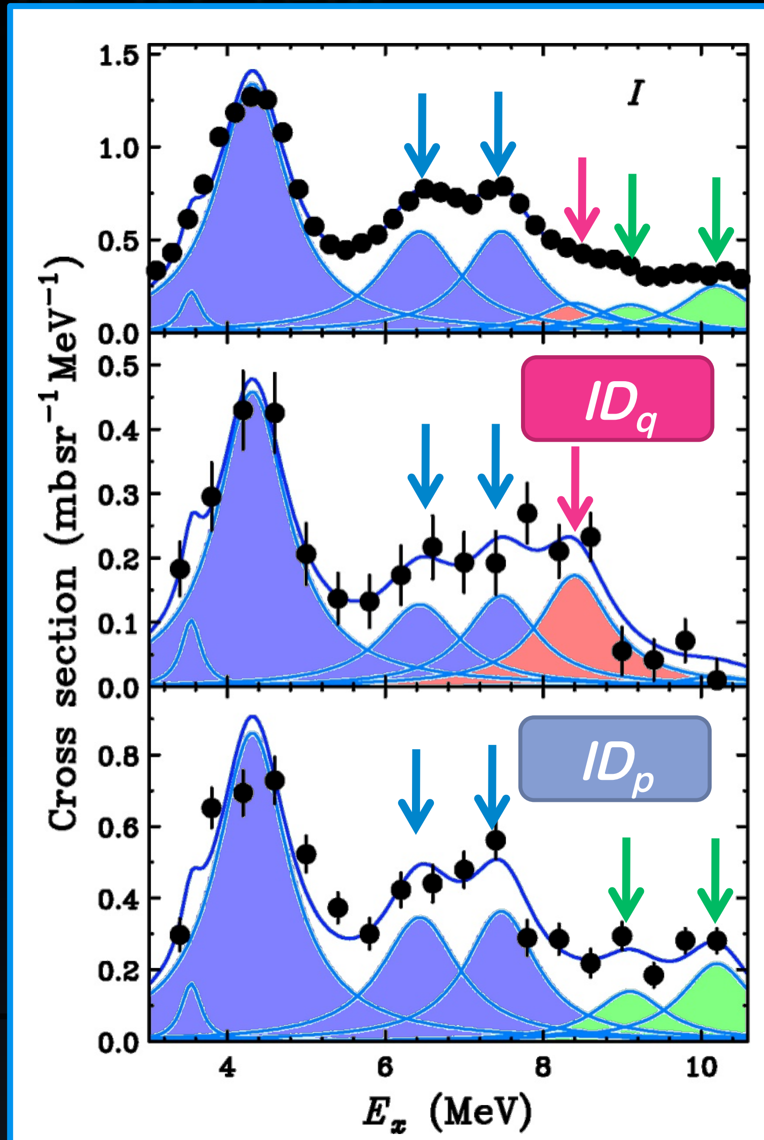
M. Dozono, T.W., et al., J. Phys. Soc. Jpn. 77, 014201 (2008).

- **Sensitive to J^π of SDR**

J^π	ID_q	ID_p
0^-	I	0
1^-	0	I
2^-	$0.4I$	$0.6I$

- E_x = 4.3 MeV (known 2^-)
  - ID_q and ID_p → 2^-
- E_x = 6.4 and 7.5 MeV
  - ID_q and ID_p → 2^- (dominant)
  - Consistent with (d,^{2}He), (^{12}C,^{12}N)
- E_x = 8.4 MeV
  - ID_q only → 0^- (dominant)
  - 1st clear observation
- E_x = 9.1 and 10.2 MeV
  - ID_p only → 1^- (dominant)

Dominant 2^- → Missing 1^- ?



Spin-Parity Composition of 7 MeV SDR

- 1^- is dominant
  - Cross sections in $^{12}C(p,n)^{12}N$
    - *B.D. Anderson et al., Phys. Rev. C 54, 237 (1996).*
    - *X. Yang et al., Phys. Rev. C 52, 2535 (1995).*
      - Contribution from "non-spin-flip" 1^- dipole
  - Particle decays in $^{12}C(d,^2He)^{12}B$ and $^{12}C(^3He,t)^{12}N$
    - *T. Inomata et al., Phys. Rev. C 57, 3153 (1998).*

- 2^- is dominant
  - Tensor analyzing power in $^{12}C(d,^2He)^{12}B$
    - *H. Okamura et al., Phys. Lett. B 345, 1 (1995).*
    - *M.A. de Huu et al., PLB 649,35(2007).*
      - Higher excitation-energy part is 1^-
  - Cross sections in $^{12}C(^{12}C,^{12}N)^{12}B$
    - *T. Ichihara et al., Nucl. Phys. A 577, 93c (1994).*
  - Complete set of polarization observables in $^{12}C(p,n)^{12}N$
    - *M. Dozono, T.W., et al., J. Phys. Soc. Jpn. 77, 014201 (2008).*
      - ONLY at 0 degrees (SDR are dominant at 4-8 degrees)

