アイソベクトル型反応で見る原子核中のパイオンの役割

若狭　智嗣（九大院理）

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萩原　洋右　君（２００５年３月修士修了）
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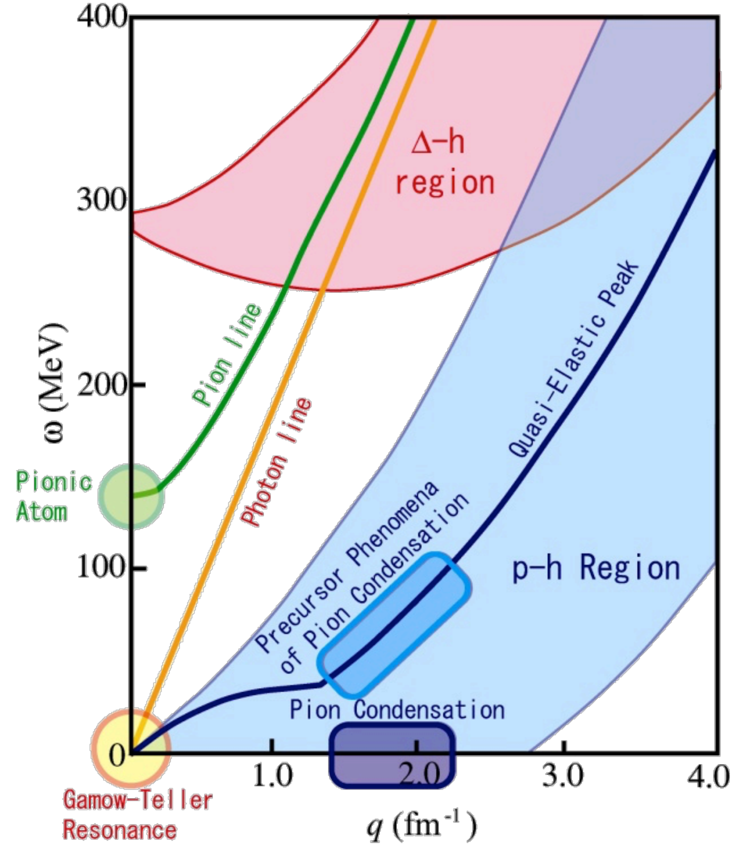
Spin-Isospin Modes in Nuclei

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*

} *Success and Problem*

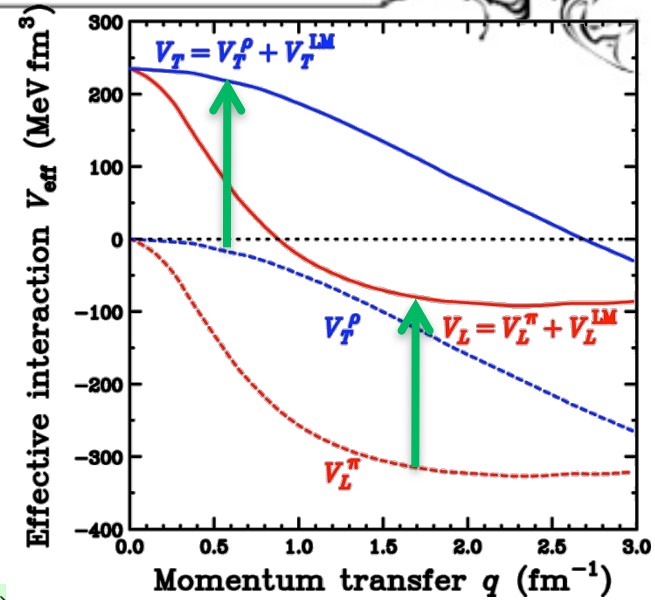
Nuclear Correlations and Δ Effects

- Effective interaction

  Spin-longitudinal (π) *Spin-transverse (ρ)*

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

- π+ρ+g' model
  - Spin-longitudinal $V_L = V_L^{\pi} + V_L^{\text{LM}}$
  - Spin-transverse $V_T = V_T^{\rho} + V_T^{\text{LM}}$



- NN(p-h) effective interaction

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

π-exchange

Short-range repulsion (Landau-Migdal interaction)

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

ρ-exchange

- Extension to N+Δ system for LM interaction

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

π- and ρ-exchange terms are also included
⇒ 2 free-parameters: g'_{NN} and $g'_{N\Delta}$

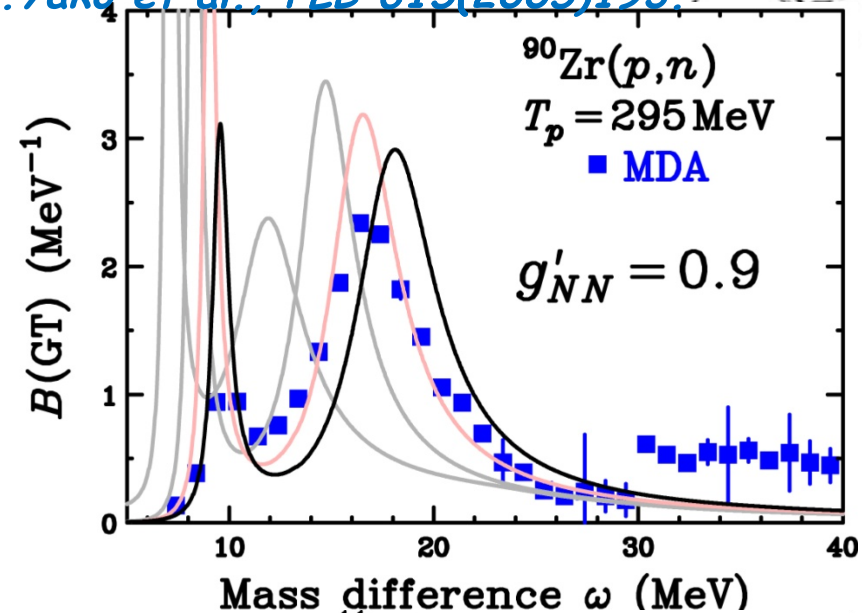
GT Strength and Landau-Migdal Parameters

K.Yako et al., PLB 615(2005)193.

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

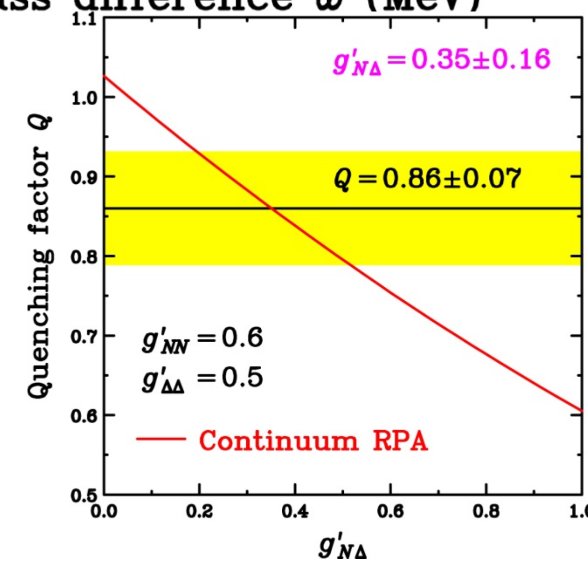
      $$g'_{NN} = 0.6 \pm 0.1$$

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



- g' $_{N\Delta}$ Dependence of 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 QES

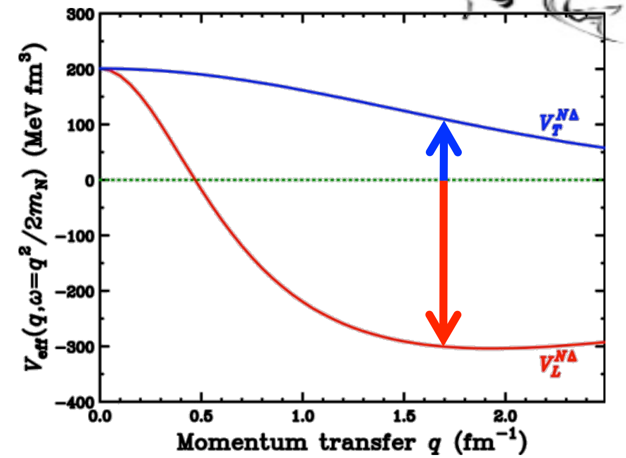
T. W. et al. PRC 69, 054609 (2004)

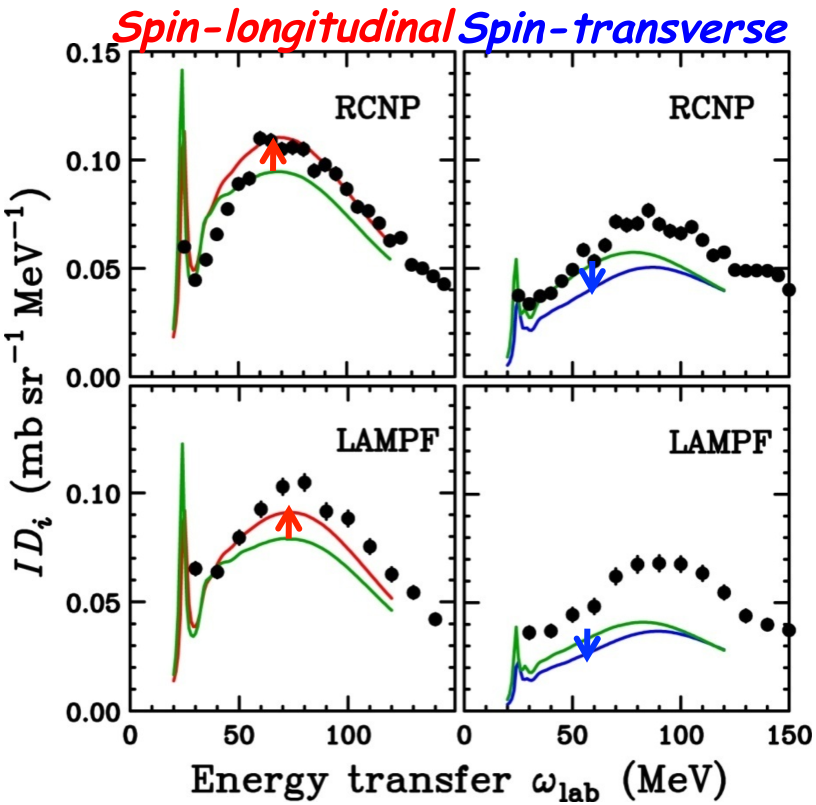
- Effective interaction at large q
  - Attractive spin-longitudinal V_L
    - Especially for NΔ with small $g'_{N\Delta}$
- Quasi-Elastic Scattering at large q
  - Spin-longitudinal mode : ID_q
    - ***Enhancement*** by attractive π- corr.
  - Spin-transverse mode : ID_p
    - ***Quenching*** by repulsive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

Pionic enhancement /correlations in nuclei

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

"Attractive" rho-mesonic correlations ?

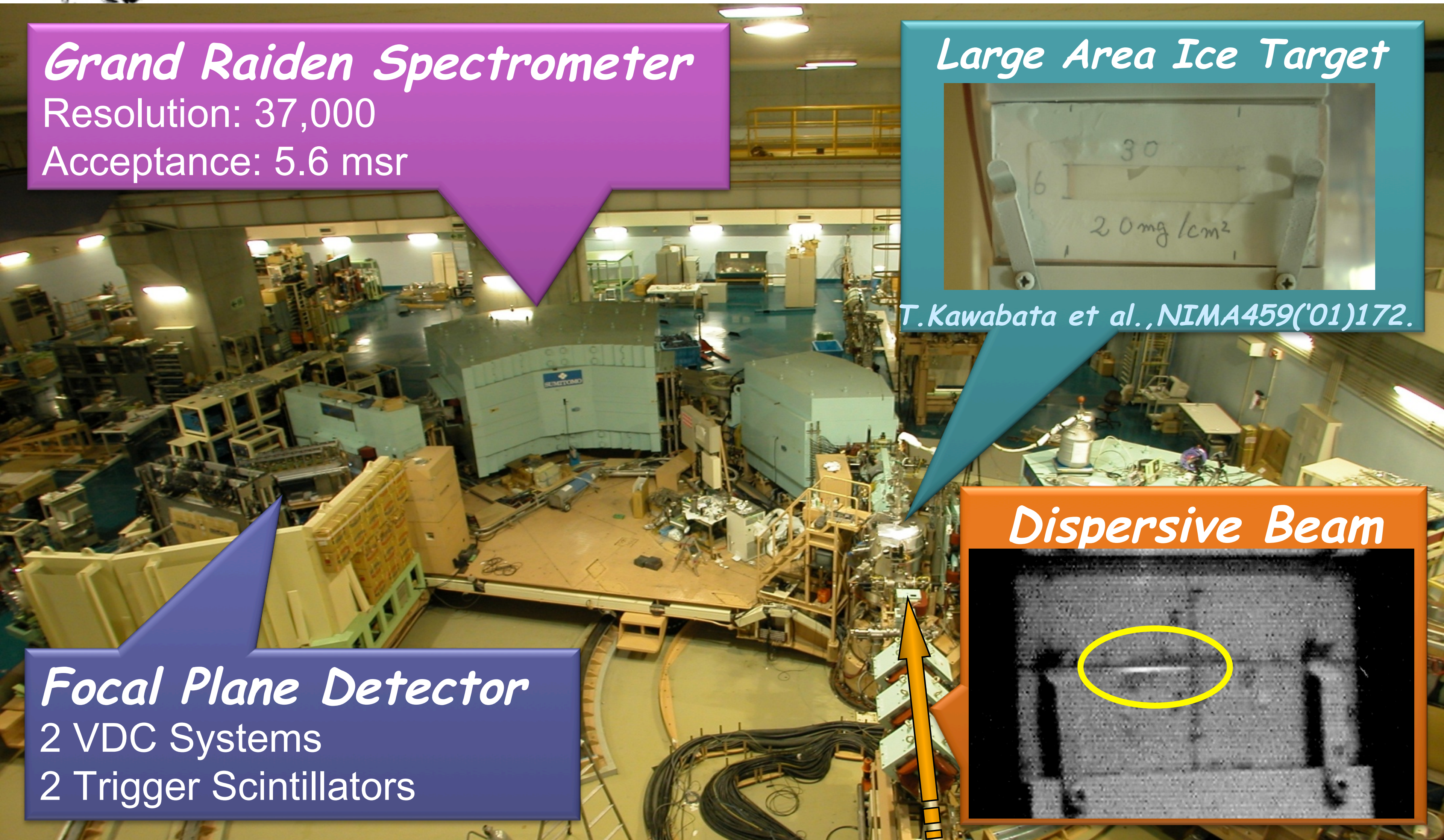




New Experiments at RCNP

- **Results of quasi-elastic scattering**
  - Enhancement of spin-longitudinal OK
  - Quenching of spin-transverse NG
  - Enhancement is really due to attractive pionic correlations ?
    - *Spin-longitudinal/transverse modes were separated with D_{ij}*
    - Simple reaction mechanism was assumed
  - QES data are limited at q～1.7 fm^{-1}
    - *Pionic-correlation effects were NOT measured at wide q*
- **New experiments**
  - Measure s of $^{16}O(p,p')^{16}O(0^-,T=1)$ … RCNP-E155
    - *Pure spin-longitudinal mode → Separation with D_{ij} is not needed*
  - Measure D_{ij} of $^{12}C(p,n)^{12}N(1^+,T=1)$ … RCNP-E256
    - q=0～2.0 fm^{-1}
    - *q-dependence of π- and ρ-exchange interactions*

Experimental Setup for $^{16}O(p,p')$



Grand Raiden Spectrometer

Resolution: 37,000

Acceptance: 5.6 msr

Large Area Ice Target

T.Kawabata et al.,NIMA459('01)172.

Dispersive Beam

Focal Plane Detector

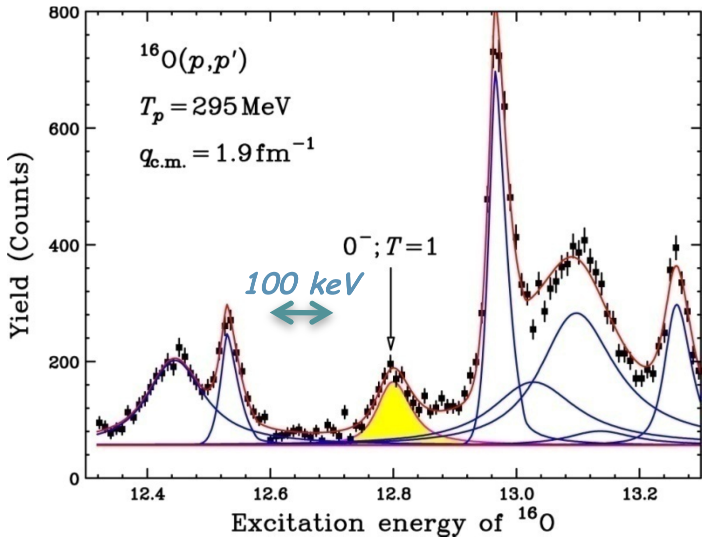
2 VDC Systems

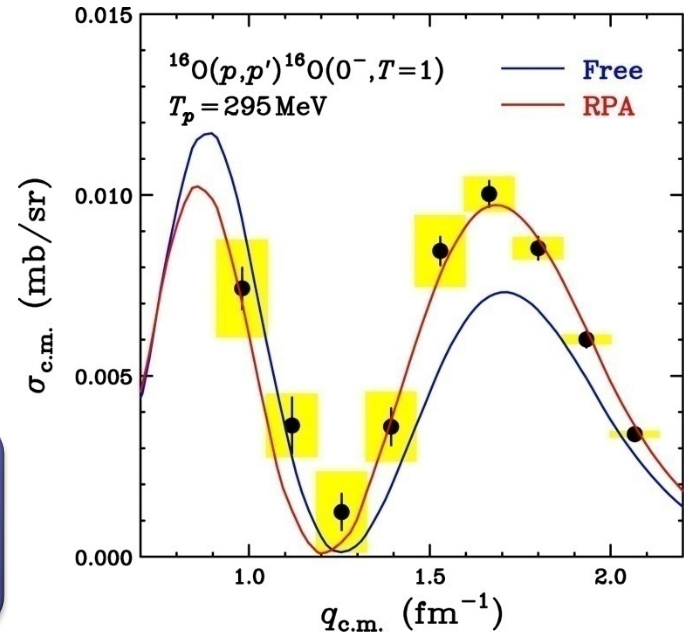
2 Trigger Scintillators

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 same as those in QES*
      - Parameter-free calculations
    - *Predict the enhancement of the 3rd peak (q=1.7fm-1)*



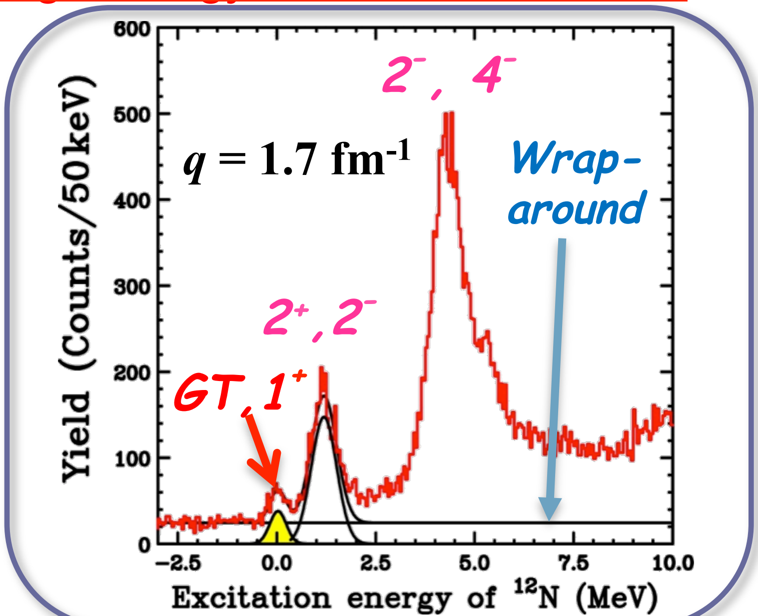


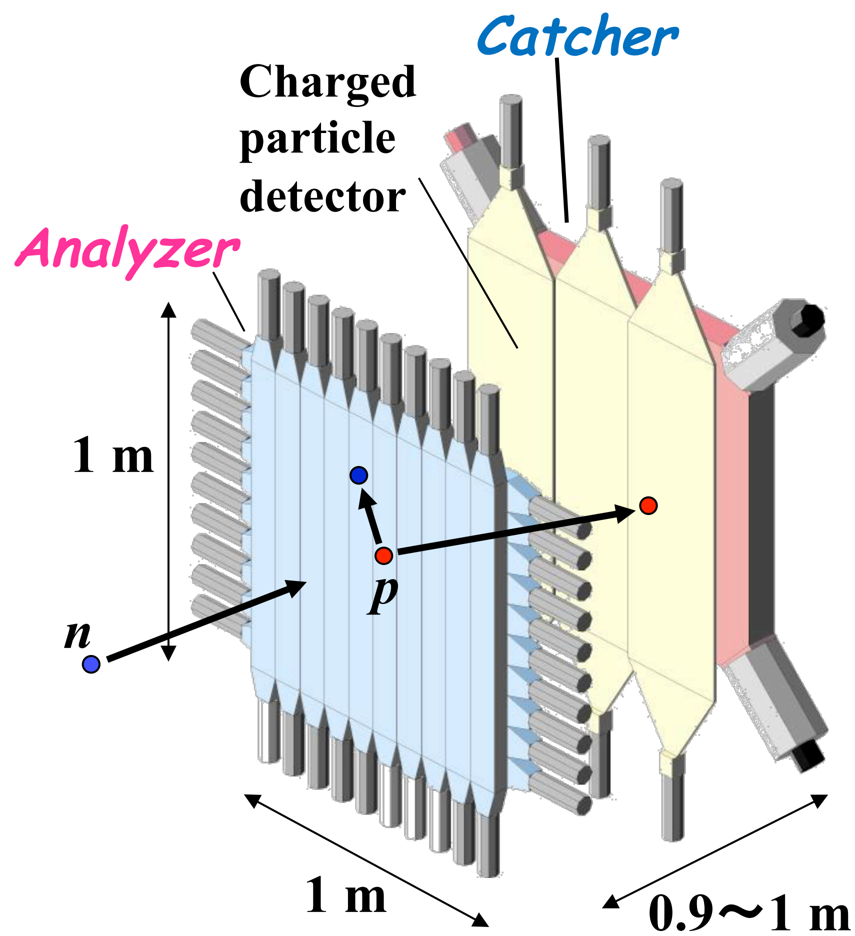
Our data support pionic enhancement
Signature of precursor for pion condensation in pure pionic mode

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

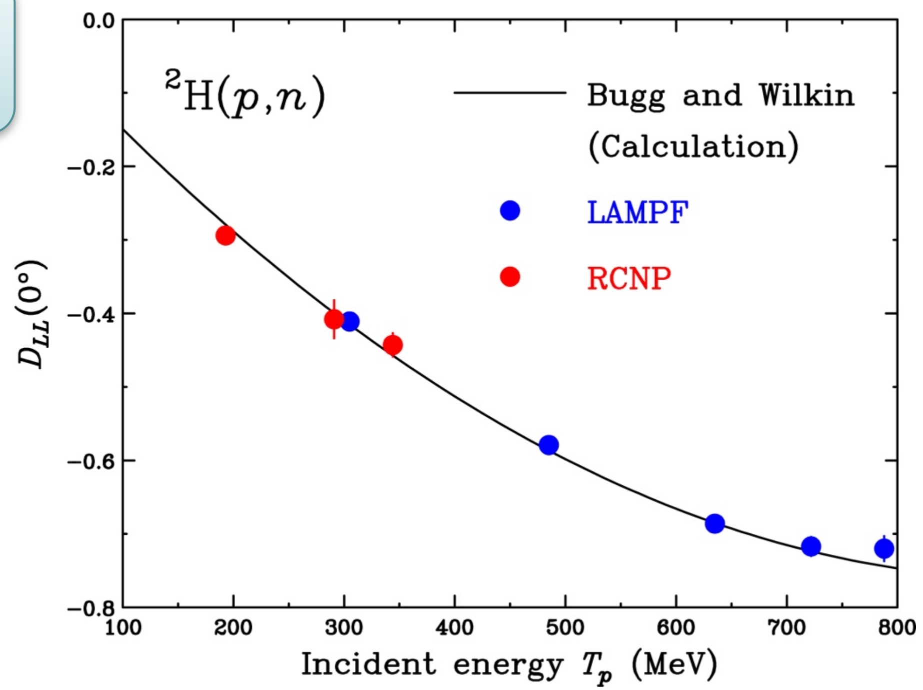
T.W., E.Ihara et al., Submitted to PRC

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

Benchmark reaction
⇒ accuracy of polarization data

- Theoretical calculations
  - Including deuteron D-state
  - Including p-p FSI (^{2}He)
- 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)

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

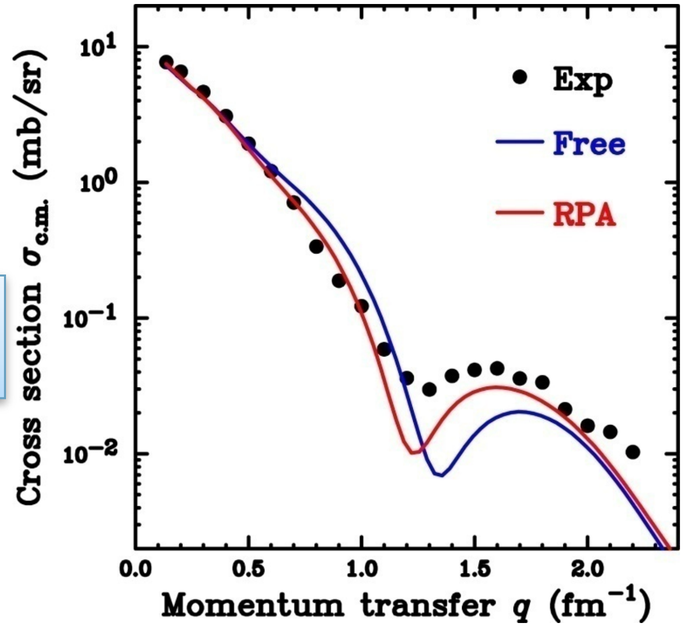
T.W., M.Dozono, et al., PLB 656(2007)38.