Detailed "experimental" information (Ratio of 2^- to 1^-)are important

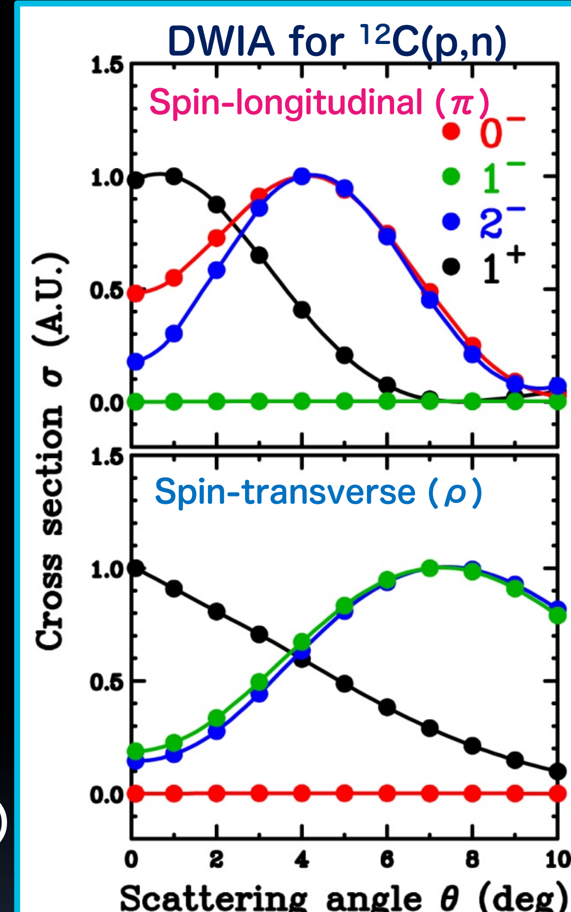
Separation of SDR into Each J^π

- Separation of SDR(L=1) into 0^-,1^-,2^- is important
  - Tensor effects depend on J^π
    - Missing 1- strength
  - Information on neutrino-induced reaction

- "Normal" multipole decomposition
  - Separate into each L component
    - Works very well to extract GT(L=0)
  - Could not separate into J^π with same L
    - Angular distributions are governed by L

- Idea to separate SDR into each J^π
  - Polarization observables are sensitive to J^π
  - Separate c.s. into longitudinal (π)-transverse (ρ)
    - 0^- : spin-longitudinal (π) only
    - 1^- : spin-transverse (ρ) only
    - 2^- : Both

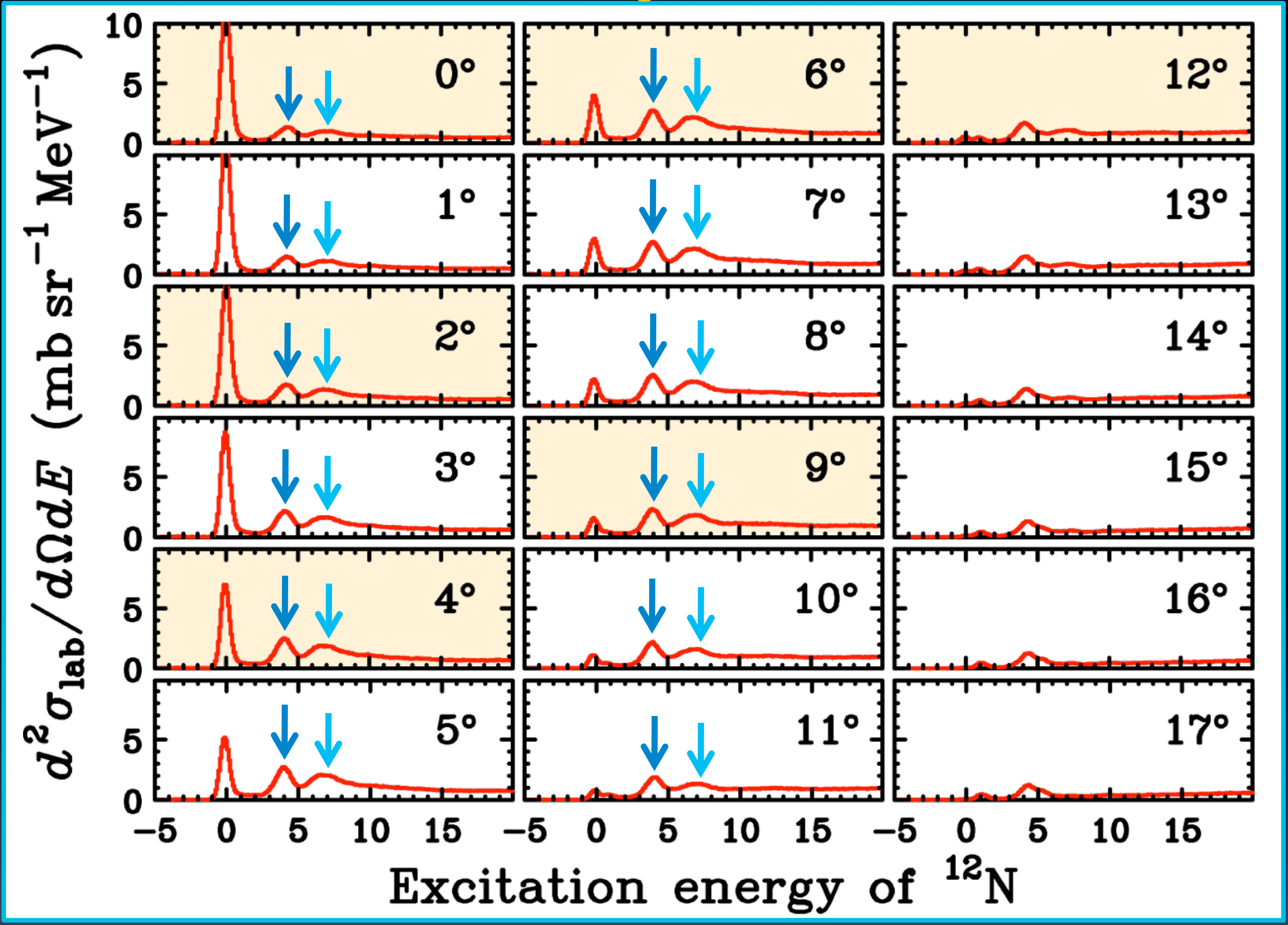
  } Easy to separate



Multipole decomposition for spin-longitudinal (π) and transverse (ρ) c.s.
→ Can separate/specify not only L, BUT ALSO J^π

New data from RCNP-E317

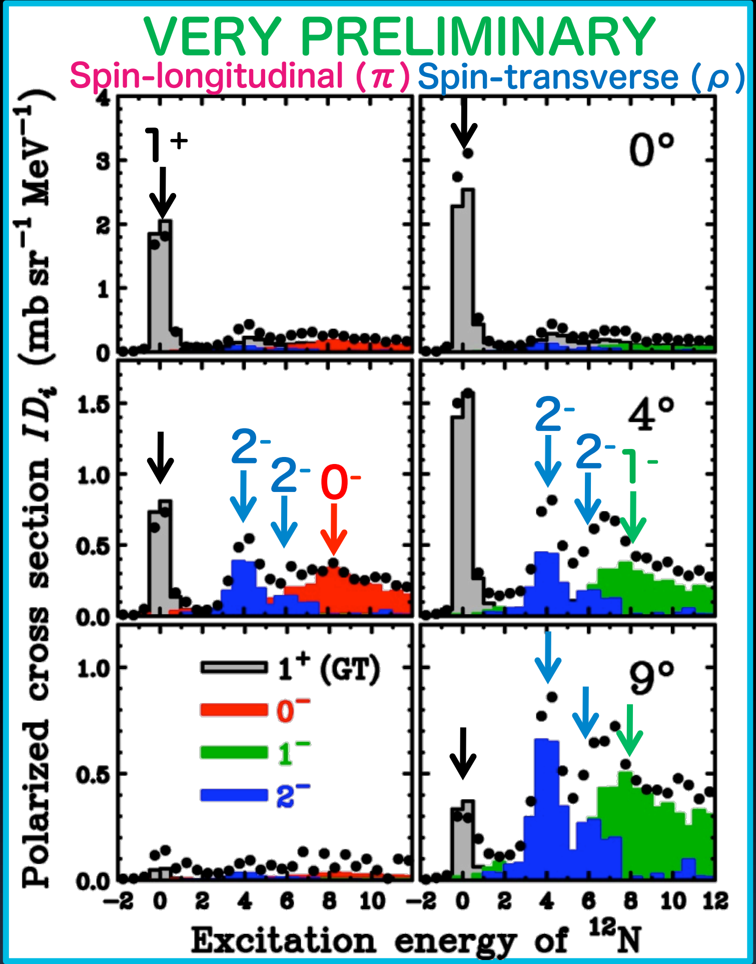
Complete sets of poarization observables have been measured at 0° ,2° ,4° ,6° ,9° ,12° (6 angles)



Challenge to Separate SDR into Each J^{π}

- Apply the new method to $^{12}C(p,n)$
  - High resolution $^{12}C(d,^{2}He)$ data are available
    - Can check the reliability
  - J^{π} for SDR at 7 MeV is still controversial
    - Information on tensor correlations

M.Dozono et al., RCNP-E317



- Preliminary results (with partial data)
  - Proper assignments for known states
    - GT at 0.0 MeV → 1^+
    - SDR at 4 MeV → 2^-
  - Identification of 0^-
    - Strength at 8 MeV → 0^-
  - Decomposition of SDR at 7 MeV
    - Lower-energy side : 2^-
    - Higher-energy side : 1^-

- Consistent with high res. $^{12}C(d,^{2}He)$
  - J^{π} decomposition seems to be reliable

Much more detailed analysis required,
But seems to be applicable to E_x > 10 MeV (continuum)

Experimental Study of SDR in ^{12}B

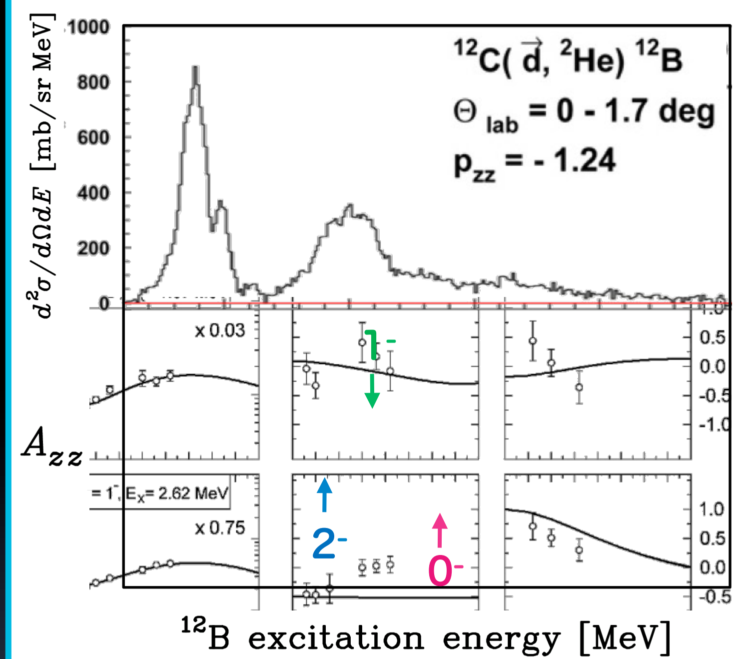
- Tensor effects depend on J^π
  - Selectivity is required
  - Tensor analyzing power A_{zz} of (d,^{2}He)