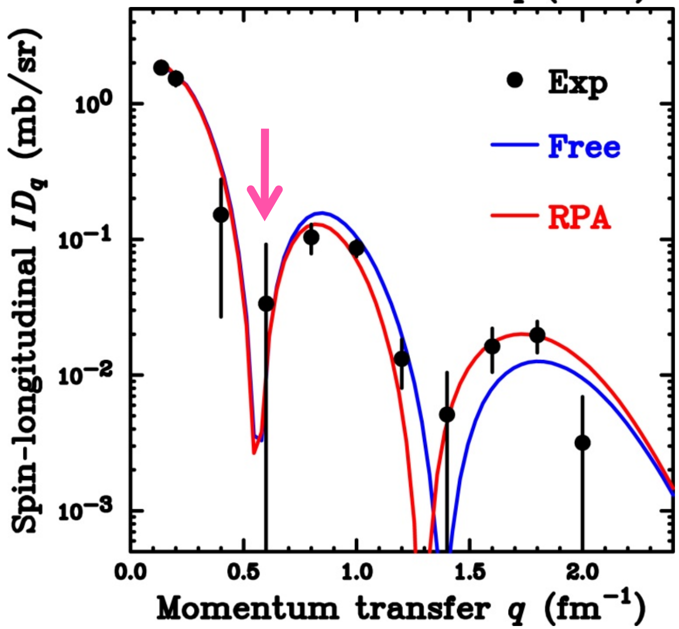
- Polarized cross section
  - $ID_q = KN\,|E|^2\,R_q$
  - $ID_p = KN\,|F|^2\,R_p$

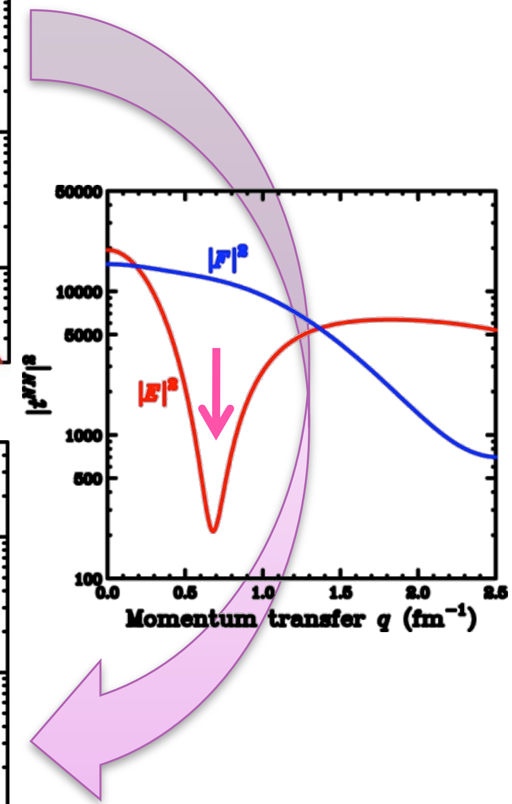
Separation of π- and ρ-mode with PTO is reliable

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

Our data support ALSO pionic enhancement
⇒ How about ρ-mode?







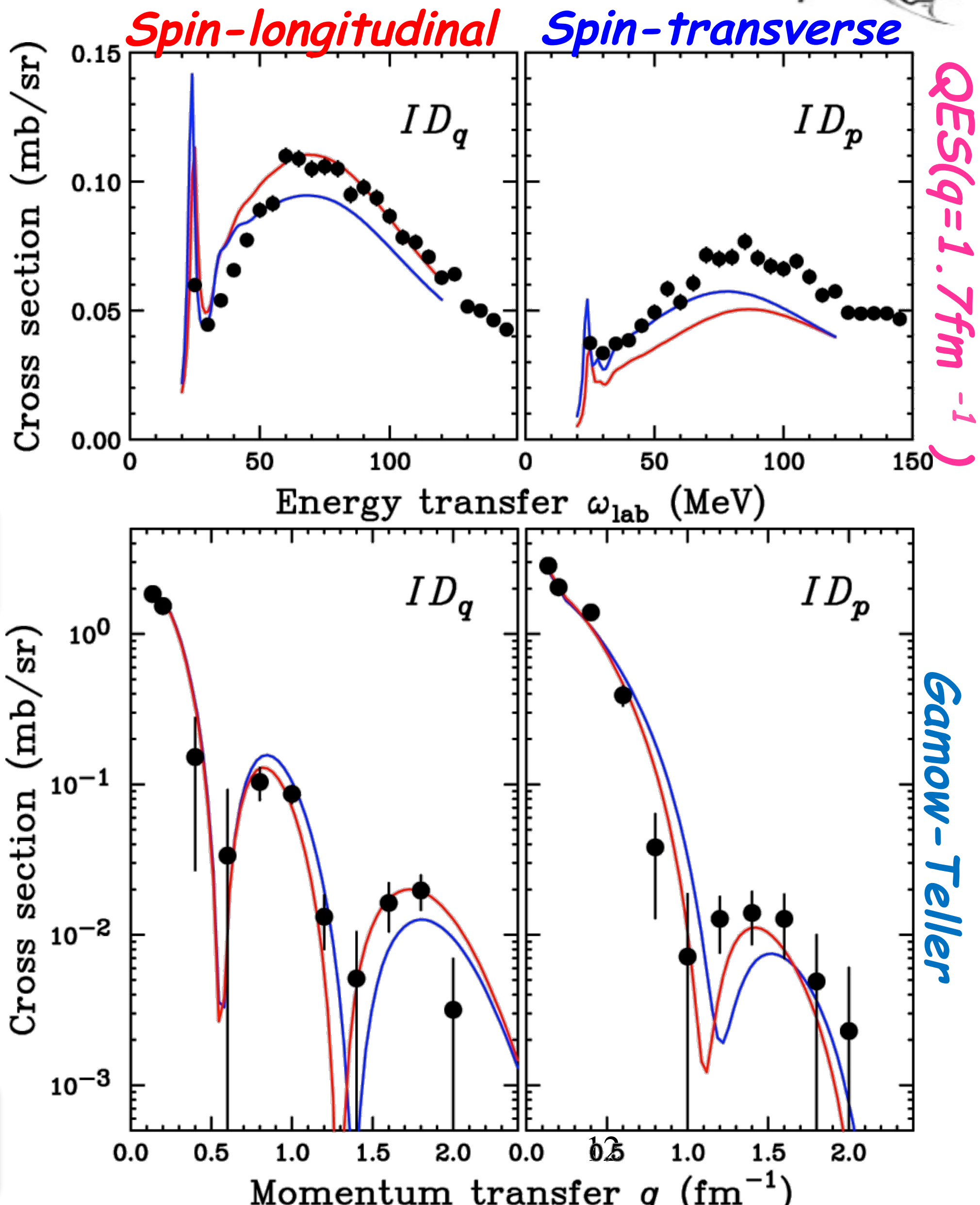
Enhancement of Spin-Transverse Mode

- Spin-longitudinal mode
  - At small q
    - Exp. = RPA = Free (w/o corr.) *(B(GT) is normalized at q=0)*
  - At large q
    - Exp. = RPA > Free (w/o corr.)

Attractive pionic correlations at large q

- Spin-transverse mode
  - At small q
    - Exp. = RPA = Free (w/o corr.)
  - At large q
    - Exp. > RPA *(within uncertainty in GT case)*

Suggest attractive ρ-correlations at large q



Short-Range Tensor Correlations

C.J.Horowitz and J.Pielarewicz, PRC 50(1994)2540.

- Central + Tensor vs. Longitudinal + Transverse

Central $[(\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q}) + (\sigma_1 \times \hat{q})(\sigma_2 \times \hat{q})]$

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

Tensor $[3(\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q}) - \{(\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q}) + (\sigma_1 \times \hat{q})(\sigma_2 \times \hat{q})\}]$

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

Longitudinal *Transverse*

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

⇒ *Longitudinal* $g'_\pi(q) = g'(q) + 2h'(q)$

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

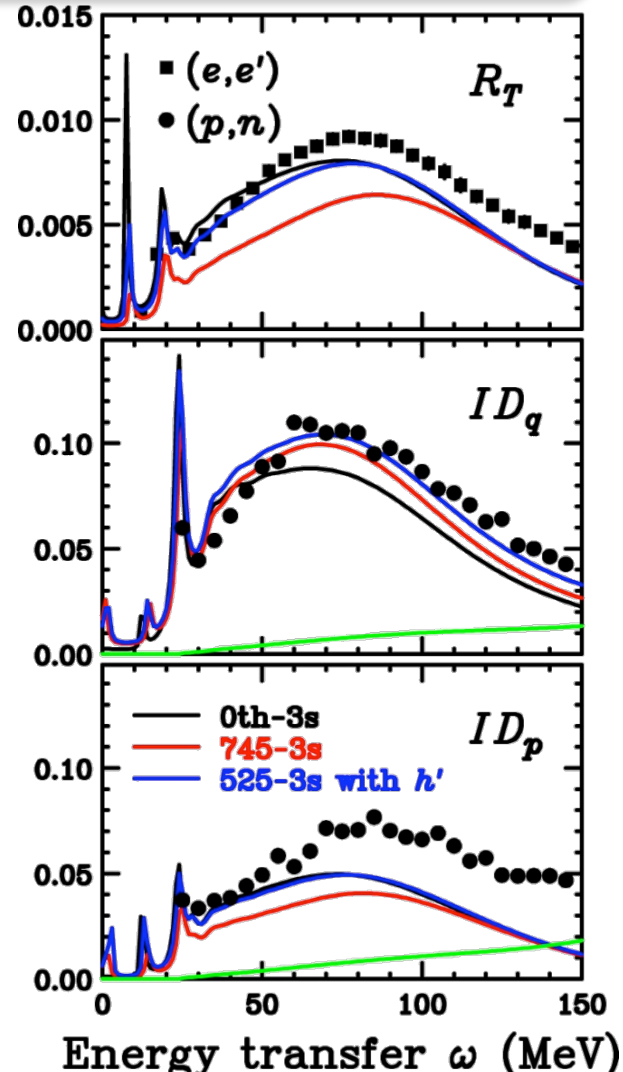
- Tensor effects for h > 0
  - Repulsive for *spin-longitudinal* (Pionic mode)
  - Attractive for *spin-transverse* (Rho-mesonic mode)
  - Effects: *spin-longitudinal* = 2 × *spin-transverse*

Phenomenological Approach

Free (w/o correlation) ⟺ g' only (g'_{NN}=0.6, $g'_{N\Delta}$=0.35)

g' +h' (g'_{NN}=0.5, $g'_{N\Delta}$=0.2, h'=0.09)

- Transverse response in (e,e')
  - Consistent with free (w/o correlation)
  - *MEC/2p2h are effectively included with h'*
- Spin-longitudinal in (p,n)
  - Consistent with Original RPA
    - g'_{NN} = 0.6 → 0.5
    - $g'_{N\Delta}$ = 0.35 → 0.2
  - *Repulsion from h' is cancelled with smaller g'*
- Spin-transverse in (p,n)
  - Consistent with free
  - Significant 2-step contributions
    - *Still underestimated*



Tensor correlations can give better description for transverse mode,
but still something missing

Difference between Two Spin-Transverse Mode

- Spin-transverse mode
  - *In-plane*

NN t-matrix　Response

$$ID_p = KN|F|^2 R_p$$

  - *Normal*

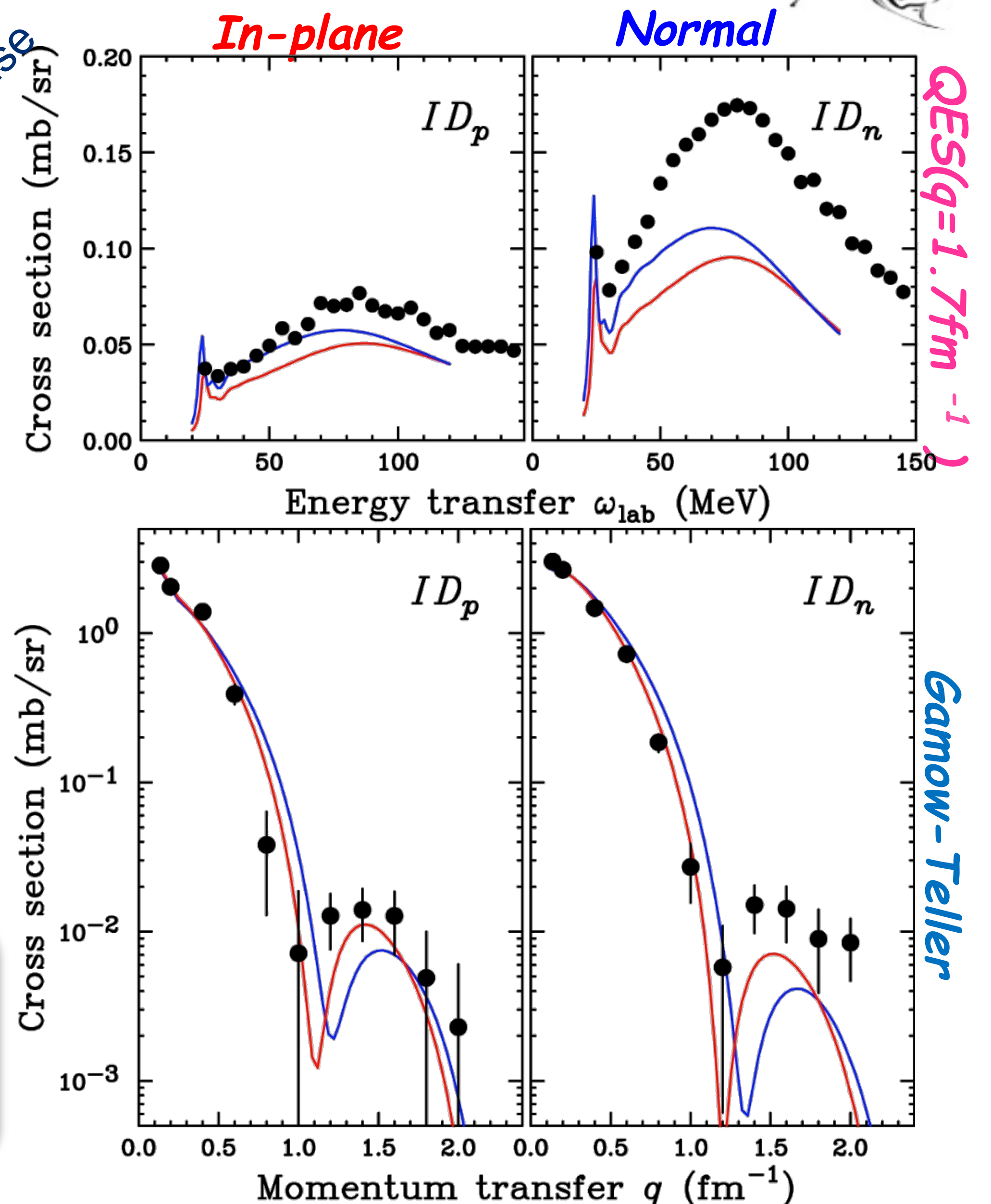
$$ID_n = KN|B|^2 R_n$$

  - In intrinsic (target) frame, **p=n**

$$R_p = R_n$$

- Experimental data
  - *In-plane*
    - Exp. > RPA
  - *Normal*
    - Exp. >> RPA

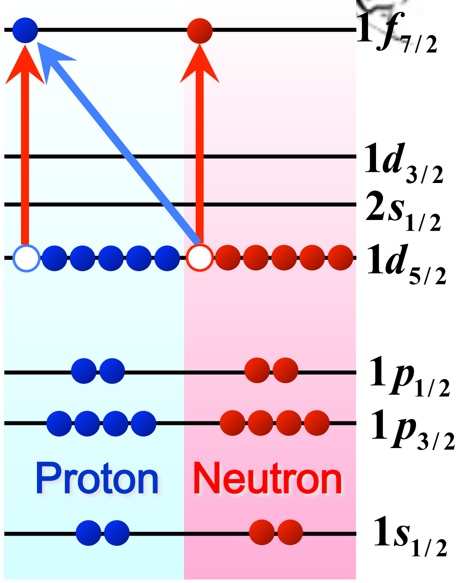
Response function (R) and distortion/kinematic factors (KN) are common
⇒ NN t-matrices are modified?



Stretched State - *R is known from (e,e')* -

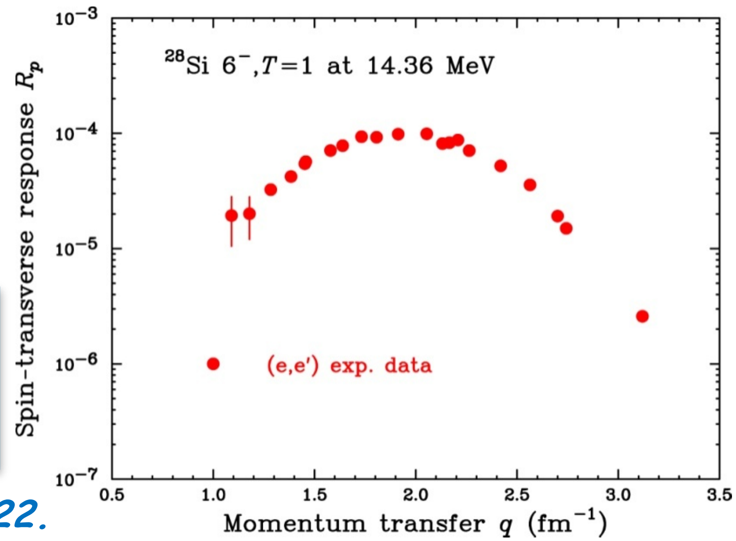
- Stretched states (ex. ^{28}Si)
  - $^{28}Si(p,p')^{28}Si$ $1d_{5/2}$ p/n-hole and $1f_{7/2}$ p/n-particle
  - $^{28}Si(p,n)^{28}P$ $1d_{5/2}$ n-hole and $1f_{7/2}$ p-particle
- Spin-transverse form factor (response) : R_p

R_p is given by the (e,e') data
→***Less ambiguity in R_p***
→***Reliable information on effective NN interaction***



- Spin-longitudinal : R_q
  - Nuclear correlation effects are small for stretched state transitions
    - Transition probability=nuclear surface

$$\frac{R_q}{R_p} = \frac{2J}{J+1} = 1.71$$ → ***Also less ambiguity in R_q***



S.Yen et al., Phys. Lett. B 289 (1992) 22.

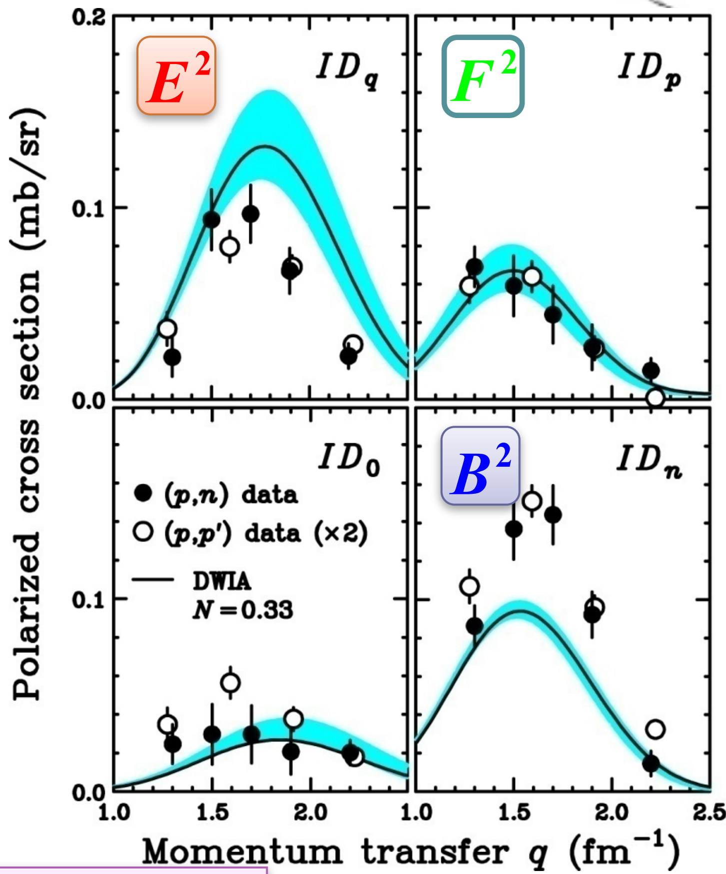
Results- *Comparison with (p,p') and DWIA-*

T.W., Y. Hagihara, et al.,PLB 645(2007)402.