$$A_{zz}(0^\circ) = \begin{cases} -2 & \text{for } 0^- \\ +1 & \text{for natural parity} \end{cases}$$

- First measurement at RIKEN
  - 0^- is identified at 9.3 MeV
  - SDR at 7 MeV is mainly 2^-
- Later High-res. Measurement at KVI
  - Confirm 0^- at 9.3 MeV
  - Lower-part of SDR at 7 MeV is 2^-
  - Upper-part of SDR at 7 MeV is 1^-

(p,n) results are consistent with (d,^{2}He)
✓ Qualitatively consistent with calculations
✓ 1^- seems to be weak (fragmented ?)
→ Systematic analysis desired

KVI data
ΔE=130 KeV

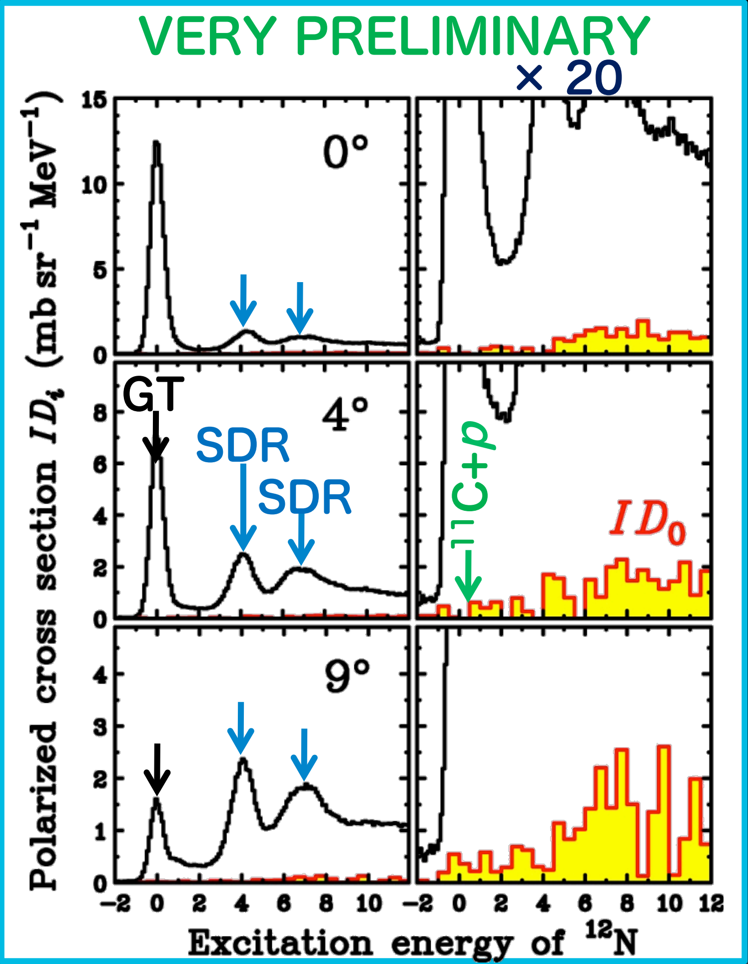


M.A. de Huu et al., PLB 649,35(2007).

Spin-Scalar Mode in $^{12}C(p,n)^{12}N$

M.Dozono et al.,
RCNP-E317

- Separate I into spin-scalar/vector
  - $I = ID_0 + ID_q + ID_n + ID_p$
    - ID_0 (spin-scalar)
      - $\Delta S=0$
    - ID_q, ID_n, ID_p (spin-vector)
      - $\Delta S=1$
- Very-weak excitation of ID_0
  - $ID_0 \leqq 0.05 \times I$ (less than 5%)
    - Predominant excitation of $\Delta S=1$
  - Physical B.G. of $\Delta S=0$ is small
- Information on $\Delta S=0$ mode
  - No concentration (resonance)
    - Continuum distribution from $^{11}C+p$
  - Less sensitive to $\Delta S=0$ (NOT conclusive)



Much more detailed analysis required,
But physical B.G. from $\Delta S=0$ is small as expected

Summary

- Pionic correlations in Gamow-Teller $^{12}C(p,n)^{12}N(1^+)$
  - Signature of pionic enhancements as a precursor of π- cond.
    - Consistent with DWIA+RPA employing $\pi+\rho+g'$
  - Attractive effects by rho-exchange at large q
  - Rho-mesonic mode is enhanced at large q
    - Short-range tensor effects
    - Medium effects (Modifications of NN interacton/t-matrix)