- Comparison with (p.p')
  - (p,p') data multiplied by 2 (Isospin C.G.)
  - (p,n) data are consistent with (p,p')

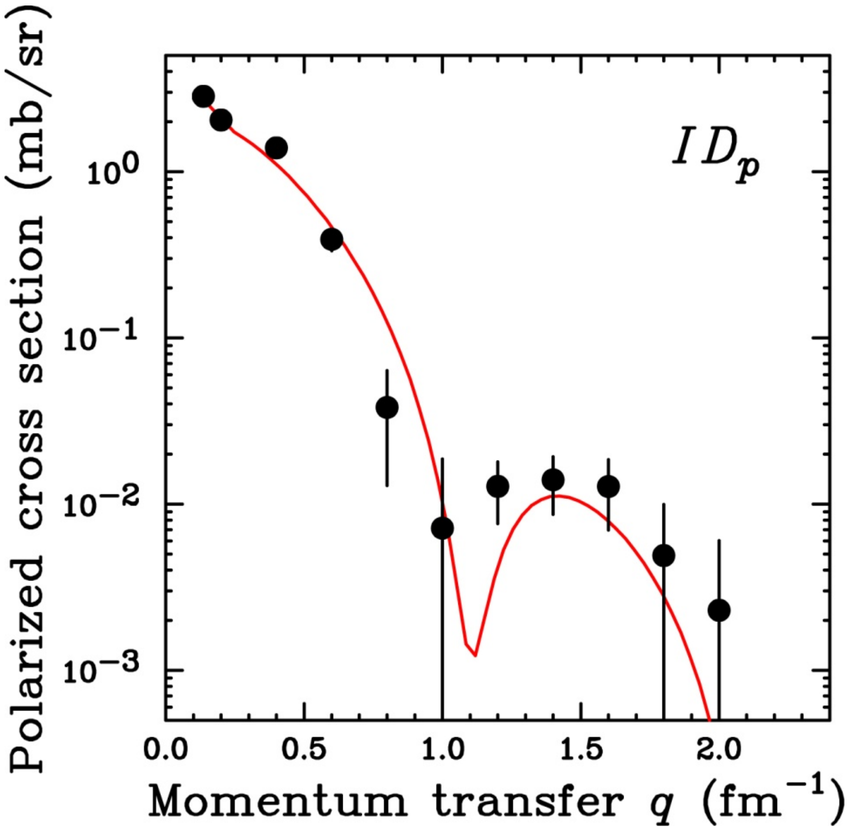
Experimentally exclude the possibility of ***isospin-mixing effects*** for the discrepancy in (p,p') case

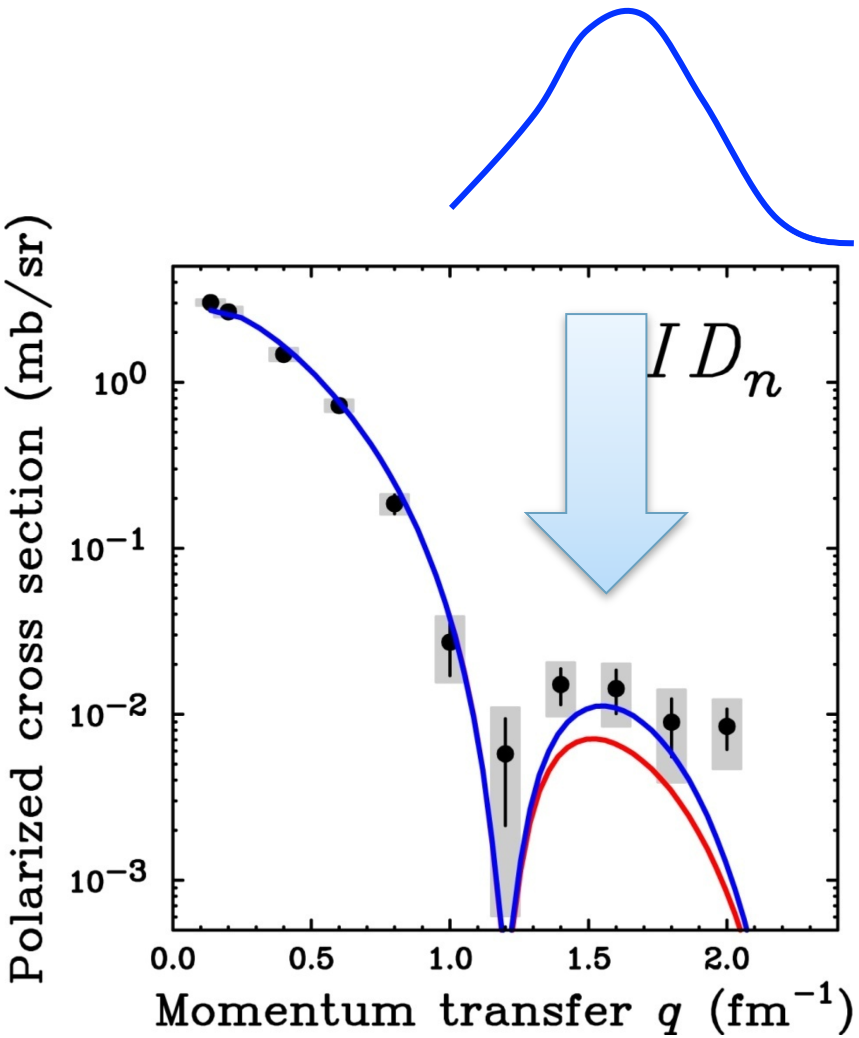
- Comparison with DWIA
  - ID_q: Over-prediction
  - ID_n: Under-prediction
  - ID_q and ID_0: Reasonable reproduction



Modification of NN amplitude in KMT
- Spin-longitudinal E : ***Small-Reduction***
- Normal spin-transverse B : ***Enhancement***
- Other amplitudes A,C, and F : ***No modification***

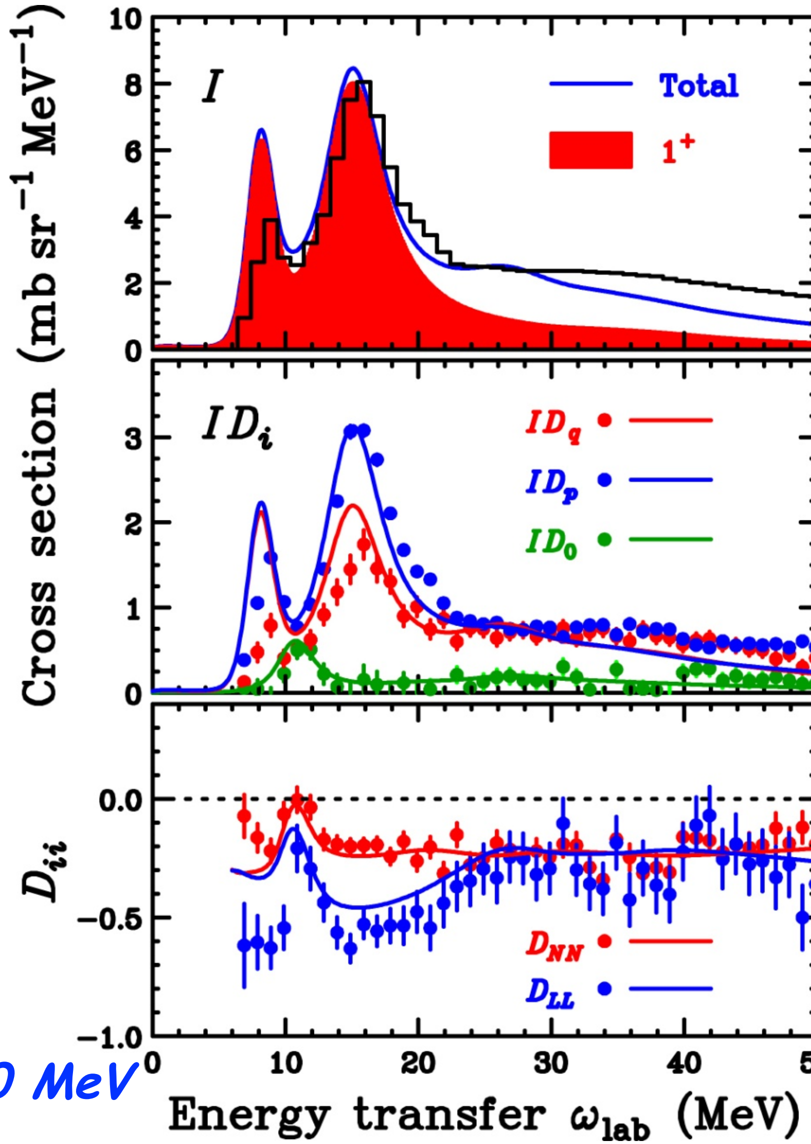
Toy-Model Calculation





Polarization transfer for $^{90}Zr(p,n)$ at 0°

- Spin-scalar ID_0
  - Negligible except at ω=11 MeV
    - IAS (0^+) contribution
  - *Spin-flip dominance*
- Spin-vector ID_q and ID_p
  - $R_q = R_p$ at q=0 (0°)
  - $ID_q < ID_p$
    - *Exchange-tensor effects*
      ($E^2 < F^2$)
- DWIA calculations
  - Reasonably reproduce PTO(D_{ii})
    - *Spin-scalar f' is also included*
  - *Multi-step seems to be small*
    - *$D_{ii} \rightarrow 0$ for multi-step*
  - *Underestimate ID_q and ID_q at ω>30 MeV*
    - *Spin-flip 2p2h contributions*



Summary and Future Perspective

- Results of recent experiments
  - Measure s of $^{16}O(p,p')^{16}O(0^-,T=1)$ … RCNP-E155
    - Pure pionic mode → Separation with D_{ij} is not needed
    - *Observe the pionic correlations (enhancement)*
  - Measure D_{ij} of $^{12}C(p,n)^{12}N(1^+,T=1)$ … RCNP-E256
    - q-dependence of π- and ρ-exchange interactions
    - *Attractive contribution from both π-/ρ-exchange at large q*
- Enhancement in spin-transverse ID_p and ID_n
  - Short-range tensor interaction would play important role *in part*
  - Medium modification of NN t-matrix in normal-spin-transverse (B)
- New experiments *(Under consideration)*
  - E317 (*Dozono-san*): Spin-dipole strengths $(0^-,1^-,2^-)$ in ^{12}N and ^{16}F
    - *Tensor correlation effects in SM*
  - E313 (*Yamada-san*) : Medium effects of p-n interaction in nuclei

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MISC for Introduction

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    - Weak **g'**$_{N\Delta}$ dependence
  - GTGR strength
    - Quenched with **g'**$_{N\Delta}$ *> 0*
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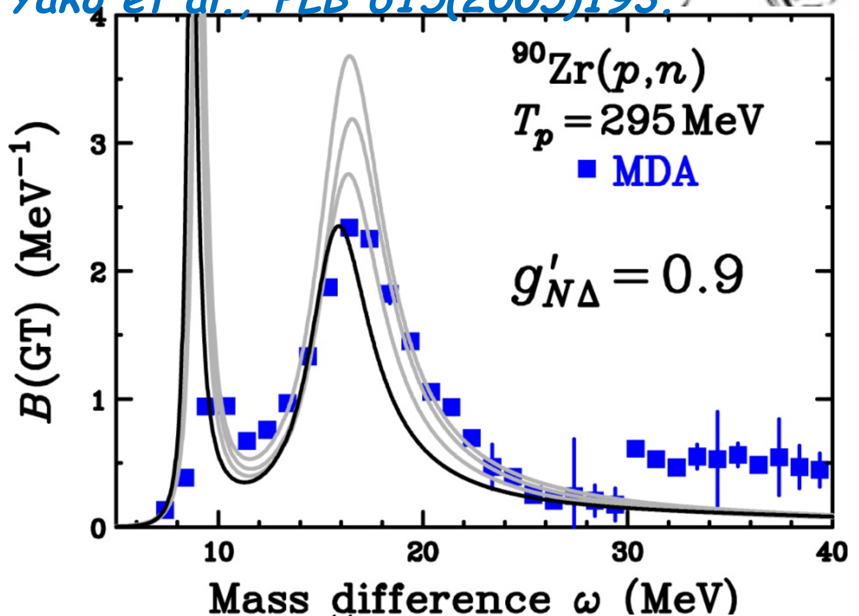

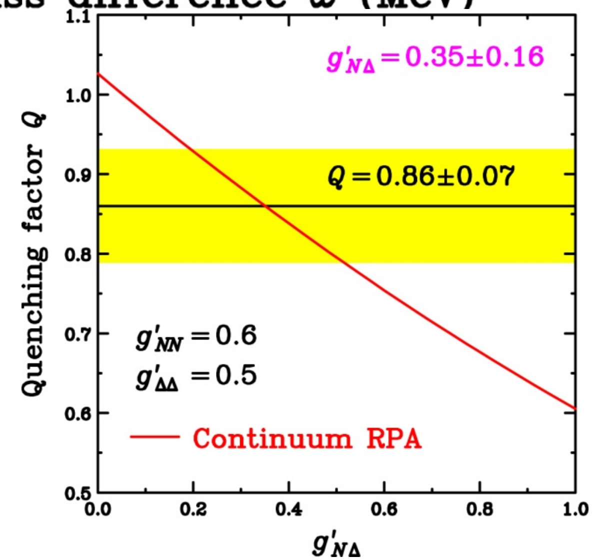

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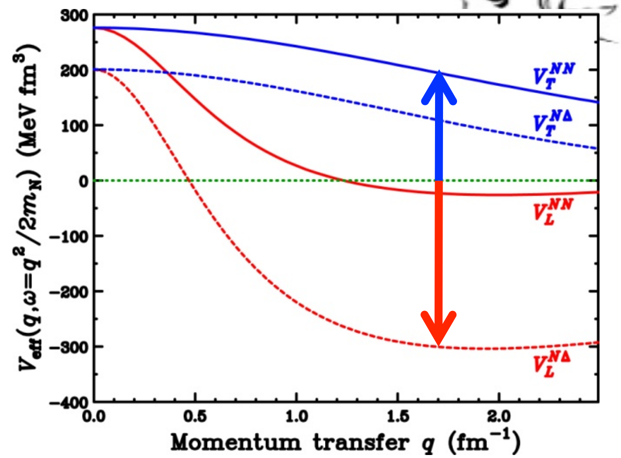
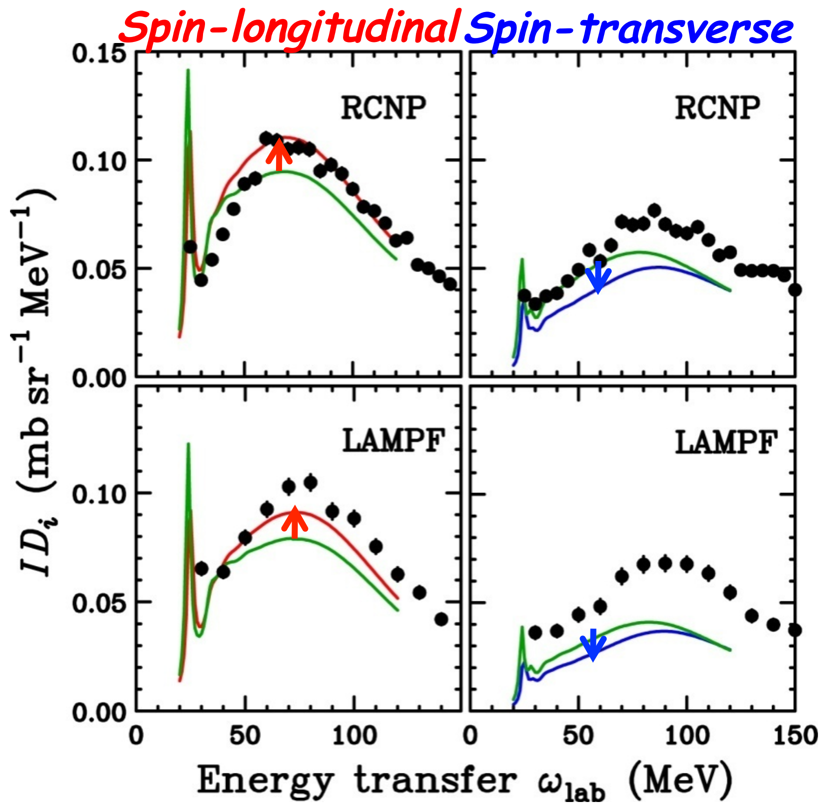


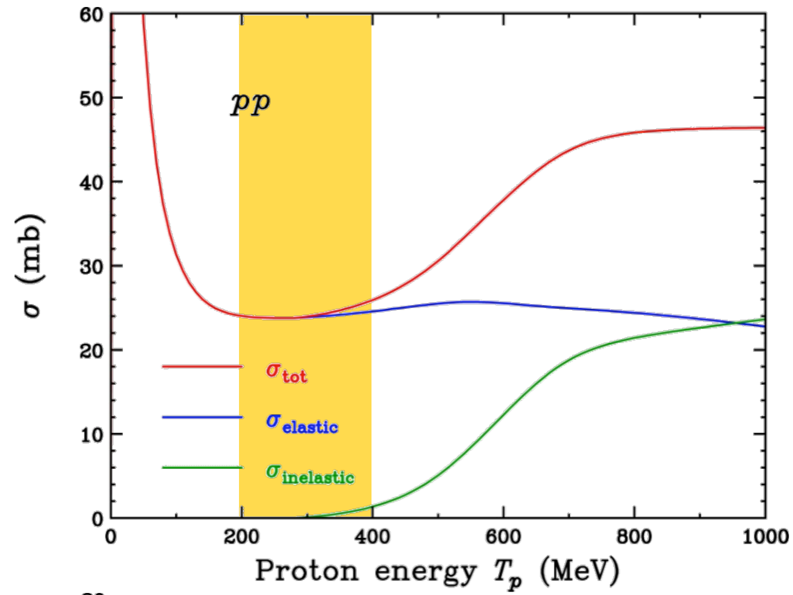


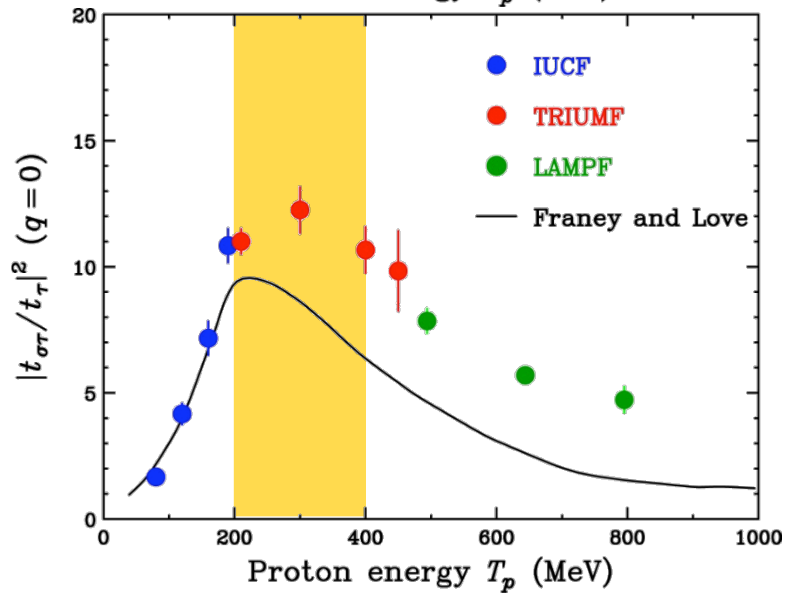
MISC for RCNP

Advantage at RCNP Energy Region

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*



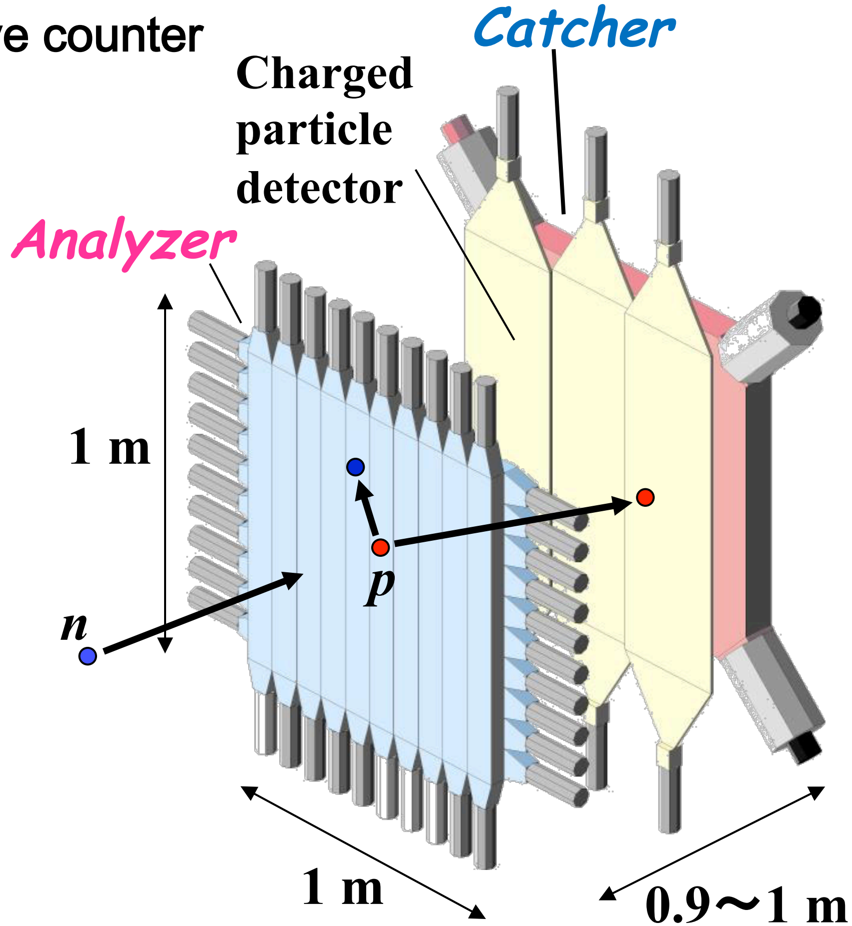


MISC for RCNP-E256

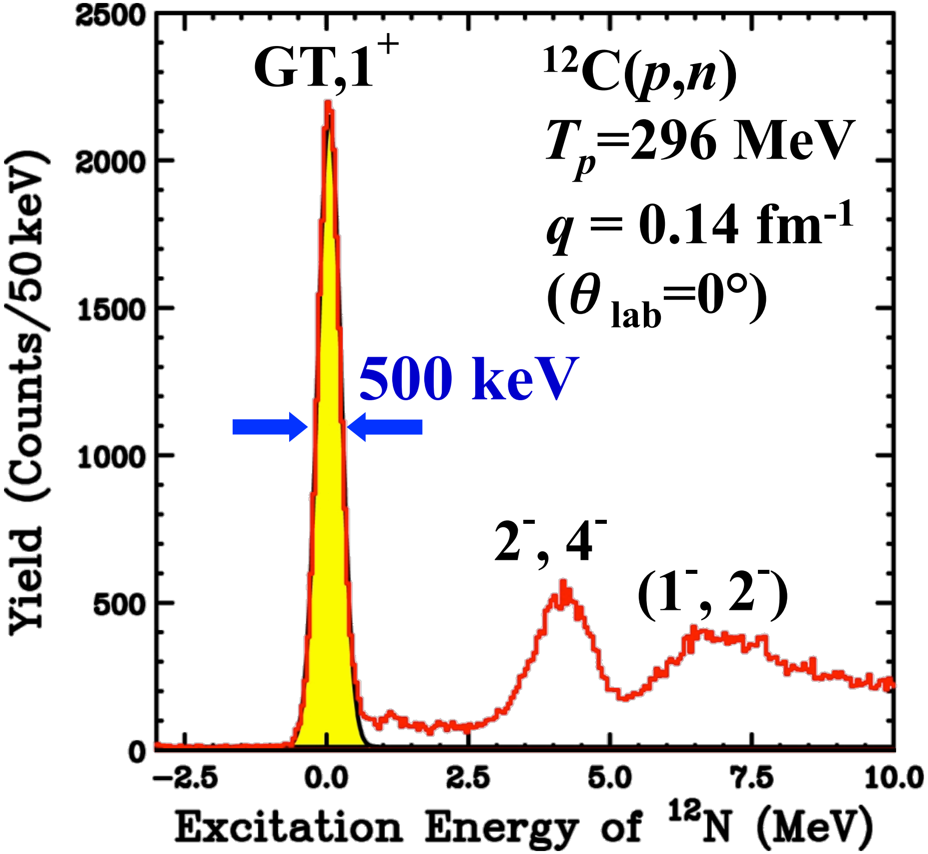
Neutron Detector/Polarimeter NPOL3

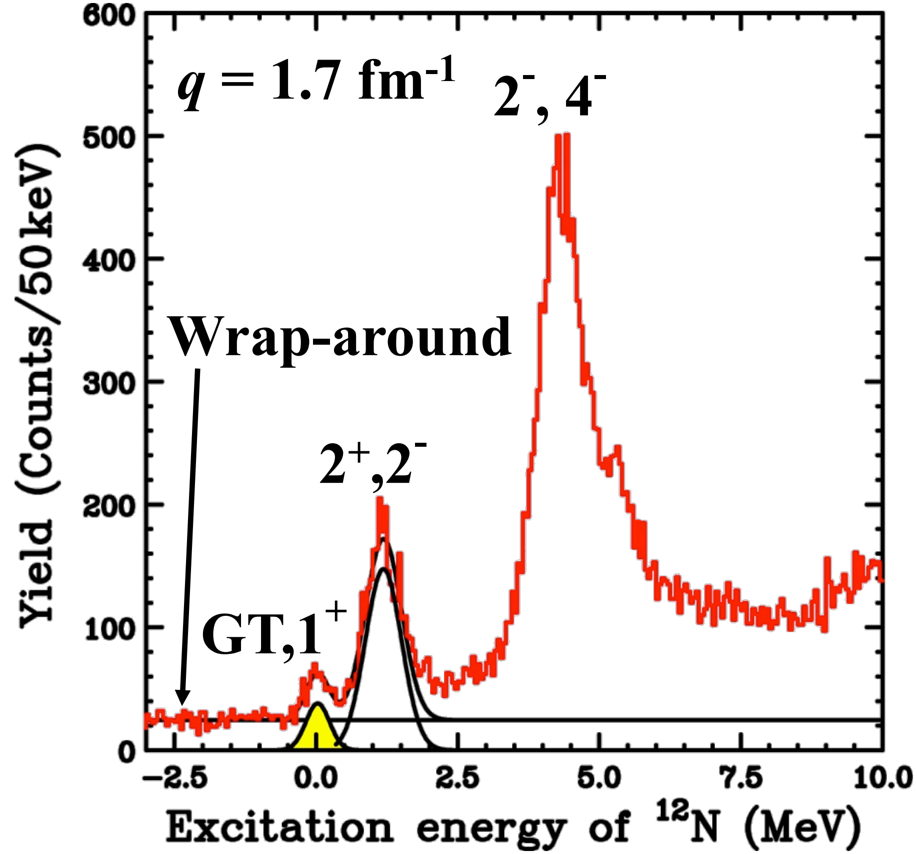
T. W., Y. Hagihara et al., Nucl. Instrum. Methods Phys. Res. A 547 (2005) 569.

- Setup
  - *Analyzer* : 20sets of 1-dimensional position-sensitive counters (hodoscopes)
  - *Catcher* : 2-dimensional position-sensitive counter
- Neutron detector mode
  - Outgoing neutrons are detected with hodoscopes
  - High energy resolution ~500 keV
- Neutron polarimeter mode
  - Polarimetry
    - $\vec{n} + p$ scatterings in hodoscopes
  - Recoiled protons are detected with catcher
  - Neutron polarization is determined from asymmetry of $\vec{n} + p$ events
  - High performance FOM=1.0×10^{-4}



High Resolution Spectra with NPOL3





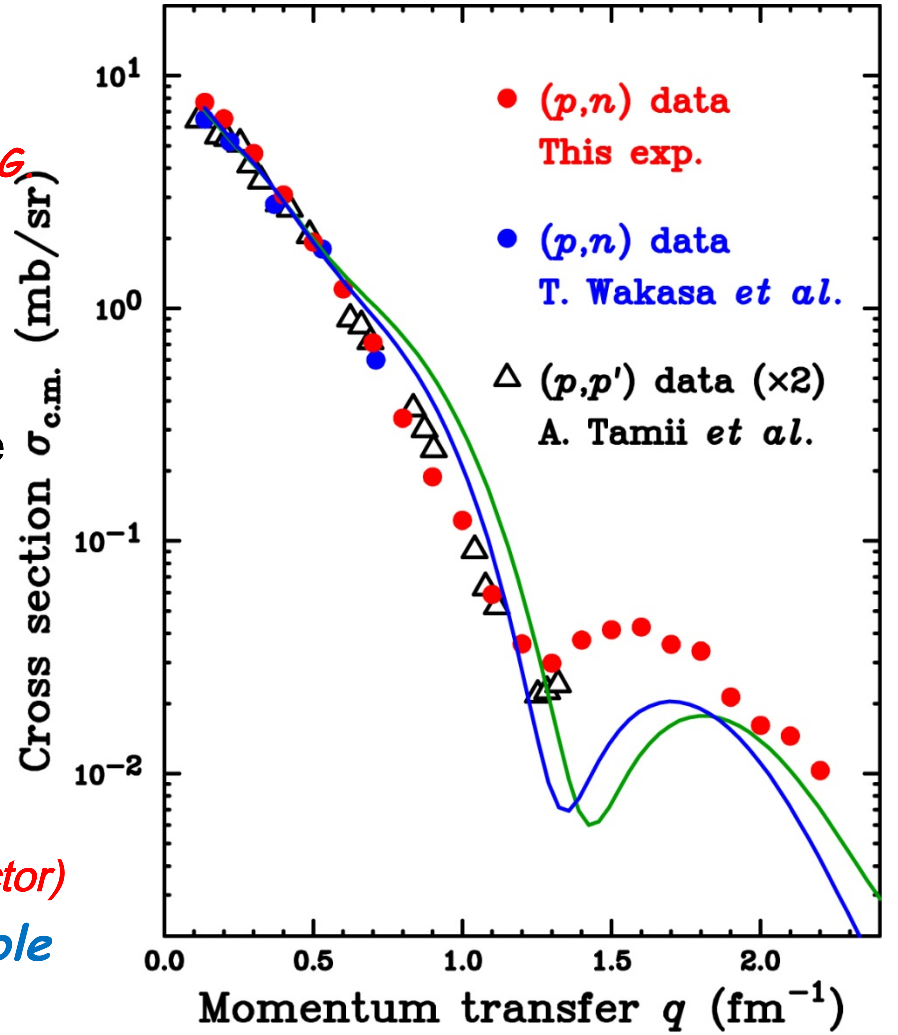
Sufficiently-high energy resolution of 500 keV

→ Clear separation of GT state from other states

⇒ *Measure polarization observables with same energy resolution*

Cross section for $^{12}C(p,n)^{12}N(1^+)$

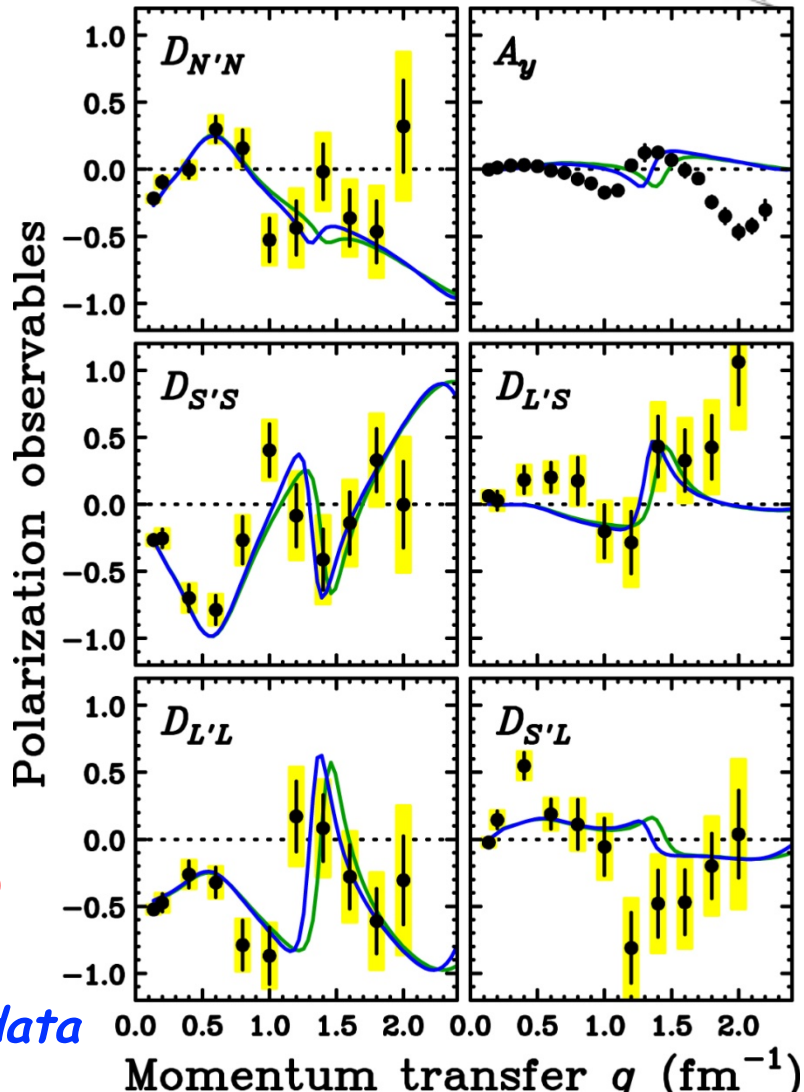
- Previous exp. Data at 300 MeV
  - $^{12}C(p,n)^{12}N(g.s.,1^+)$
  - $^{12}C(p,p')^{12}C(15.1MeV,1^+)$ *×2 by Isospin C.G.*
- This experiment
  - Consistent with previous data
  - Cover up to 2.2 fm^{-1}
    - Spin-longitudinal would be attractive
- DWIA w/o correlations
  - B(GT) is normalized to β-decay value
  - *Different q-dependence (2^{nd}-peak)*
  - *Underestimation at large-q*
- Effects of non-locality in mean field
  - Effective mass $m^*(r=0)=0.7m_N$ *(Perey factor)*
  - *q-dependence (2^{nd}-peak) is reasonable*
  - *Still underestimate at large-q*



Enhancement at large q ⇒ ***Signature of attractive pionic correlation ?***

Polarization Observables for $^{12}C(p,n)^{12}N(1^+)$

- This experiment
  - Bar : ***Stat. error***
  - Band : ***Stat.+syst. error***
  - Cover up to 2.0 fm^{-1}
    - σ_{cm}~0.01 mb/sr (10μb/sr)
- DWIA w/o correlations
  - Roughly reproduce q-dependence
  - Reflect q-dependence of NN t-matirx
  - ***Our D_{ij} data are reliable (NOT a fluctuation)***
- Effects of non-locality in mean field
  - Effective mass $m^*(r=0)=0.7m_N$ *(Perey factor)*
  - q-dependence (2^{nd}-peak) is reasonable
  - ***DWIA w/o correlation can reproduce data***



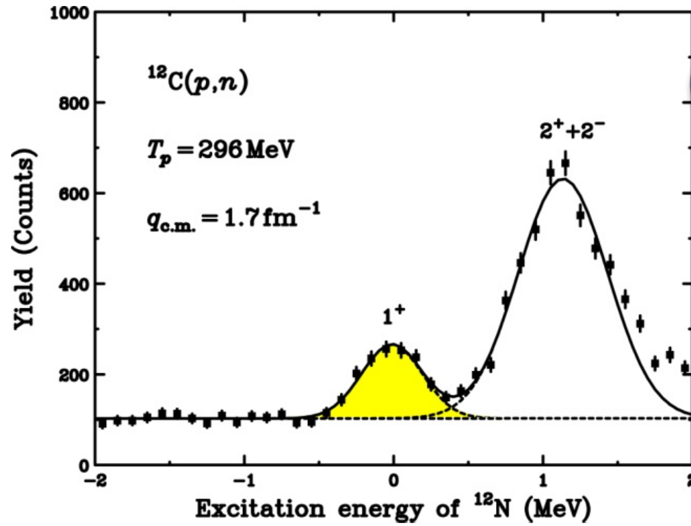
Separate pionic/rho-mesonic modes ⇒ *Study pionic correlation effects separately*

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

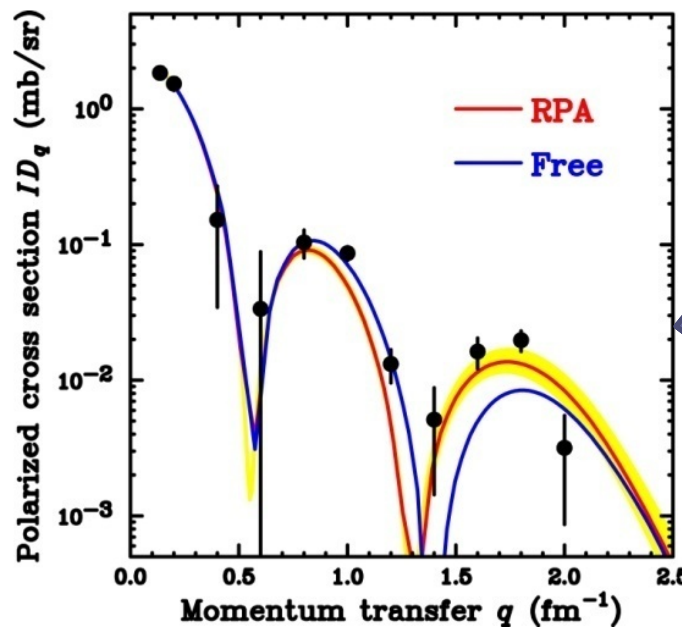
T.W., M.Dozono, et al., PLB 656(2007)38.

- **Isovector $J^{\pi}=1^+$ excitations**
  - Both π- and ρ-modes are excited
  - *π-mode is separated with PTO*
- **Experiment: $^{12}C(p,n)^{12}C(1^+,T=1)$**
  - ΔE=500 keV with NPOL3
  - $q_{c.m.}$ = 0.1– 2.0 fm^{-1}
- **Comparison with Theory**
  - — Without correlation (Free)
    - Significant enhancement
  - — With RPA correlation
    - g'_{NN}=0.7,g'_{ND}=0.4 (RCNP-QES)
    - *Predict the enhancement of the 3rd peak (q=1.7fm^{-1})*
    - precursor for pion condensation
  - Our data are consistent with QES

Separation of π- and ρ-mode with PTO is reliable



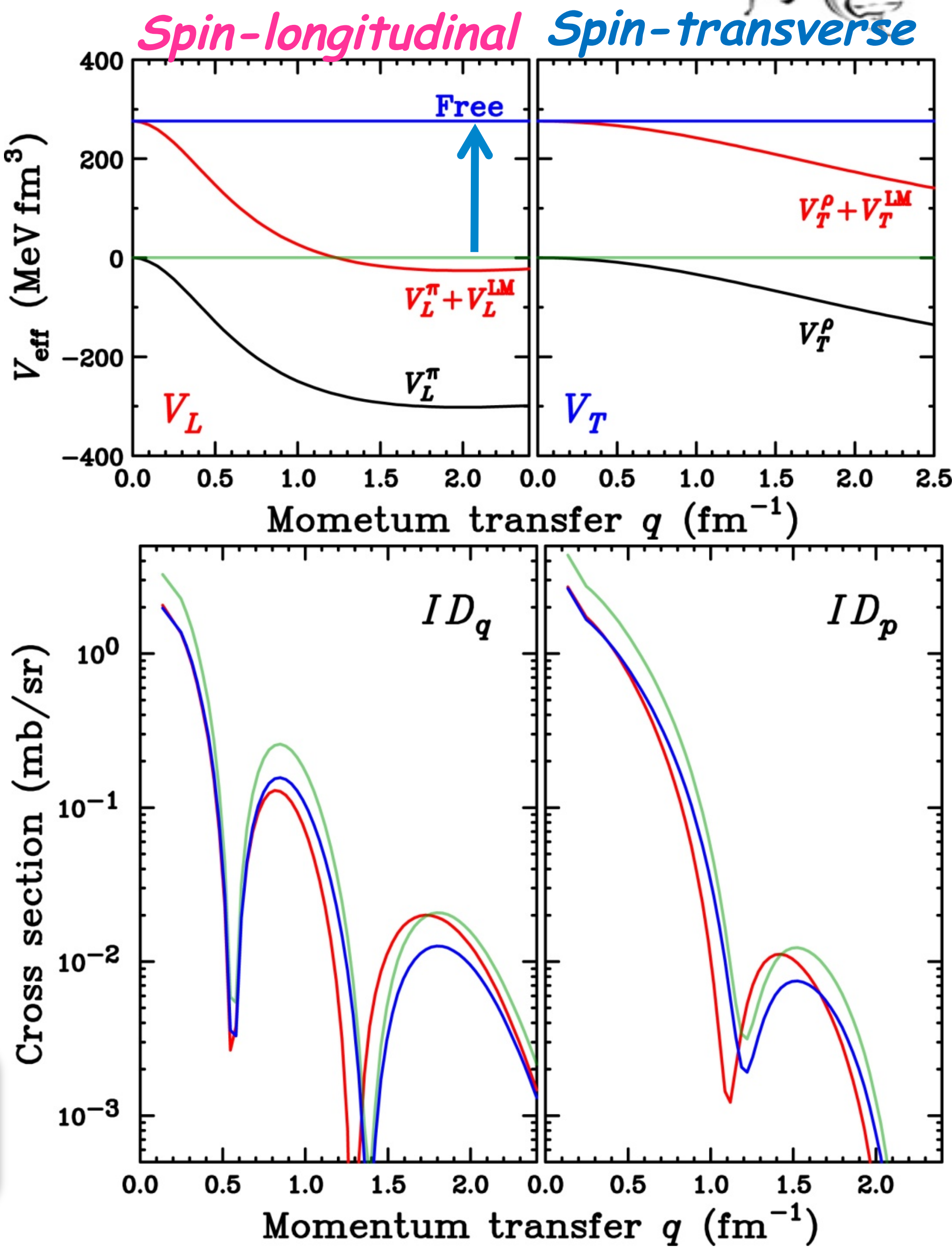
PTO (D_{ij})



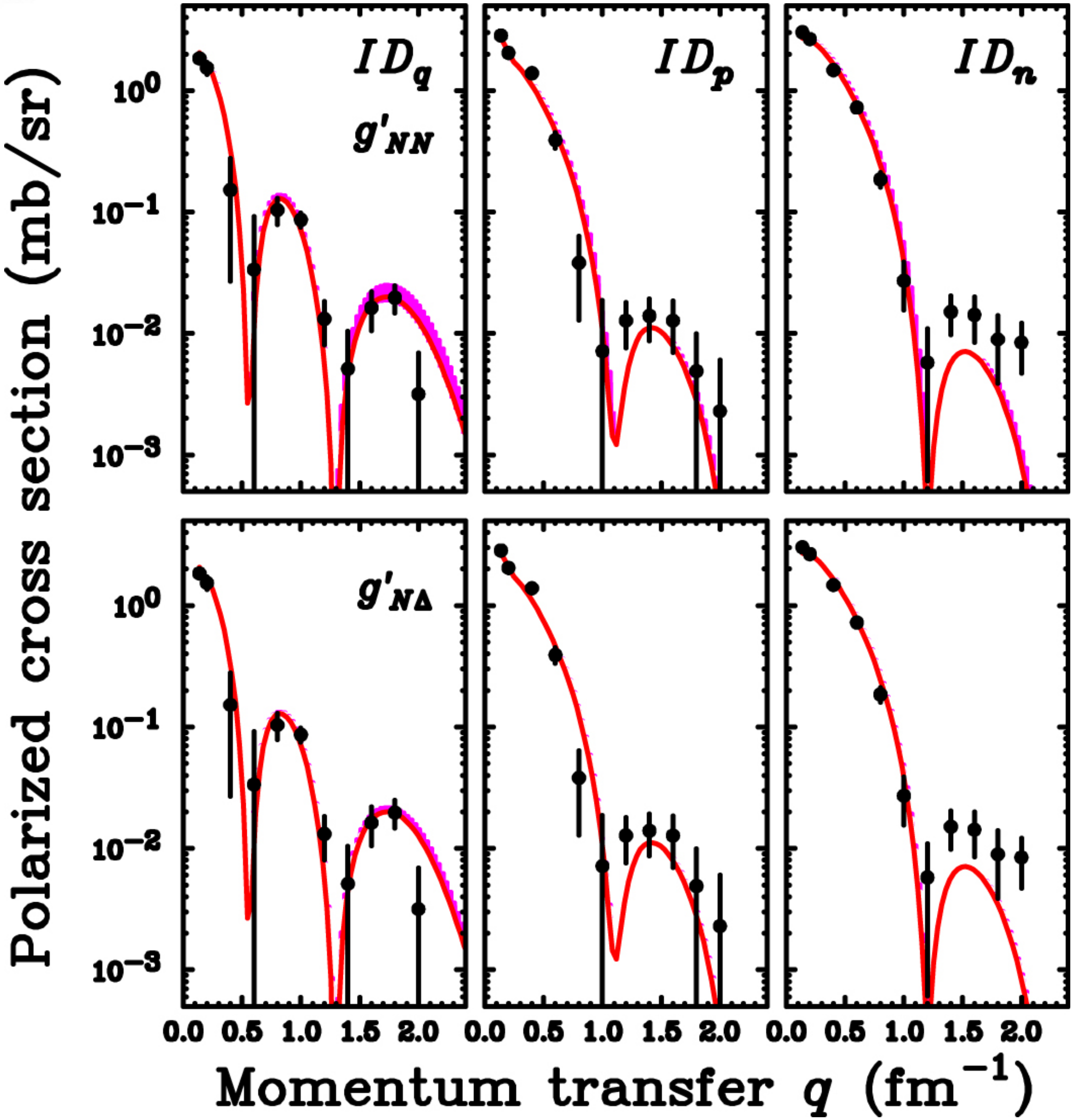
Exclusion of g' Effects

- Original DWIA+RPA calculations
  - RPA correlations
    - Shape change of R in r-space
    - *Modify q-dependence*
  - Quenching at small-q in ID_q and ID_p
  - *Quenching becomes small due to attractive π- and ρ-exchange*
- Response function R at q=0
  - *B(GT) is known from β-decay*
  - Normalization to exp. B(GT)
    - RPA(q=0) = Free(q=0)
    - *Shift the Free results*
- Normalized DWIA+RPA results
  - g'-effects are included in Free

⇔ g' effects are excluded in RPA
π- and ρ-correlations are attractive



g' dependence of $^{12}C(p,n)^{12}N(1^+,T=1)$



g'_{NN} dependence

$g'_{N\Delta}$ dependence

MISC for h’ effects

Momentum Transfer Dependence of g' and h'

E.Oset, H.Toki, and W.Weise, Phys. Rep. 83(1982)281.