- Spin-Dipole transitions by $^{12}C(p,n)^{12}N$
  - 0^- state has been identified at 8.4 MeV
    - Roughly consistent with SM employing tensor int. (9 MeV)
    - $^{12}B(0^-)$ at 9.3 MeV
  - Spin-parity structure of SDR at 7 MeV
    - Lower-energy side : 2^-
    - Higher-energy side : 1^-
  - Strengths can be experimentally extracted via MDA
    - 0^-,1^-, and 2^- strengths will be extracted in E_x > 10 MeV
    - Comparison with sum-rule values

Acknowledgement

- Thanks to all collaborators involved with RCNP-E236, E256 and E317 experiments, in particular to
  - M. Dozono (Kyushu University)
    - *M. Dozono, T.W., et al., J. Phys. Soc. Jpn. 77, 014201 (2008).*
    - *M. Dozono T.W., et al., Phys. Lett. B 656, 38 (2007).*
  - E. Ihara (Kyushu University)
    - *E. Ihara, T.W., et al., Phys. Rev. C 77, 054611 (2008).*
    - *E. Ihara, T.W., et al., Phys. Rev. C 78, 024607 (2008).*
  - Y. Hagihara (Kyushu University)
    - *Y. Hagihara, T.W., et al., NIM A 547, 569 (2005).*

Thank you for your attention

Backup

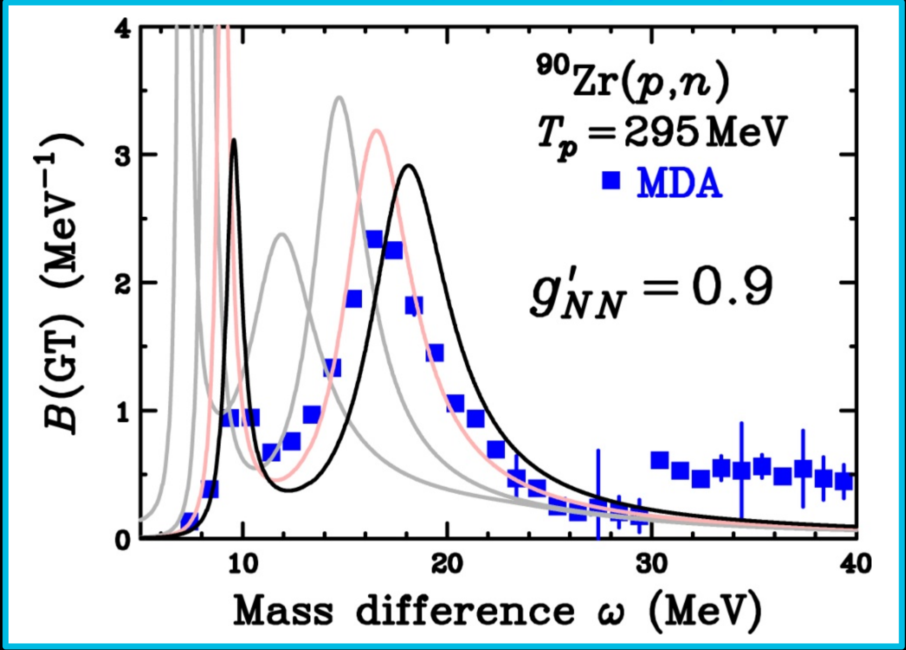
GT Strength and Landau-Migdal Parameters

K.Yako et al., PLB 615(2005)193.
T.W. et al., PRC 72(2005)067303.

- g' dependence on GTGR
  - RPA(1p1h) by Ichimura group
  - GTGR peak position
    - Strongly depends on g'_{NN}

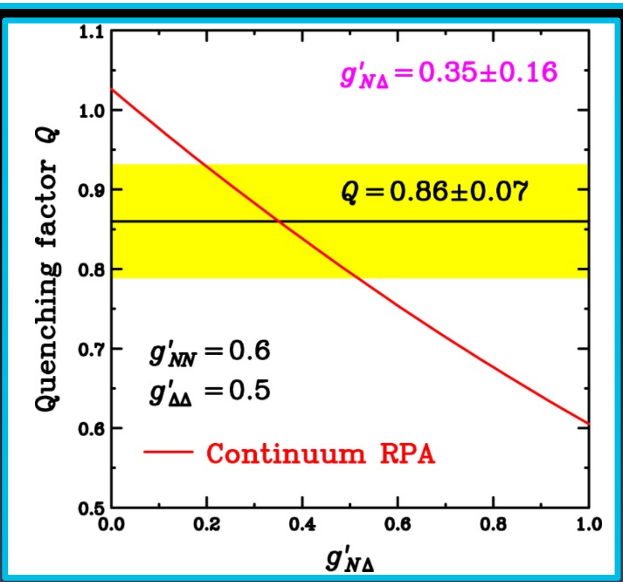
$$g'_{NN} = 0.6 \pm 0.1$$

    - Weak $g'_{N\Delta}$ dependence



- $g'_{N\Delta}$ dependence on GT quenching Q
  - Q=0.86±0.07 (*quadratic sum of errors*)
  - Q evaluated in RPA
    - Strongly depends on $g'_{N\Delta}$