- Theoretical Model of Oset, Toki, and Weise at $t = \omega^2 - q^2$

$$\frac{f_\pi^2}{m_\pi^2} g'(q,\omega) = \frac{1}{3}\frac{f_\pi^2(m_0^2 - t)}{m_\pi^2}\frac{m_0^2 + q^2}{m_0^2 + m_\pi^2 - t} + \frac{2}{3}\frac{f_\rho^2}{m_\rho^2}\frac{m_0^2 + q^2}{m_0^2 + m_\rho^2 - t}$$

$$\frac{f_\pi^2}{m_\pi^2} h'(q,\omega) = \frac{1}{3}\frac{f_\pi^2(m_0^2 - t)}{m_\pi^2}\frac{q^2}{m_0^2 + m_\pi^2 - t} - \frac{1}{3}\frac{f_\rho^2}{m_\rho^2}\frac{q^2}{m_0^2 + m_\rho^2 - t}$$

  - h' effects at small q

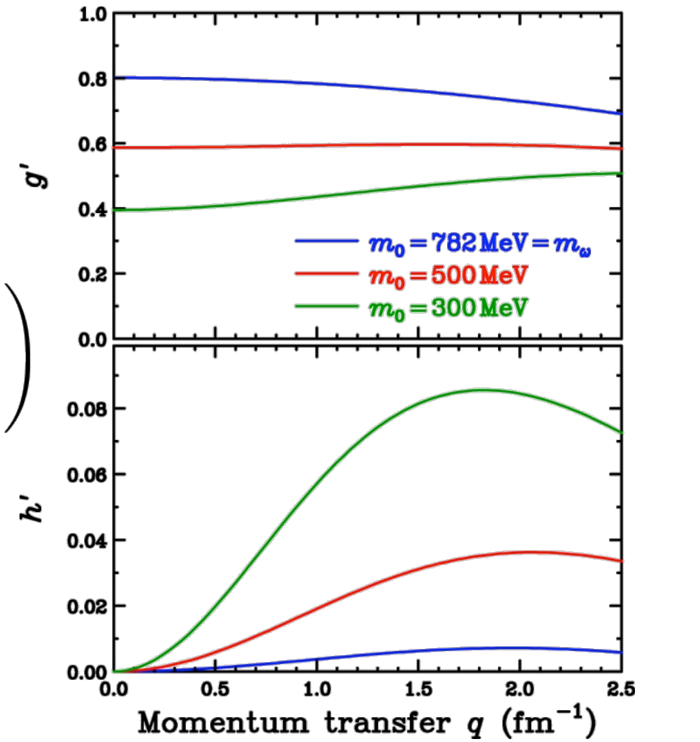
$$\frac{h'(q,\omega)}{g'(q,\omega)} \sim \mathcal{O}\left(\frac{q^2}{m_0^2}\right)$$

- Assumption

$$f_\pi = f_\pi \Gamma_\pi(t) \qquad \Gamma_{\pi/\rho}(t) = \left(\frac{\Lambda_{\pi/\rho}^2 - m_{\pi/\rho}^2}{\Lambda_{\pi/\rho}^2 - t}\right)$$

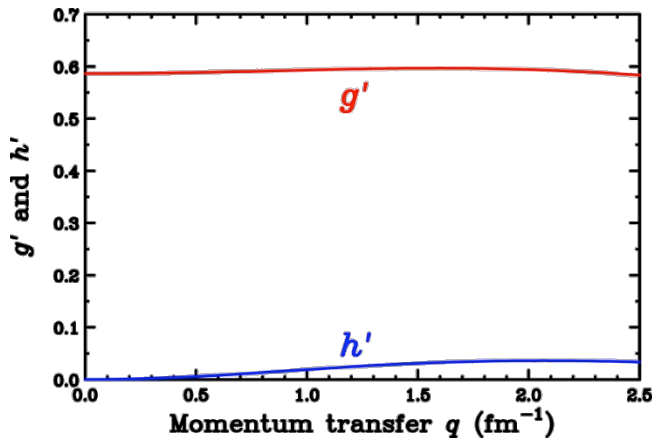
$$f_\rho = f_\rho \Gamma_\rho(t)$$

- m_0 dependence
  - m_0=500MeV → g'=0.6 : most likely
  - h' would be less than 10% of g'

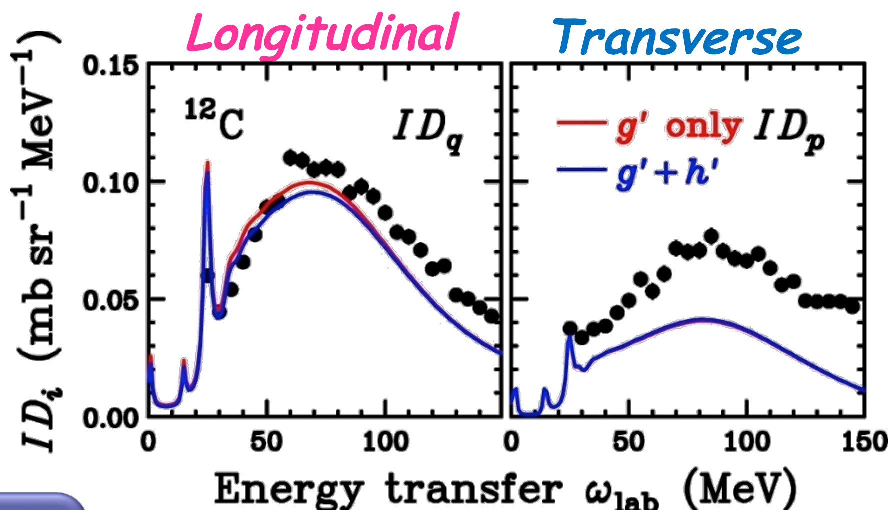


Realistic *h'* Effects on DWIA Calculation

- Momentum-transfer dependence
  - Parameter m_0=500 MeV
    - *g'* = 0.6 (const.) for wide-*q*
      - Consistent with experimental results
    - *h'* = 0.03 at *q*=1.7 fm^{-1}
      - Universality is assumed



- DWIA results
  - *Spin-longitudinal*
    - Small repulsive contribution
    - Small quenching
  - *Spin-transverse*
    - Negligible contribution
    - Negligible effects



- Phenomenological approach

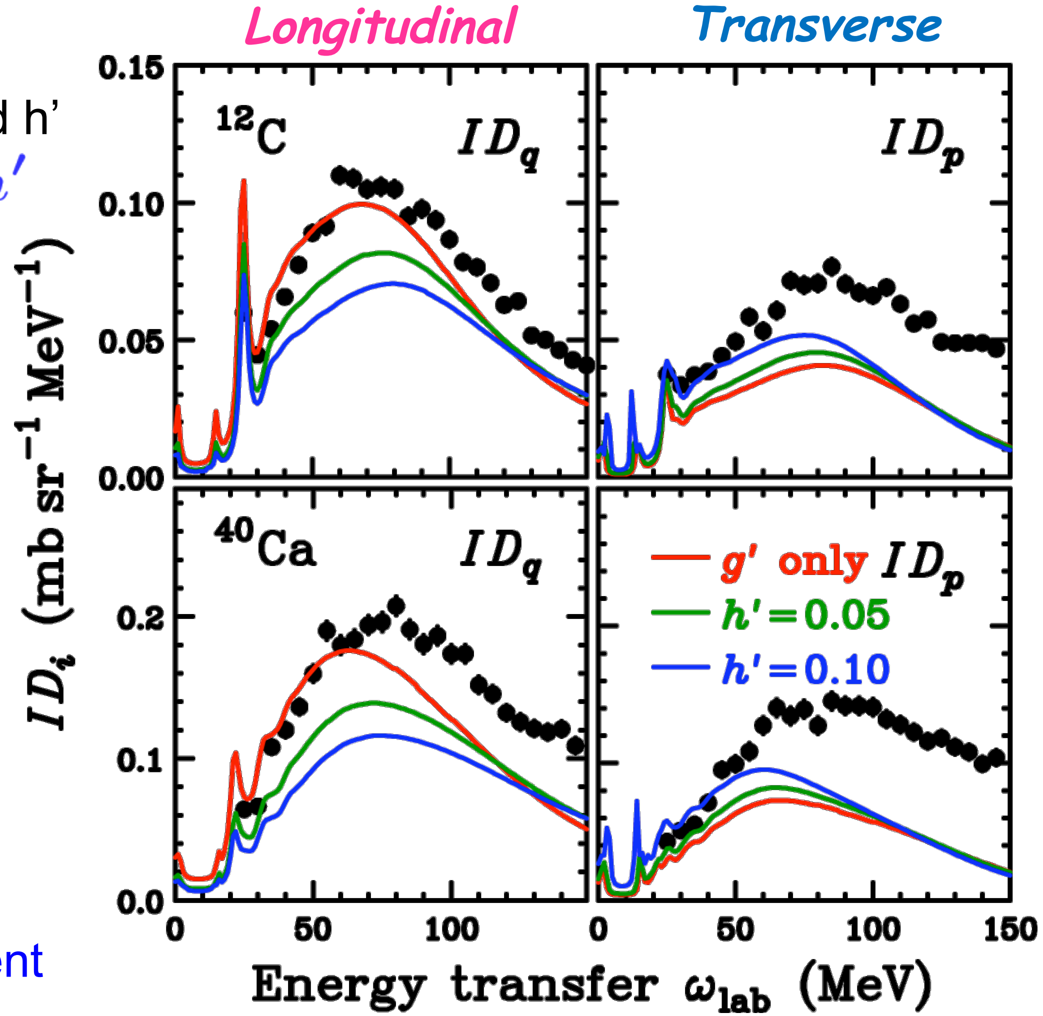
Is there a phenomenological *h'* value which can reproduce experimental data consistently ?

h' Dependence of DWIA Calculation

- Most "simple" case
  - Neglect *q*-dependence of g' and h'

    Longitudinal $g'_\pi = g' + 2h'$

    Transverse $g'_\rho = g' - h'$
- For *h'* > 0
  - *Spin-longitudinal*
    - Repulsive contribution
    - Quenching
  - *Spin-transverse*
    - Attractive contribution
    - Enhancement
- Results
  - Quenching in ID_q is too large
  - Enhancement in ID_p is insufficient

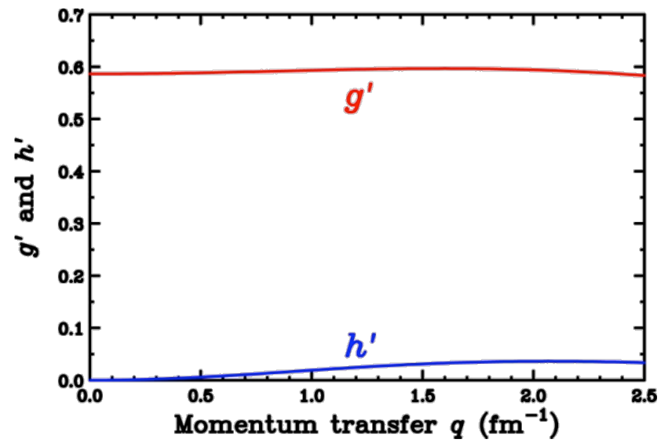


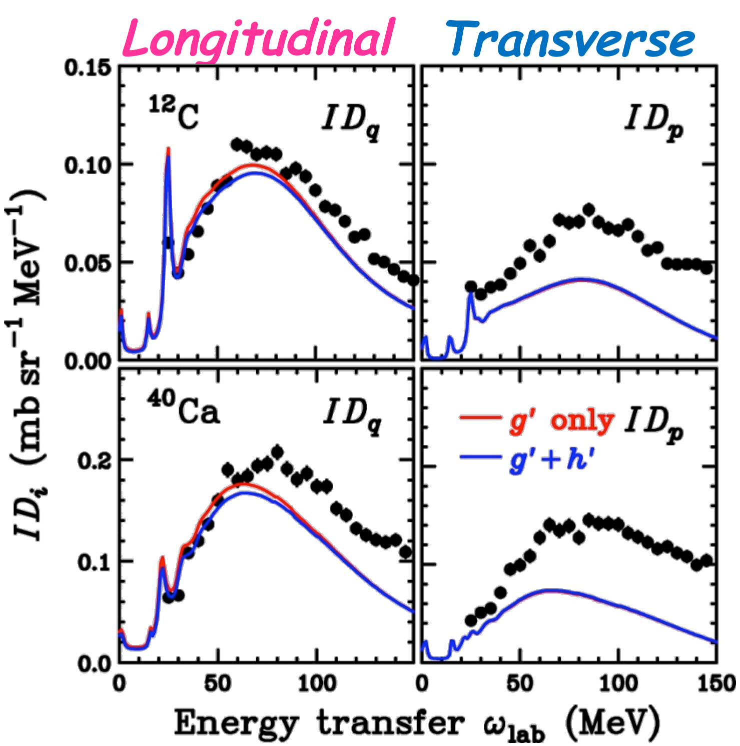
Quenching in ID_q can be recovered with larger g'
⇒ *Enhancement in ID_p is cancelled*

Realistic *h'* Effects on DWIA Calculation

- Momentum-transfer dependence
  - Parameter m_0=500 MeV
    - *g'* = 0.6 (const.) for wide-*q*
      - Consistent with experimental results
    - *h'* = 0.03 at *q*=1.7 fm^{-1}
      - Universality is assumed
- DWIA results
  - *Spin-longitudinal*
    - Small repulsive contribution
    - Small quenching
  - *Spin-transverse*
    - Negligible contribution
    - Negligible effects
- Phenomenological approach

Is there a phenomenological *h'* value which can reproduce experimental data consistently ?

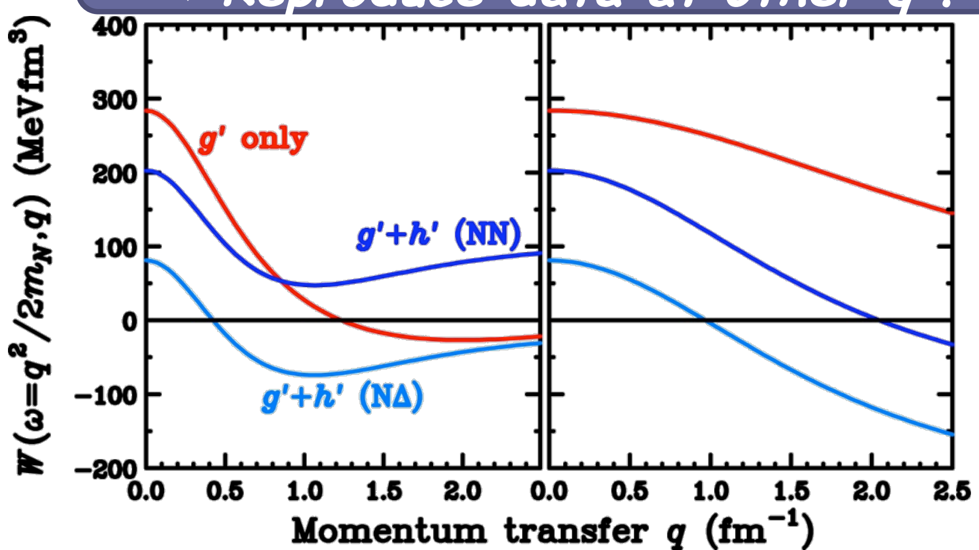


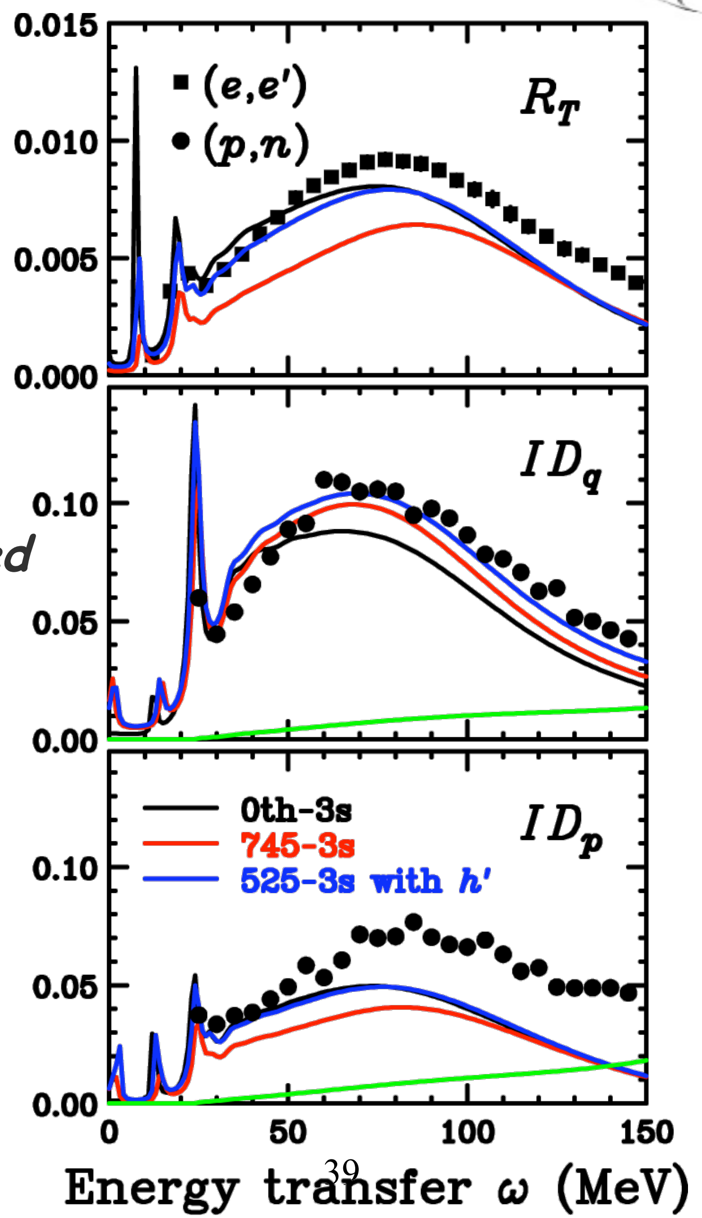


Phenomenological Approach

- 3-types of residual interaction
  - Free (without correlation)
  - Original
    - g'$_{NN}$=0.7, g'$_{N\Delta}$=0.4
  - Phenomenological (Fit)
    - g'$_{NN}$=0.5, g'$_{N\Delta}$=0.2 (within uncertainty)
    - h'=0.2 at q=1.7fm^{-1}
  - *Significant 2-step contiribution is expected*

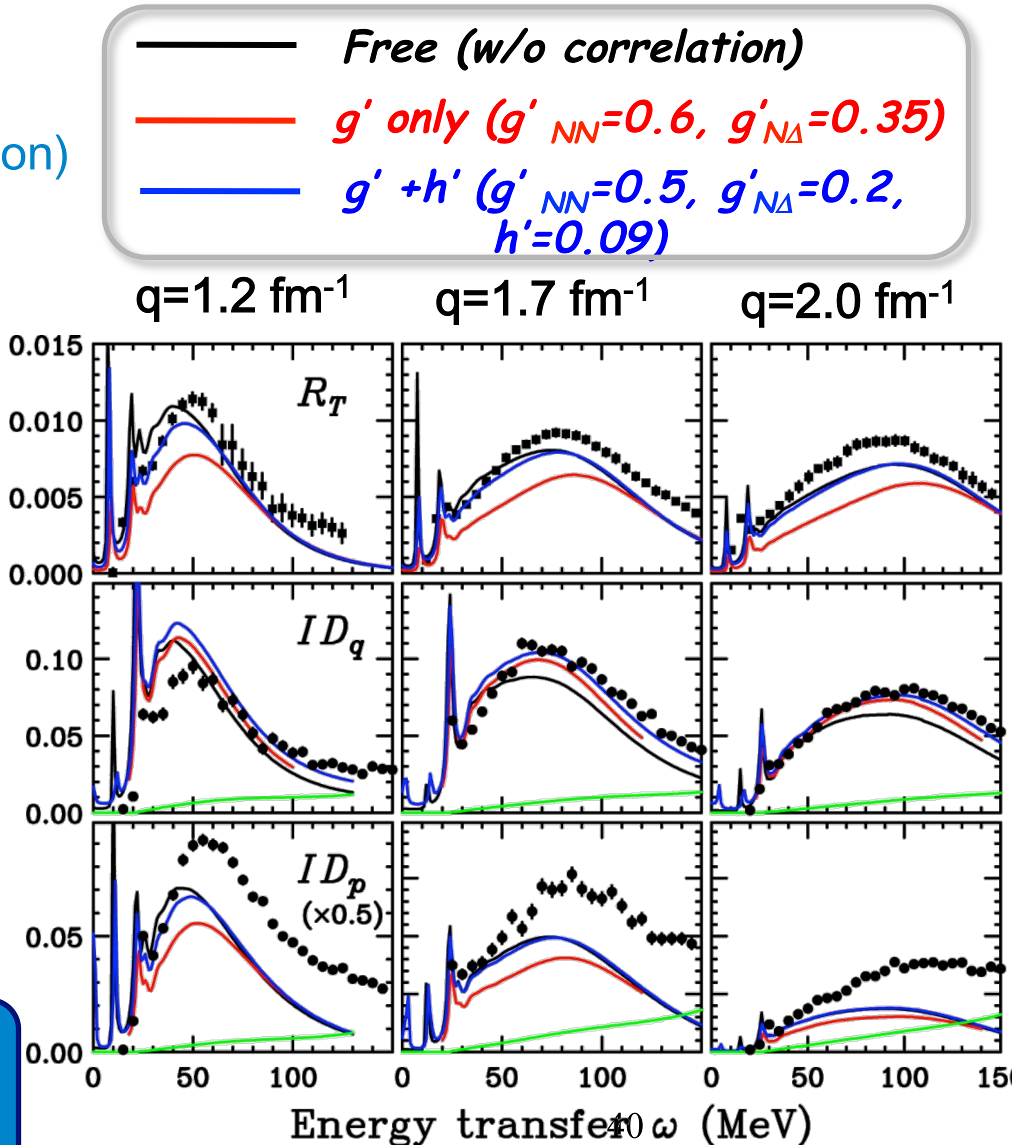
Reproduce both (e,e') and (p,n)
⇒ Reproduce data at other q ?