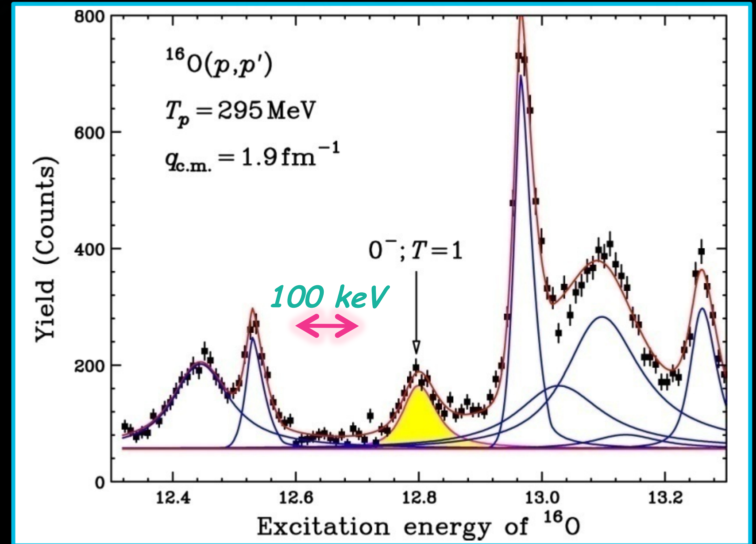
$$g'_{N\Delta} = 0.35 \pm 0.16$$

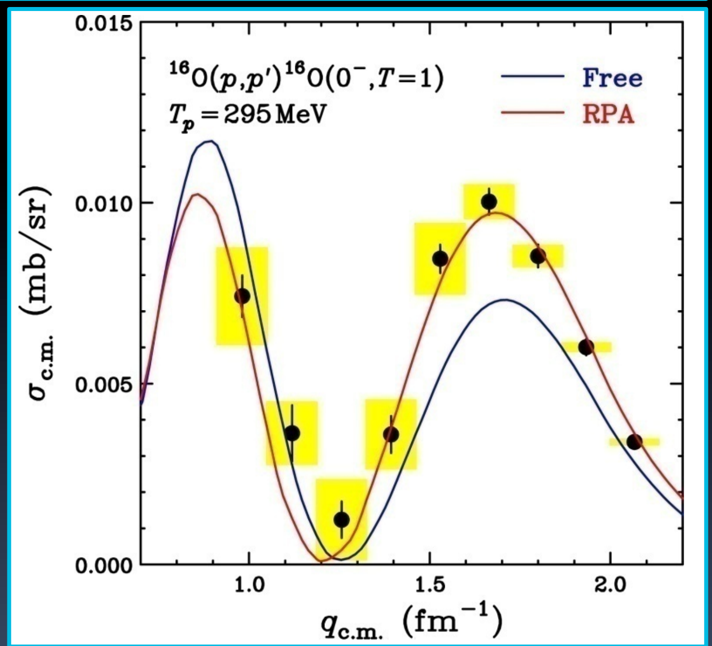


Pionic Enhancement in $^{16}O(p,p')^{16}O(0^-,T=1)$

T.W. et al., PLB 632(2007)485.

- **Isovector $J^\pi=0^-$ excitations**
  - Carry π-like quantum number
  - Pure information on pionic mode
- **Experiment: $^{16}O(p,p')^{16}O(0^-,T=1)$**
  - ΔE=30 keV with WS+GR
  - $q_{c.m.}$ = 0.9 – 2.1 fm^{-1}
- **Comparison with Theory**
  - — Without correlation (Free)
    - Significant enhancement
  - — With RPA correlation
    - g's are the same as those in QES
      - Parameter-free calculations
    - Predict the enhancement of the 3rd peak (q=1.7fm^{-1})





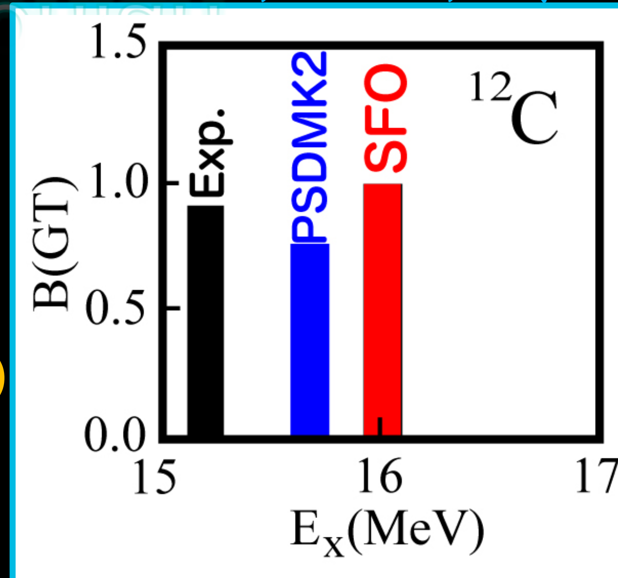
The data supports pionic enhancement
Signature of precursor for pion condensation in pure pionic mode

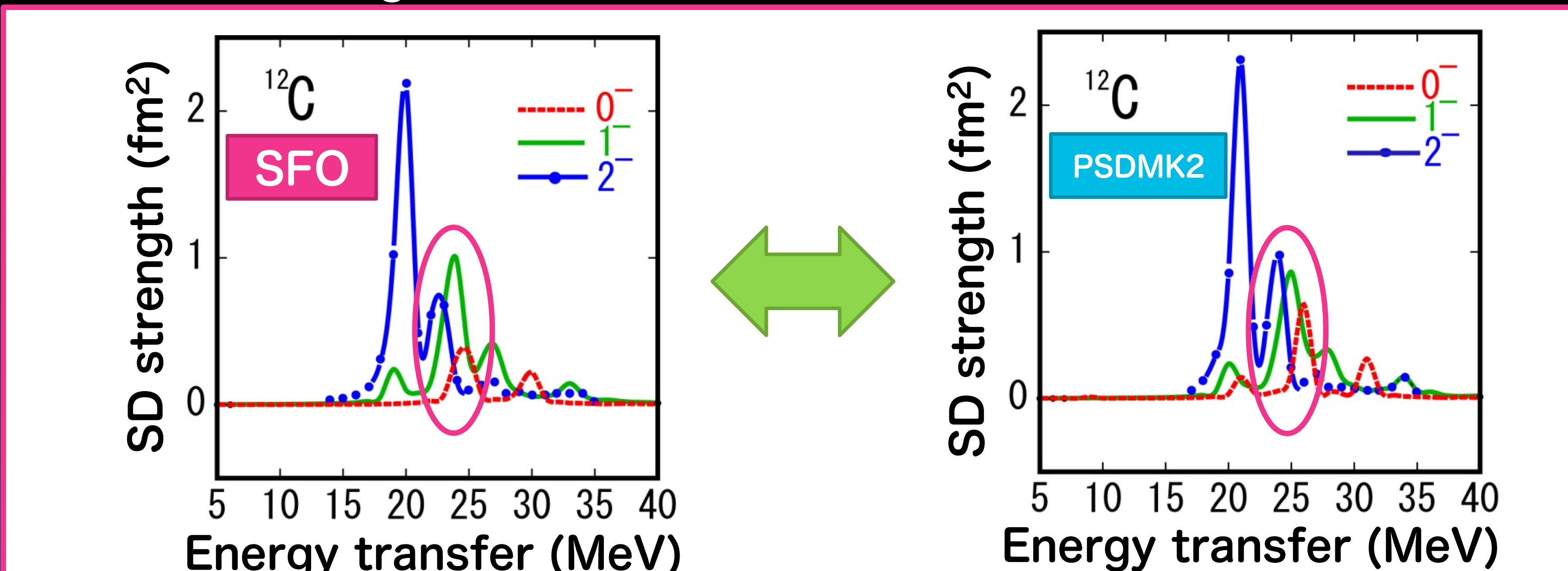
New Shell-Model Hamiltonian

- SFO Shell-Model Hamiltonian
  - By T.Suzuki, R.Fujimoto, and T.Otsuka
  - Modified tensor components

- Comparison with conv. SM (PSDMK2)
  - Better description of B(GT) for $^{12}N(1^+)$
  - Different prediction for 2nd SDR
    - 1^- strength is dominant
    - 0^- strength is weak

T.Suzuki et al.,PPNP 59,486(2007).



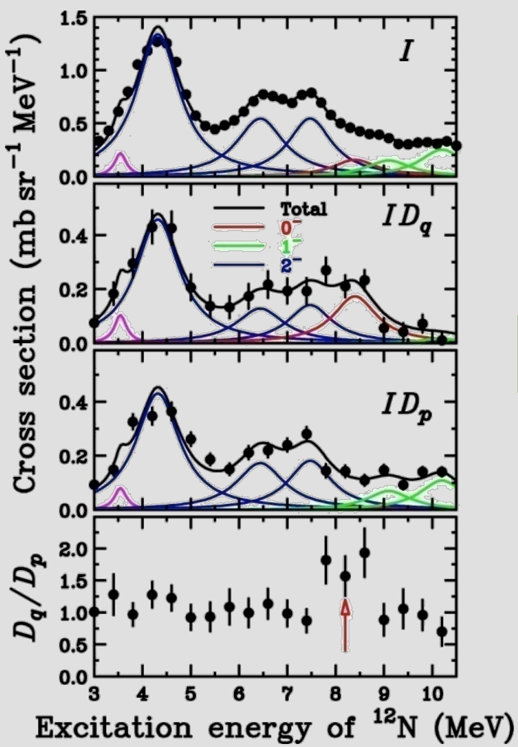


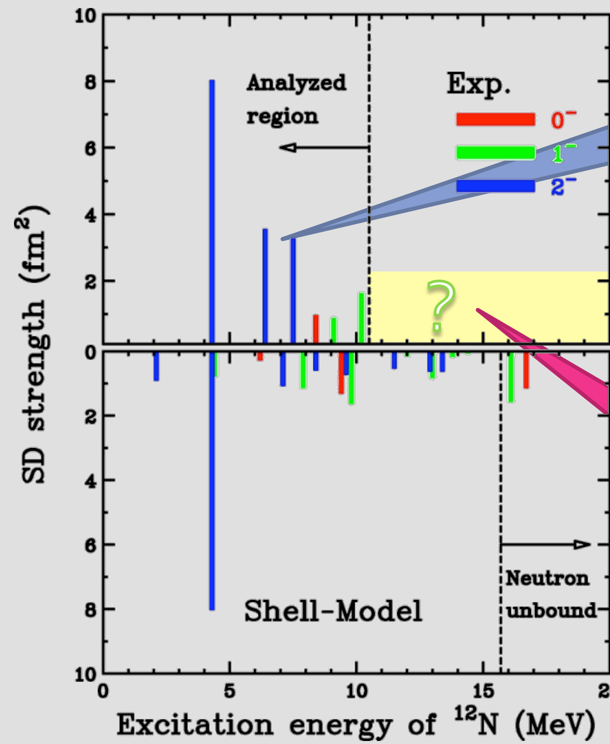
Results for SDR in ^{12}N (RCNP-E256)

M. Dozono, T.W., et al., J. Phys. Soc. Jpn. 77, 014201 (2008).

- E_x = 4.3, 6.4, and 7.5 MeV
  - ID_q and ID_p → 2^- (dominant)
- E_x = 8.4 MeV
  - ID_q → 0^- (enhancement in D_q/D_p)
- E_x = 9.1 and 10.2 MeV
  - ID_p → 1^-

- 2^- strength
  - ~100% NEWS
  - E_x=6.4 and 7.5 MeV have other J^π
    → High quality data is required
- 0^- and 1^- strengths
  - Consistent with SM including tensor
  - Large strengths in high E_x in SM





Including other J^π ?