Phenomenological Approach for wide *q*

- Transverse response in (e,e')
  - Well reproduced with g'+h'
  - Consistent with free (w/o correlation)
  - *MEC/2p2h effects are effectively included with h'*
- Spin-longitudinal in (p,n)
  - Consistent with Original RPA
    - g'_{NN} = 0.6 → 0.5
    - $g'_{N\Delta}$ = 0.35 → 0.2
  - *Repulsion from h' is cancelled with smaller g'*
- Spin-transverse in (p,n)
  - Consistent with free
  - Significant 2-step contributions
    - *Still underestimated*

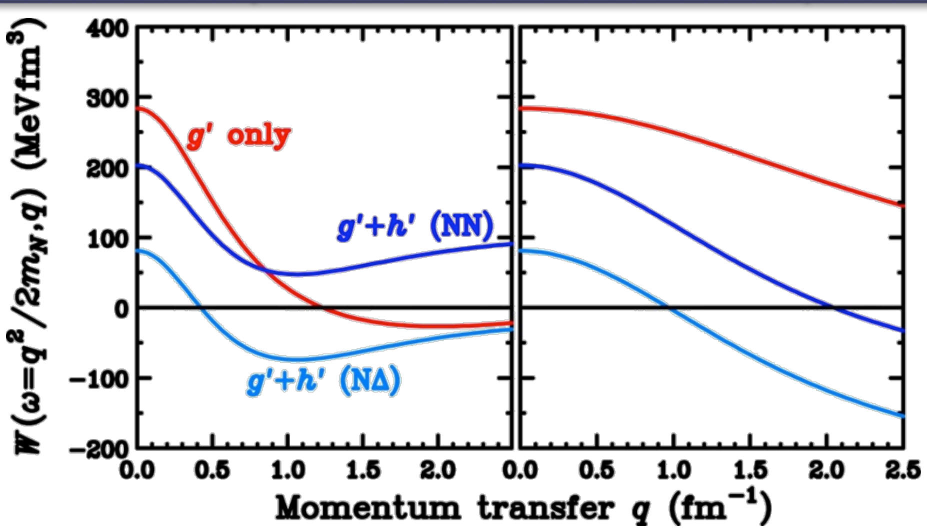


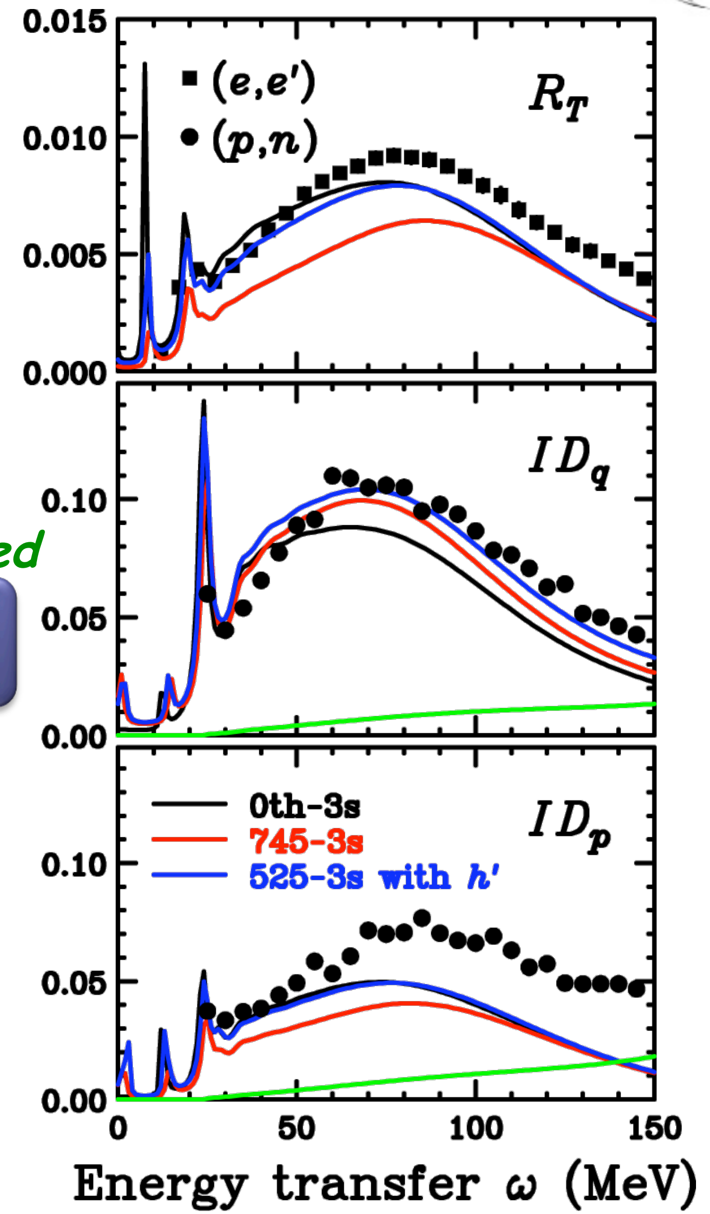
Tensor correlations can give better description for transverse mode, but still something missing

Phenomenological Approach

- 3-types of residual interaction
  - Free (without correlation)
  - Original
    - g'_{NN}=0.6, $g'_{N\Delta}$=0.35
  - Phenomenological (Fit)
    - g'_{NN}=0.5, $g'_{N\Delta}$=0.2 (within uncertainty)
    - h'=0.2 at q=1.7fm^{-1}
  - *Significant 2-step contiribution is expected*

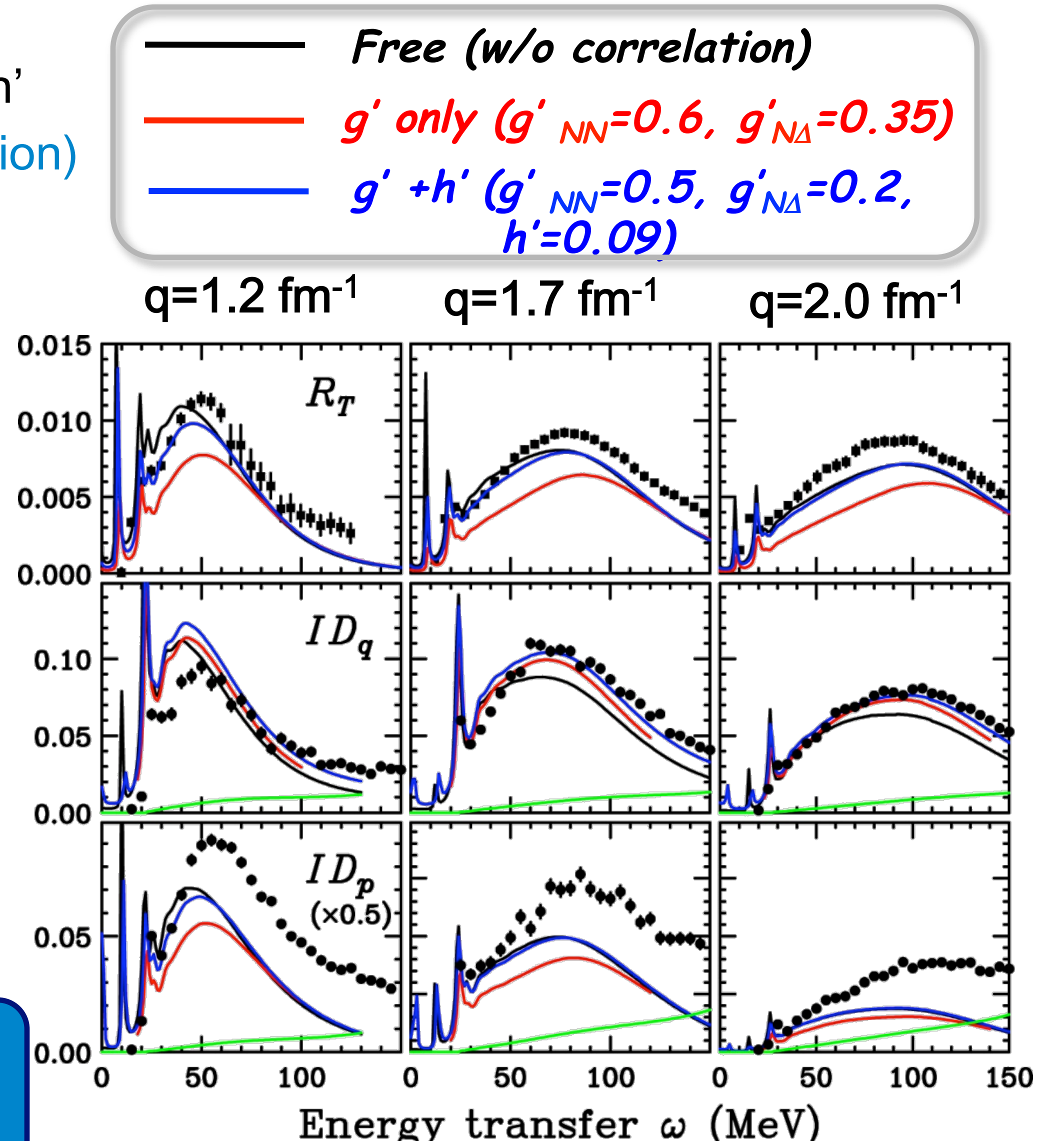
Explain discrepancy for (e,e') & (p,n) in part
⇒ Reproduce data at other q ?





Phenomenological Approach for wide q

- Transverse response in (e,e')
  - Reasonably reproduced with g'+h'
  - Consistent with free (w/o correlation)
  - *MEC/2p2h effects are effectively included with h'*
- Spin-longitudinal in (p,n)
  - Consistent with Original RPA
    - $g'_{NN} = 0.6 \rightarrow 0.5$
    - $g'_{N\Delta} = 0.35 \rightarrow 0.2$
  - *Repulsion from h' is cancelled with smaller g'*
- Spin-transverse in (p,n)
  - Consistent with free
  - Significant 2-step contributions
    - *Still underestimated*



Tensor correlations can give better description for transverse mode, but still something missing

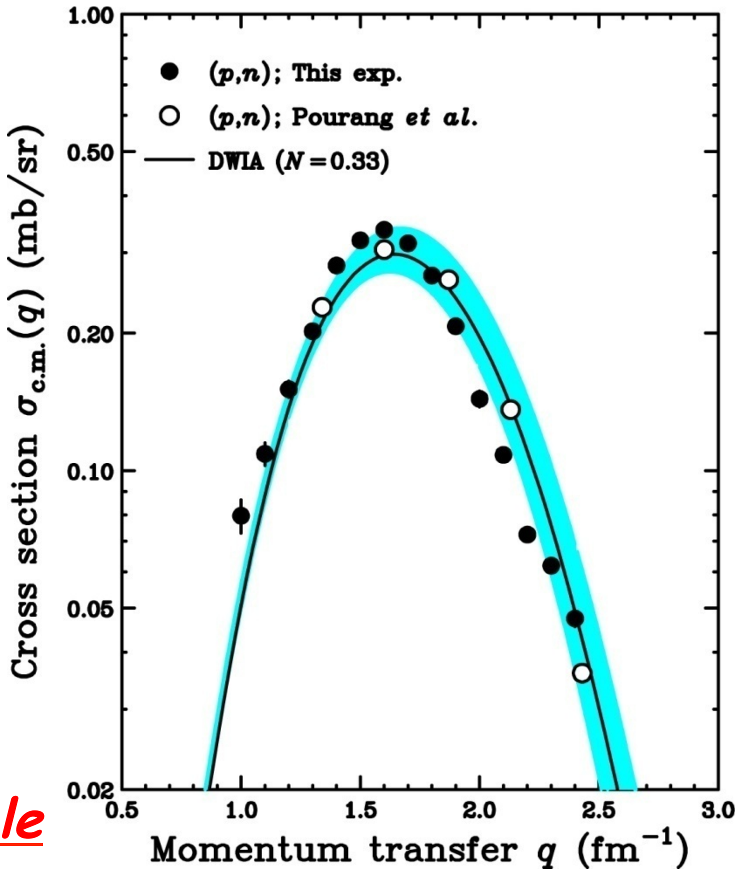
MISC for RCNP-E236

Cross Section and DWIA Calculation

T.W., Y. Hagihara, et al.,PLB 645(2007)402.

- Smooth q-dependence specified by L=6
  - Clear separation of 6^- from neighboring states with ΔE=500keV
  - Consistent with previous work
- DWIA calculations
  - Slightly sensitive to OMP (shown by band)
  - DWIA reproduces our data
    - q-dependence
    - Absolute values
      - *OMP (Distortions)*
      - *S-Factor (Form factor)*

Reliable



Comparison with DWIA enables us to obtain
the information on absolute values of NN interaction

Enhancement of ID_n - *Common at large q-*

T.W., Y. Hagihara, et al.,PLB 645(2007)402.

- Two spin-transverse ID_i

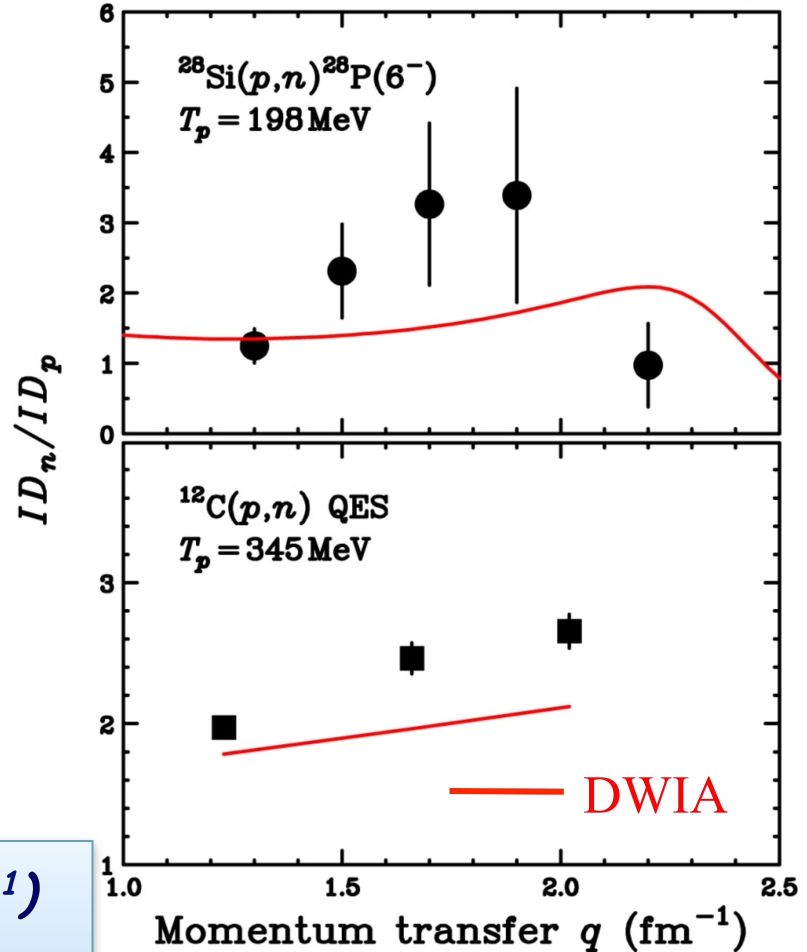
$$ID_p \approx N_D \cdot F^2 \cdot R_p \qquad ID_n \approx N_D \cdot B^2 \cdot R_n$$

Spin-transverse response is common ($R_p = R_n$)

$$\Rightarrow \frac{ID_n}{ID_p} = \frac{B^2}{F^2}$$

"Insensitive to response/distortion"

- Momentum-transfer dependence
  - Enhancement of ID_n/ID_p
    - Stretched state in ^{28}Si(p,n)
    - QE scattering in ^{12}C(p,n)



Enhancement of B at large q (1.5 - 2.0 fm^{-1})

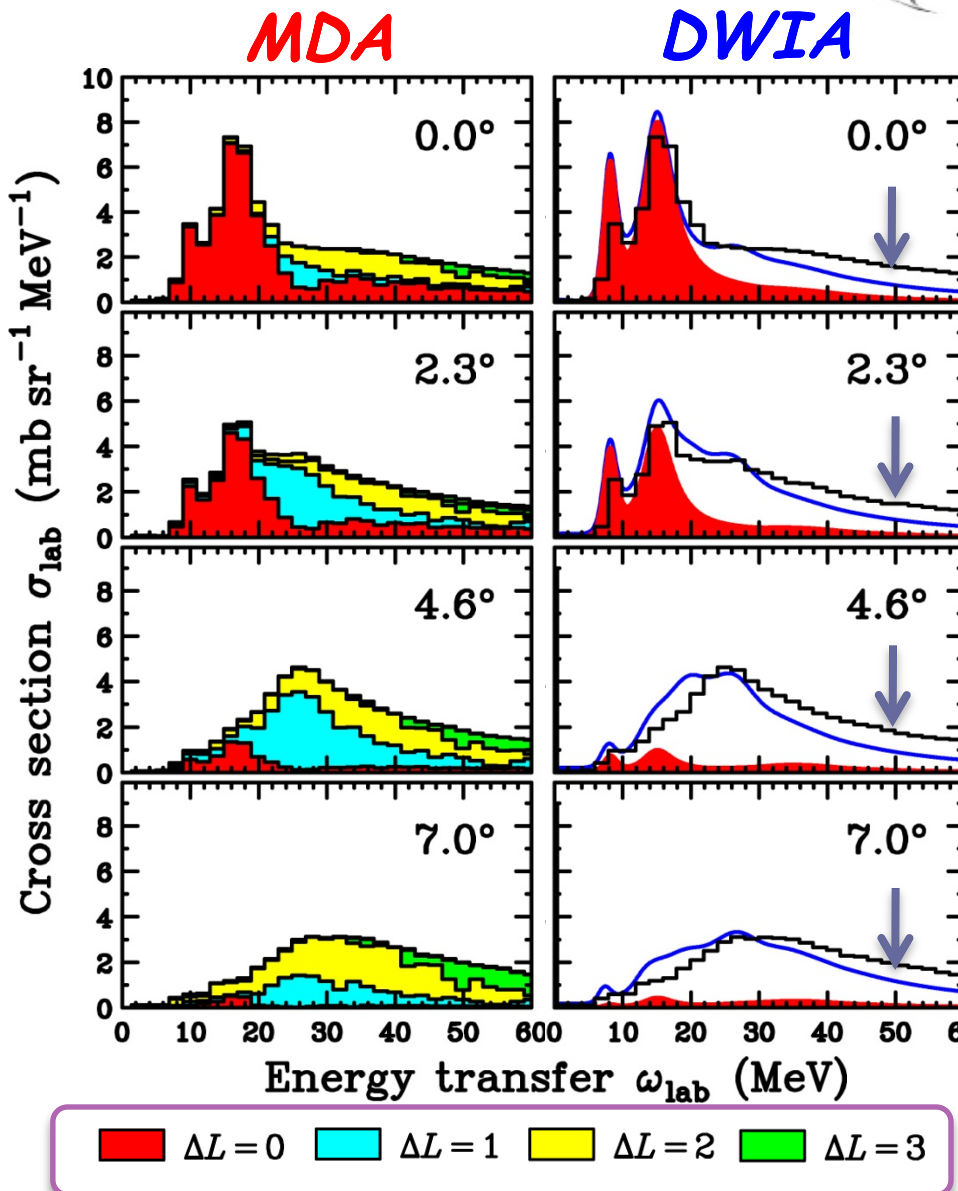
◆Common to (p,n) reaction

◆Common to intermediate energies

MISC for crdw

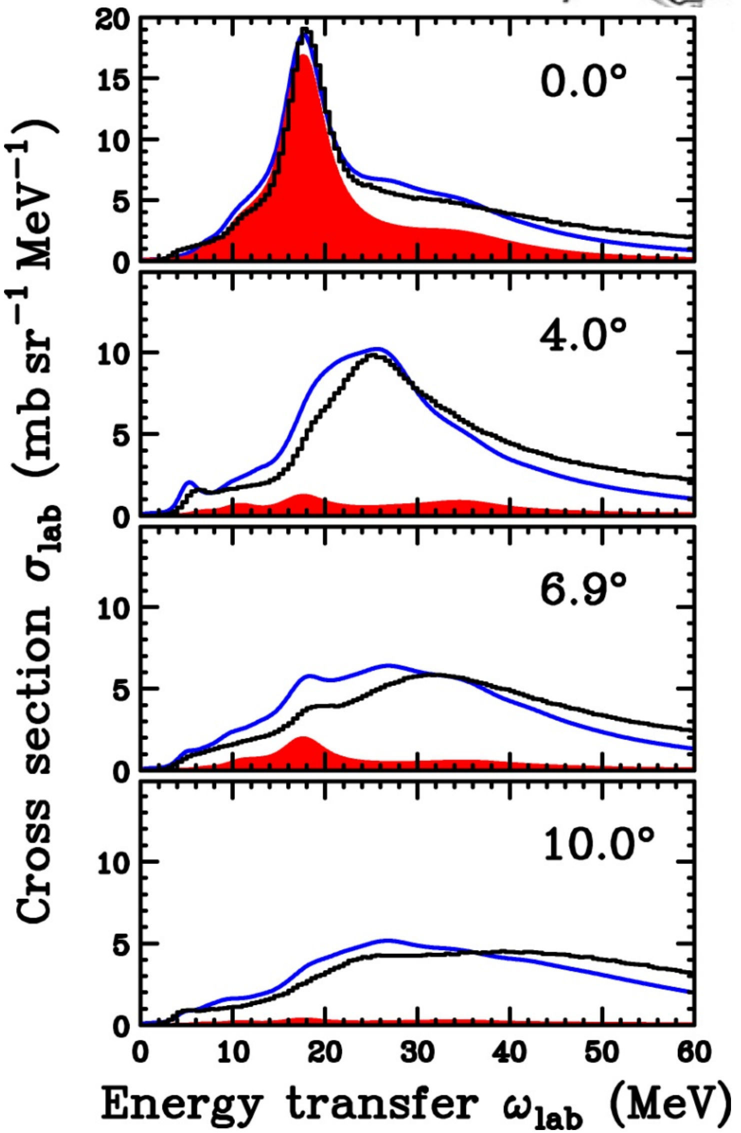
Return to ^{90}Zr(p,n) ; MDA vs. DWIA

- Experimental data
  - ^{90}Zr(p,n) at 295 MeV at RCNP
  - 0°～12.3° with ～2° steps
- DWIA calculations
  - *Parameter-free calculations*
    - Global OMP for ^{90}Zr
    - Franey-Love NN interaction
    - RPA with π+ρ+g'
    - Phenomenological spreading-width
  - Reasonably reproduce GTGR/SDR
    - π+ρ+g' *interaction is reasonable*
  - Underestimation at ω > 30 MeV
    - *2p2h effects are important (1+ strength is also underestimated)*