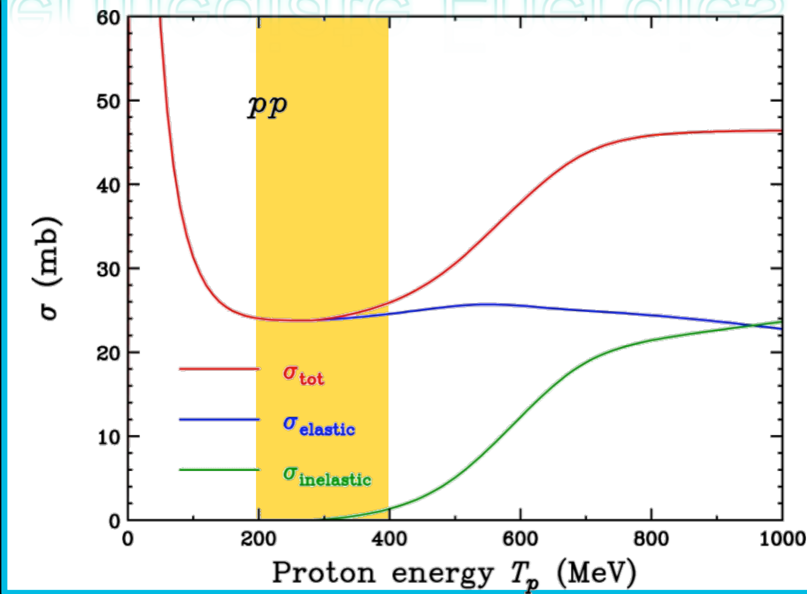
New E317

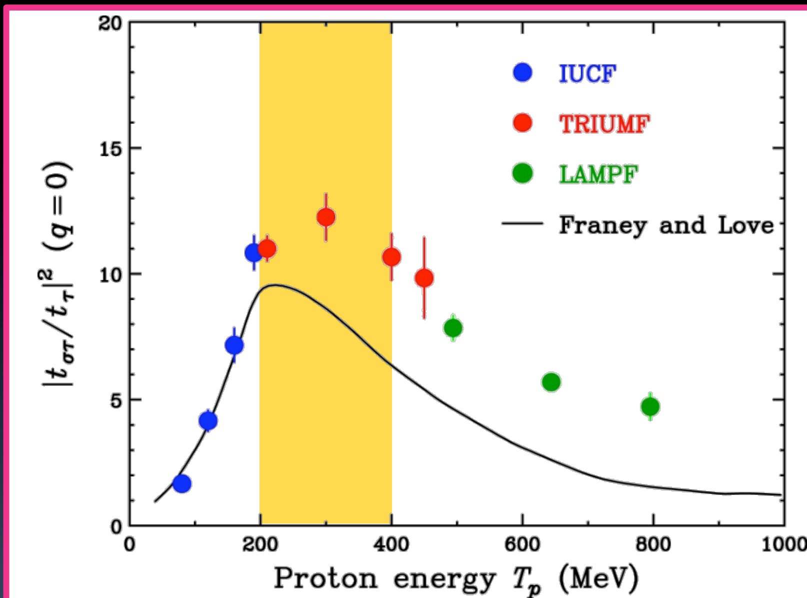
Fragmented SDR ?

Charge Exchange at Intermediate Energies

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

- **Smallest distortion**
  - NN total cross section is minimum
  - Clean measurement
  - Simple reaction mechanism
    - One-step direct
    - Impulse approximation
- **Spin-flip dominance at q=0**
  - Spin-Vector ($\sigma\tau$) > 10×Spin-Scalar(τ)
  - GT(1^+) is predominantly excited
- **Spin-flip dominance at small-q**
  - Spin-flip modes are also dominant at small q
  - Spin-Dipole Resonance (0^-, etc) is also predominantly excited





Challenge to Separate SDR into Each J^{π}

M.Dozono et al.,
RCNP-E317

- Apply the new method to $^{12}C(p,n)$
  - High resolution $^{12}C(d,^{2}He)$ data are available
    - Can check the reliability
  - J^{π} for SDR at 7 MeV is still controversial
    - Information on tensor correlations

- Preliminary results (with partial data)
  - Proper assignments for known states
    - GT at 0.0 MeV → 1^{+}
    - SDR at 4 MeV → 2^{-}
  - Identification of 0^{-}
    - Strength at 8 MeV → 0^{-}
  - Decomposition of SDR at 7 MeV
    - Lower-energy side : 2^{-}
    - Higher-energy side : 1^{-}

- Consistent with high res. $^{12}C(d,^{2}He)$?