DWIA Calculations for ^{208}Pb(p,n)

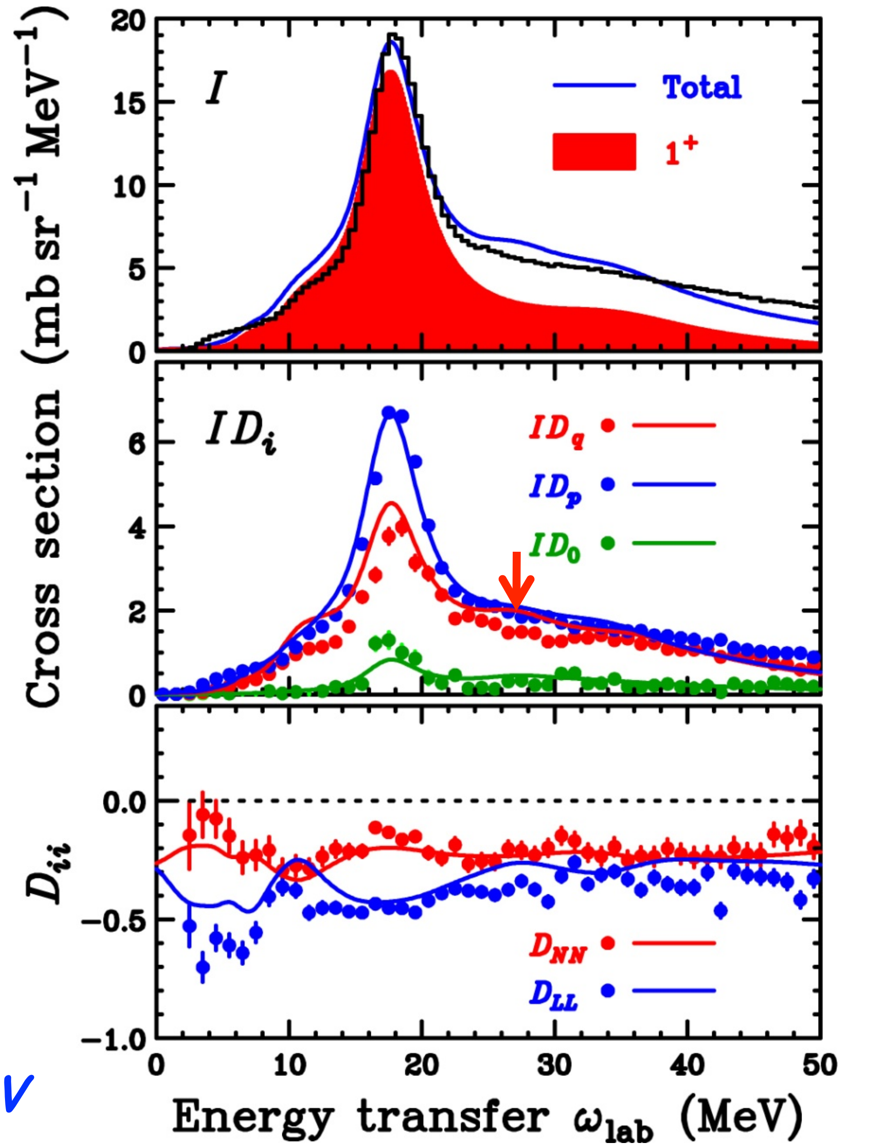
- Experimental data
  - ^{208}Pb(p,n) at 295 MeV at RCNP
  - 0°～13.4° with ～1° steps
- DWIA calculations
  - *Parameter-free calculations*
    - Global OMP for ^{208}Pb
    - Franey-Love NN interaction
    - RPA with π+ρ+g'
    - Phenomenological spreading-width
  - Reasonably reproduce GTGR/SDR
    - π+ρ+g' *interaction is reasonable*
  - Underestimation at ω > 35 MeV
    - *2p2h effects are important*
- 1^+ strengths
  - GTGR is dominant with 1^+(L=0)
  - 1^+ at ω > 30 MeV has IVSM(L=0)/SGQR(L=2)



MDA is now in progress ⇔ *DWIA with 2p2h is highly desired*

Polarization transfer for $^{208}Pb(p,n)$ at 0°

- Spin-scalar ID_0
  - Negligible except at ω=17 MeV
    - IAS (0^+) contribution
  - *Spin-flip dominance*
- Spin-vector ID_q and ID_p
  - $R_q = R_p$ at q=0 (0°)
  - $ID_q < ID_p$
    - *Exchange-tensor effects ($E^2 < F^2$)*
- DWIA calculations
  - Reasonably reproduce PTO(D_{ii})
    - *Spin-scalar f' is also included*
  - *Multi-step seems to be small*
    - *D_{ii} → 0 for multi-step*
  - *Overestimation for ID_q at ω=28 MeV*
    - *0^- contribution → Fragmented ?*

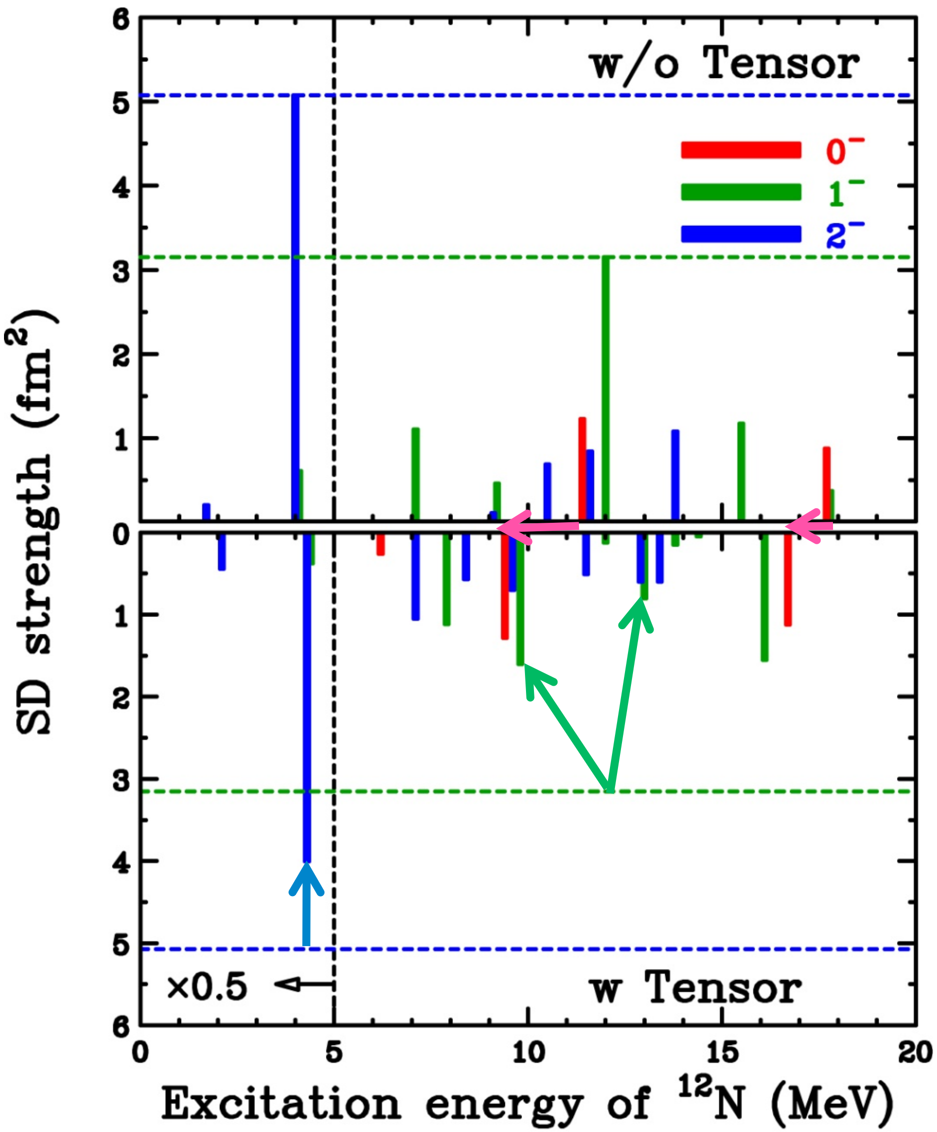


MISC for SDR

Tensor Effects on SDR Strengths

T.Suzuki and H.Sagawa, NPA 637, 547 (1998).

- Shell-Model calculations
  - M3Y interaction
    - w/o Tensor (Upper panel)
    - w Tensor (Lower panel)
  - 3hω model space
- 2^- strength
  - Quench the state at 4 MeV
- 1^- strength
  - Quenching and fragmentation
  - *Repulsive tensor correlation*
- 0^- strength
  - Shift to lower E_x
  - *Attractive tensor correlation*



Extended MDA (RCNP-E317)

M. Dozono, T.W., et al., RCNP Proposal E317

- Multipole Decomposition Analysis
  - *Normal* : Separate each L
  - *Extended* : Separate each J^π
- Extended MDA procedure (up to L=2)

Separation to each J^π

- Separate cross section I into ID_q and ID_p using D_{ij}
- Separate ID_q to each L using normal MDA

$$ID_q = \underbrace{ID_q^{1^+}}_{L=0} + \underbrace{ID_q^{0^-} + ID_q^{2^-}}_{L=1} + \underbrace{ID_q^{3^+}}_{L=2},$$

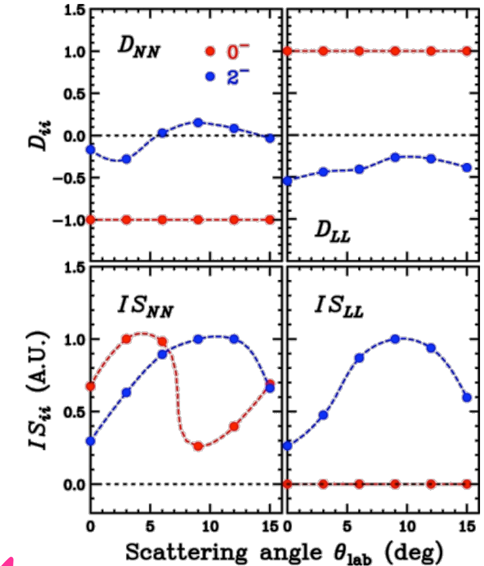
Normal MDA

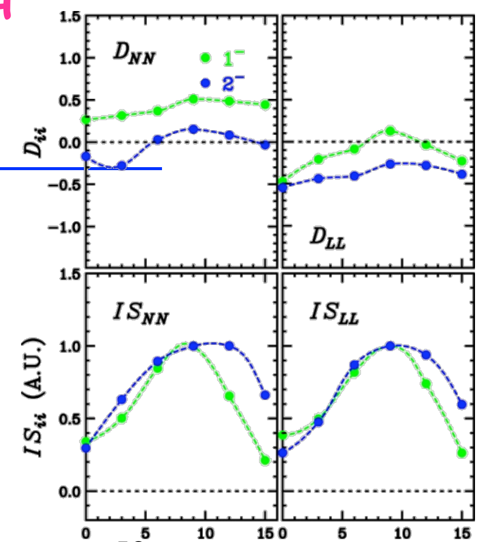
- Separate ID_q^{0-} and ID_q^{2-} with IS_{NN} and IS_{LL}
  - No 0^- contribution in IS_{LL} *Extended MDA*
- Separate ID_p to each L using normal MDA

$$ID_p = \underbrace{ID_p^{1^+}}_{L=0} + \underbrace{ID_p^{1^-} + ID_p^{2^-}}_{L=1} + \underbrace{ID_p^{2^+} + ID_p^{3^+}}_{L=2}$$

Normal MDA

- Separate ID_p^{1-} and ID_p^{2-} with D_{NN} and D_{LL}
  - Significant difference in D_{ij} *Extended MDA*



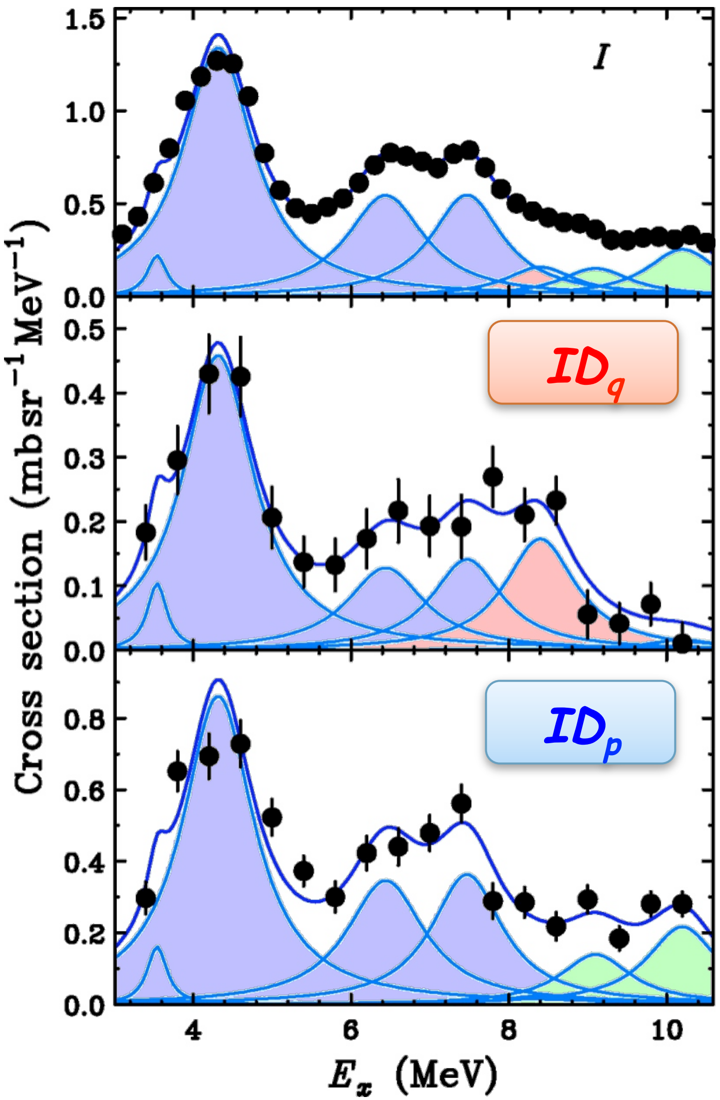


J^{π} Components of SDR in ^{12}N

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

- E_x = 4.3 MeV (2^-)
  - ID_q and ID_p
  - Consistent with 2^- case
- 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)
- E_x = 9.1 and 10.2 MeV
  - ID_p only
  - 1^- (dominant)

Consistent with recent calculations
⇒1^- strengths are quenched and fragmented by tensor correlations



Experimental Deduction of SD Strengths

- Separate cross section into polarized cross sections using D_{ij}

Non-Spin / Spin-Transverse

$$I = ID_0 + ID_q + ID_n + ID_p$$

Spin-Longitudinal

- Relation between ID_i and response functions R_i

NN t-matrix

Spin-longitudinal $ID_q = KN|E|^2 R_q$

Spin-transverse $ID_p = KN|F|^2 R_p$

Kinematic and Distortion factors

Response functions

- Selective contributions to R_i in SD excitations

0^- : R_q only

2^- : R_q and R_p

Spin-longitudinal $ID_q^{SD} = ID_q^{0^-} + ID_q^{2^-}$

Spin-transverse $ID_p^{SD} = +ID_p^{1^-} + ID_p^{2^-}$

1^- : R_p only

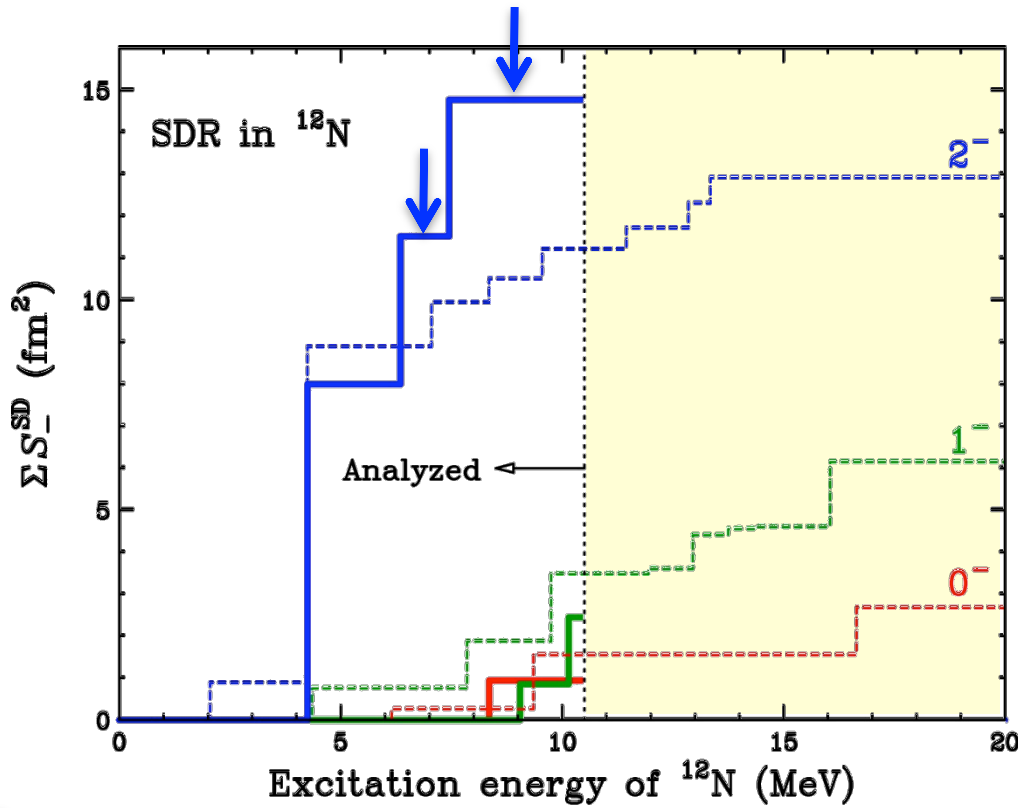
Separation to ID_i → Rigorous J^π assignment

Cumulated Sum of SDR in 12N

- SDR strength in E < 10 MeV
  - 2^- : *Exceeds* total strength (sum-rule)
  - $0^-/1^-$: *quenched*

2^- at 6.4 and 7.5 MeV
→ Might have $0^-/1^-$ components
⇒ *Separation* of $0^-/1^-$ from 2^-

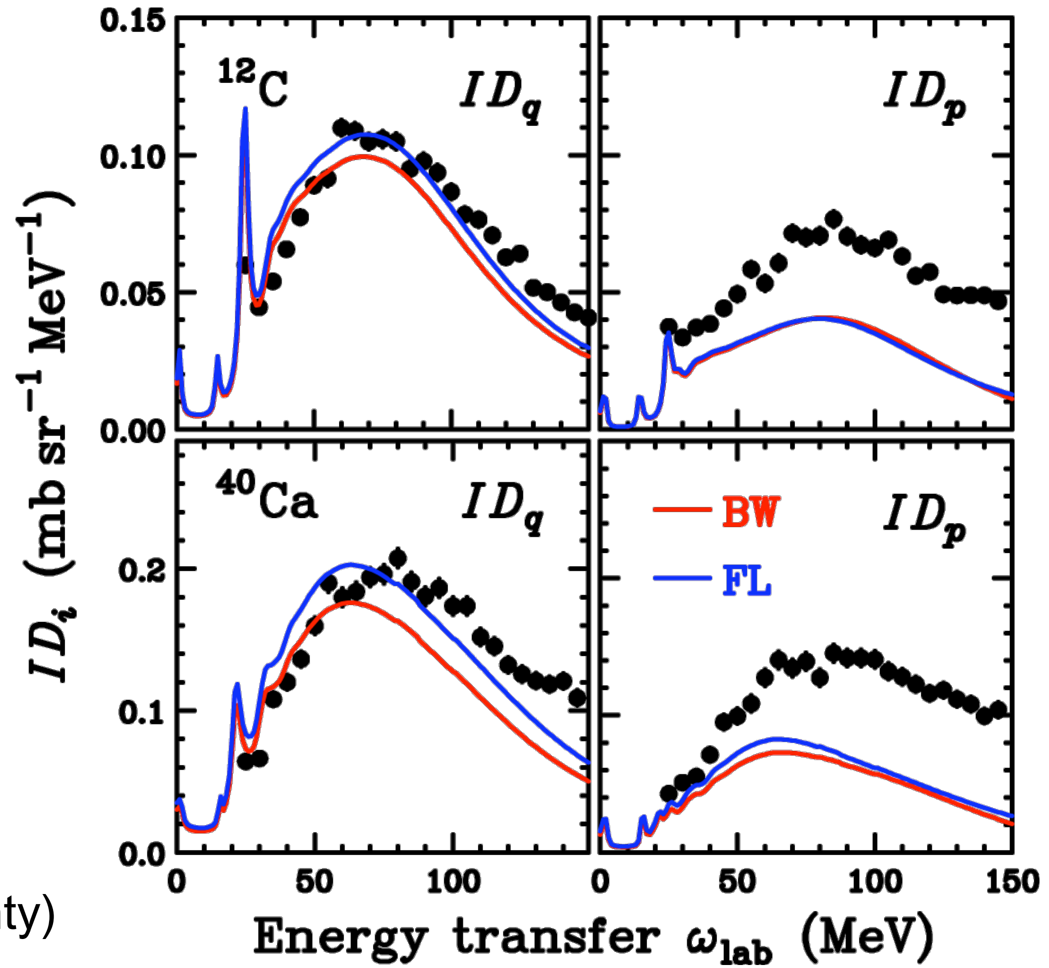
- Prediction in E > 10 MeV
  - Significant $0^-/1^-$ strengths
- Experimental deduction of SDR
  - *Separation* of SDR (L=1) from other contributions (SQR)



MDA not only for L but also for J^π is required

NN Interaction Dependence

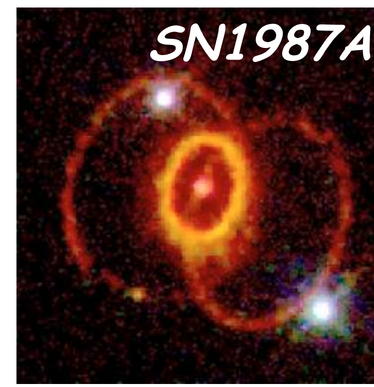
- Bugg-Wilkin (BW)
  - Scattering amplitude
    (Based on NN phase-shift)
  - Optimum-frame approx.
    - (E,q) of NN is a function of (ω,q) of NA
- Franey-Love (FL)
  - t-matrix in r-space
    (Fitted to NN on on-shell)
  - FL-type kinematics
    - E of NN is fixed (T_p)
    - q of NN is a function of (ω,q) of NA
- Results
  - ID_q slightly depends on NN interaction (within g' uncertainty)
  - ID_p is insensitive



MISC for RCNP-E317

ientific Motivation for SD Resonance

- **Search/Identify missing 0^- states**
  - Model (roughly) independent sum-rule
    - Missing strength is crucial problem in nuclear physics.
  - 0^- is the quantum number of pions
    - 0^- strength is sensitive to pions in nuclei
    - Useful information on tensor correlations in nuclei (Toki and co-workers / RCNP theory group)



- **Search/Identify missing 1^- states**
  - Recent (p,n) and (d,^{2}He) experiments in A=12
    - Part of 1^- strength is re-assigned to 2^-
    - 1^- strength is missing compared with sum rule

- **Importance of A=16 system**
  - SD excitations in ^{16}O relates to the neutrino detection from supernovae with Super-Kamiokande
    - SD strengths information in ^{16}F is very important

SD Sum Rules

Non-Energy-Weighted Sum Rule (NEWS)

- SD operator *T.Suzuki and H. Sagawa, NPA 637, 547 (1998).*

$$\hat{O}^{\lambda,\mu}_{\pm} = \sum_i \tau^i_{\pm} r_i [Y_1(\hat{r}_i) \times \vec{\sigma}_i]^{\lambda}_{\mu}$$

- SD sum rule

$$S^{\lambda}_{-} - S^{\lambda}_{+} = \langle 0 | [\hat{O}^{\lambda,\mu}_{-}, \hat{O}^{\lambda,\mu}_{+}] | 0 \rangle = \frac{2\lambda+1}{4\pi} (N\langle r^2 \rangle_n - Z \langle r^2 \rangle_p)$$

- SD sum rule values
  - Analytical values with harmonic-oscillator W.F. in 1hω
    - ^{12}C

$$S^{\lambda}_{-} = \sum_{\mu} |\langle \lambda\mu | \hat{O}^{\lambda,\mu}_{-} | 0 \rangle|^2 = \begin{cases} \frac{3}{4\pi}\frac{20}{3} b^2 = 4.28\,\mathrm{fm}^2, & \lambda = 0^- \\ \frac{3}{4\pi}\frac{54}{3} b^2 = 11.56\,\mathrm{fm}^2, & \lambda = 1^- \\ \frac{3}{4\pi}\frac{70}{3} b^2 = 14.98\,\mathrm{fm}^2, & \lambda = 2^- \end{cases}$$

$S^0_- : S^1_- : S^2_- = 1 : 2.7 : 3.5$ *for jj-closed nuclei*

    - ^{16}O

$$S^{\lambda}_{-} = \sum_{\mu} |\langle \lambda\mu | \hat{O}^{\lambda,\mu}_{-} | 0 \rangle|^2 = \begin{cases} \frac{3}{4\pi} 8 b^2 = 5.98\,\mathrm{fm}^2, & \lambda = 0^- \\ \frac{3}{4\pi} 24 b^2 = 17.95\,\mathrm{fm}^2, & \lambda = 1^- \\ \frac{3}{4\pi} 40 b^2 = 29.92\,\mathrm{fm}^2, & \lambda = 2^- \end{cases}$$

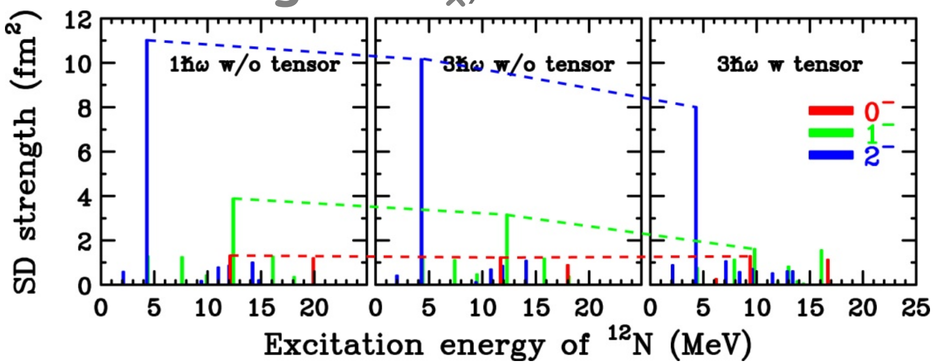
$S^0_- : S^1_- : S^2_- = 1 : 3 : 5$ *for ls-closed nuclei*

0^- strength is weak ⇔ 2^- strength is string (×3.5~5)

nsor and Model Space Effects

T.Suzuki and H. Sagawa, NPA 637, 547 (1998).

- SD strenghts for E_x < 25 MeV in SM (M3Y)
  - 2^- : consistent with NEWS
  - 0^- and 1^- : about 70% (fragmentation to higher E_x)
- Tensor correlation effects
  - 0^- : 20% **enhancement**
  - 1^- and 2^- : less sensive
- Configuration space effects
  - 1^- : significant **quenching**
  - 0^- and 2^- : less sensitive



Interaction	Space	0^-	1^-	2^-
NEWS	1hω	4.28	11.56	14.98
M3Y w/o tensor	1hω	2.55	8.78	14.59
M3Y with tensor	1hω	3.09	8.02	14.51
M3Y with tensor	3hω	2.93	6.23	12.99

Enhancement

Quenching

perimental Deduction of SD Strengths

- Separate cross section into polarized cross sections using D_{ij}

$$I = ID_0 + ID_q + ID_n + ID_p$$

- Relation between ID_i and response functions R_i

NN t-matrix

$$\text{Spin-longitudinal } ID_q = KN|E|^2 R_q$$

$$\text{Spin-transverse } ID_p = KN|F|^2 R_p$$

Kinematic and Distortion factors

Response functions

- Selective contributions to R_i in SD excitations

0^- : R_q only

2^- : R_q and R_p

$$\text{Spin-longitudinal } ID_q^{SD} = ID_q^{0^-} + ID_q^{2^-}$$

$$\text{Spin-transverse } ID_p^{SD} = + ID_p^{1^-} + ID_p^{2^-}$$

1^- : R_p only

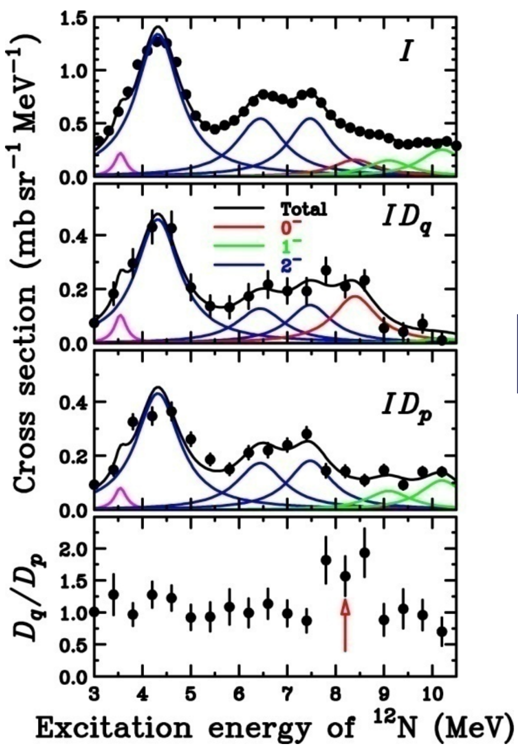
Separation to ID_i → Rigorous J^π assignment

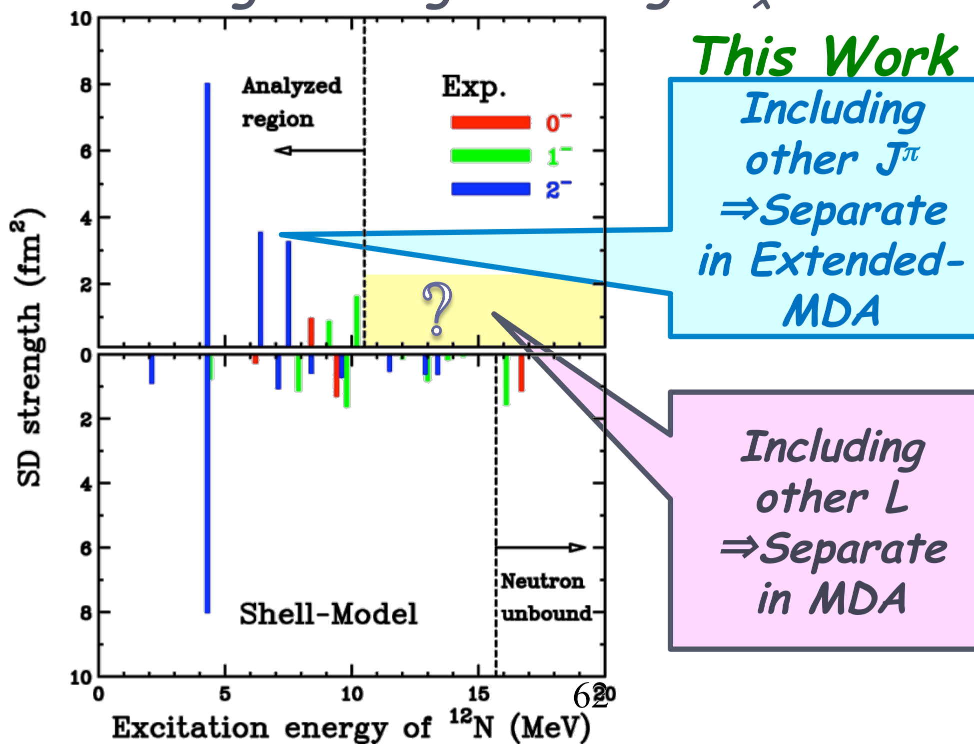
(Pr)evious Results for SDR in ^{12}N

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
    ⇒ (Extended-)MDA is important
- 0^- and 1^- strengths
  - Consistent with SM including tensor
  - *Large strengths in high E_x in SM*

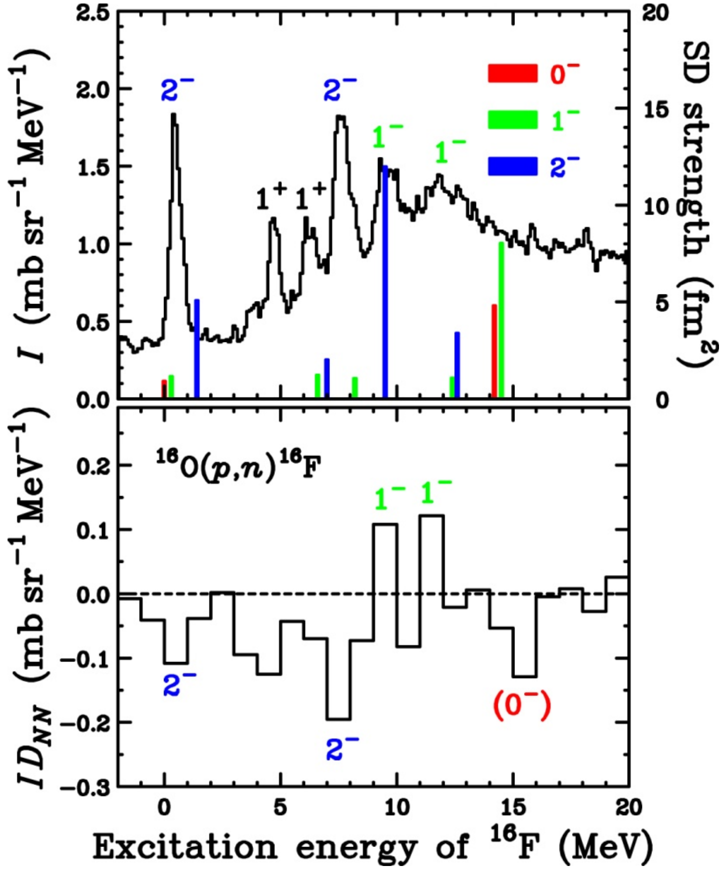




...evious Results for SDR in ^{16}F

J.W.Watson et al.,NPA 599, 79c (1994).

- ^{16}O(p,n)^{16}F at 135 MeV
  - Measure σ and D_{NN} only
  - *Could not separate to ID_q and ID_p*
- Several peaks (SDR) were observed
  - Assign J^π with D_{NN} only
  - *Signature of 0^- at 15 MeV*
- Quantitative information (SD strength) could not be deduced
  - D_{LL} data are missing
    - *J^π assignment is model dependent*
  - Relatively large physical B.G.
    - *MDA (finite angle data) is important*



Quantitative information on SDR strengths is important for ***nuclear physics*** and ***astro physics***

…portance of SDR in A=16

- Supernova evolution *K. Langanke et al., PRL 76, 2629 (1996).*
  - Gravitational B.E. of nascent N.S. is released by ν-ν̄ production

$$T_{\nu_x} = 8\,\mathrm{MeV} \quad > \quad T_{\bar{\nu}_e} = 5\,\mathrm{MeV} \quad > \quad T_{\nu_e} = 3.5\,\mathrm{MeV}$$

$$\langle E_{\nu_x} \rangle = 25\,\mathrm{MeV} \quad > \quad \langle E_{\bar{\nu}_e} \rangle = 16\,\mathrm{MeV} \quad > \quad \langle E_{\nu_e} \rangle = 11\,\mathrm{MeV}$$

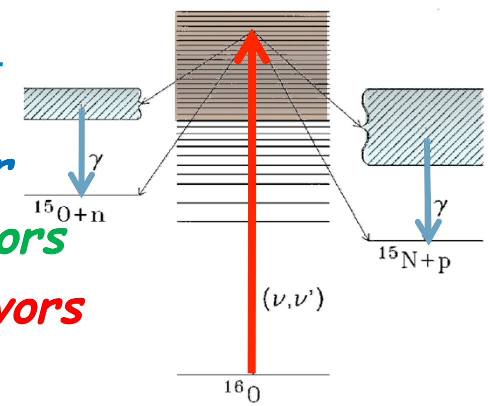
SDR excitation ~~*SDR excitation*~~

- Neutrino detection in SK (γ *-detection from A=15*)

$\bar{\nu}_e + p \rightarrow n + e^+$ *Sensitive to e-flavor*

$\nu + e \rightarrow \nu' + e'$ *Sensitive to all-flavors*

${}^{16}\mathrm{O}(\nu_x, \nu_x')^{16}\mathrm{O}^*(\mathrm{SDR}, \mathrm{GDR})$ *Sensitive to μ/τ-flavors*



- Theoretical prediction for ^{16}O(ν,ν$_x$')^{16}O(SDR)

Model	σ_{tot} in (ν,ν') (10^{-42} cm^2)	σ_{tot} in ($\bar{\nu}$,$\bar{\nu}$') (10^{-42} cm^2)	$\bar{E}$ in SDR
PSDMK2 in SM	4.07	3.02	25.8 MeV
WBT in SM	6.22	4.68	22.8 MeV
RPA by Langanke	5.90	4.48	

50% Difference

Significant Difference

SDR strength distributions (=$\bar{E}$) are important

This RCNP-E317 Proposal

- Identify missing 0^- and 1^- states in ^{12}N and ^{16}F expected in SM
  - *0^- distribution is sensitive to tensor correlations in nuclei*
  - *1^- (and 2^-) distribution in ^{16}F is important to calculate the heavy-flavor neutrino detection response for supernova with SK*
- SD strengths should be identified up to $E_x<30$ MeV
  - SD(L=1) should be separated from other (L=0,2) contributions
    - Multipole decomposition analysis (MDA) should be performed
  - $J^\pi=0^-,1^-$, and 2^- should be separated
    - Polarization observables (D_{ij} and ID_i) are sensitive to J^π
    - *Extended-MDA would be performed*
- Extended-MDA is important for lower SDR
  - SDR in ^{12}N at E_x=6.4 and 7.5 MeV would be mixtures of 2^- and 1^-
    - For ^{12}B, SDR at E_x=7.5 MeV is a mixture of 2^- and 1^- from $^{12}C(d,^2He)$

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

  - *Quantitative separation into 2^- and 1^- is important*

Extended Multipole Decomposition Analysis

- Multipole Decomposition Analysis
  - *Normal* : Separate each L
  - *Extended* : Separate each J^{π}
- Extended MDA procedure (up to L=2)

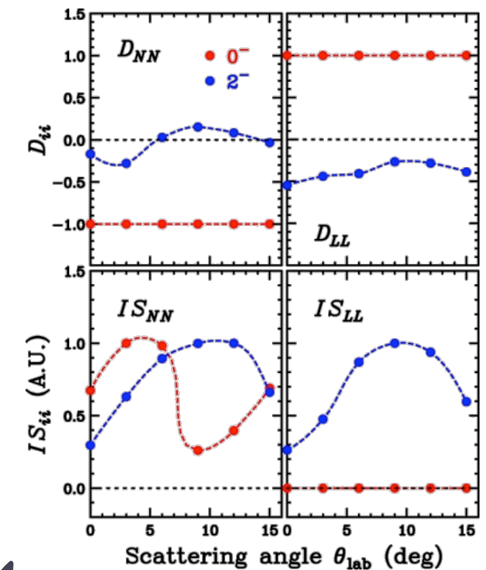
Separation to each J^{π}

- Separate cross section I into ID_q and ID_p using D_{ij}
- Separate ID_q to each L using normal MDA

$$ID_q = \underbrace{ID_q^{1^+}}_{L=0} + \underbrace{ID_q^{0^-} + ID_q^{2^-}}_{L=1} + \underbrace{ID_q^{3^+}}_{L=2},$$

Normal MDA

- Separate ID_q^{0-} and ID_q^{2-} with IS_{NN} and IS_{LL}
  - No 0^- contribution in IS_{LL} — *Extended MDA*

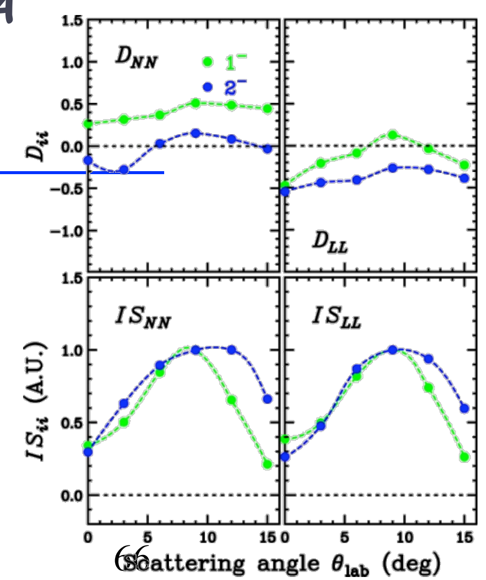


- Separate ID_p to each L using normal MDA

$$ID_p = \underbrace{ID_p^{1^+}}_{L=0} + \underbrace{ID_p^{1^-} + ID_p^{2^-}}_{L=1} + \underbrace{ID_p^{2^+} + ID_p^{3^+}}_{L=2}$$

Normal MDA

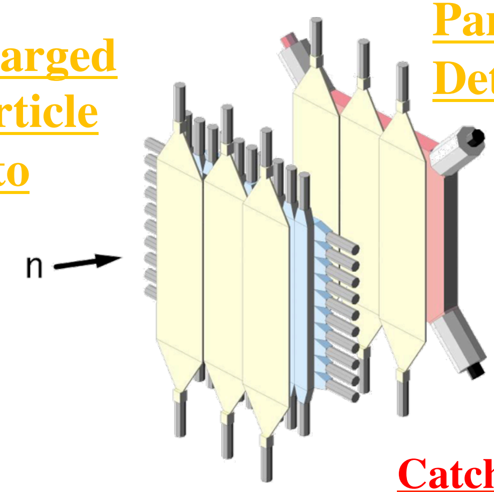
- Separate ID_p^{1-} and ID_p^{2-} with D_{NN} and D_{LL}
  - Significant difference in D_{ij} — *Extended MDA*



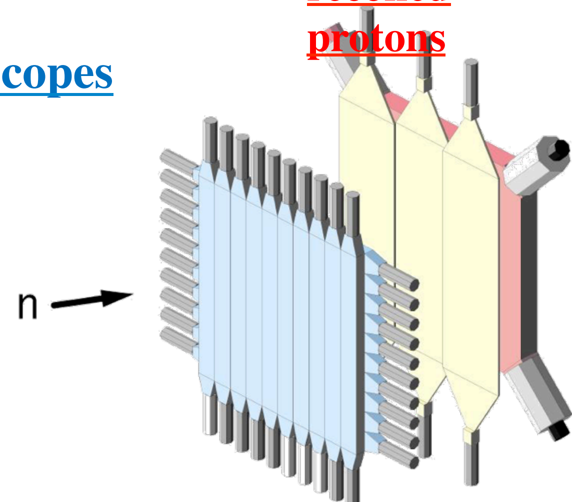
utron Detector/Polarimeter NPOL3

T.Wakasa et al., NIM A 547,569(2005).

- **20 sets of 100cm×10cm×5cm**
  - PMT: Hamamatsu H2431 and H1941
    - Fast response (rise time < 2ns)
  - Large volume of 100cm×100cm×10cm
    - Solid angle : 0.4 msr at 50m
    - *Efficiency :e～ 0.01*
  - Energy resolution
    - *500keV for 300 MeV neutrons*



- **Polarimeter mode**
  - Polarimetry
    - n+p scattering in hodoscopes
  - Scattered neutrons/recoiled protons are detected with catcher detector (part of NPOL2)
  - FOM for polarimetry
    - *FOM = 1.0 × 10^{-4}*



am Time Requirements

- Required data
  - ID_i with δID_i=10% at 0°—15° (6 angles) for extended-MDA
  - Energy resolution=1 MeV (FWHM) for discrete/narrow states
- Beam tuning (Polarized proton beams) 1.5 days
  - N,S, and L-type beams 12 hours × 3 settings 72 hours
- Calibration of NPOL3 1.5 days
  - Measure ε by using ^{7}Li(p,n) ^{7}Be(g.s.+0.43MeV) 12 hours
  - Measure $A_{y;eff}$ using ^{2}H(p,n) 24 hours
- Cross sections and analyzing powers (0°～15°) 1.5 days
  - ^{12}C(p,n) 1 hours × 16 angles 16 hours
  - ^{16}O(p,n) 1 hours × 16 angles 16 hours
- Polarization transfer observables (0°～15°) 12.0 days
  - ^{12}C(p,n) 6 hours × 4 settings × 6 angles 144 hours
  - ^{16}O(p,n) 6 hours × 4 settings × 6 angles 144 hours
- Total 16.5 days

...am and Budget Requirements

- **Beam requirements**
  - Type of particle — Polarized protons
  - Beam energy — ～300 MeV
  - Beam intensity — > 500 nA on target before pulse selection
  - Time resolution — < 300 ps (FWHM)
  - Beam polarization — > 0.6
  - Injection mode — High current mode
  - Pulse selection — 1/5 or 1/1
  - *We need excellent beam with*
    - ***high intensity & high time-resolution & high polarization***
- **Budget requirement**

– Experimental expenses		3,900,000
• *Ice target system*	*700,000*	*Different from E313*
• *Plastic Scinti. BC408 × 2*	*1,500,000*	Repair neutron counters
• *PMT(H6410 × 2, H2431 × 2)*	*900.000*	
• *Support system for NPOL3*	*1,000,000*	
• *Base for the support*	*500,000*	Used with NPOL2 In TOF tunnel
– Travel expenses		800,000
– Total		4,700,000

Collaborators

Kyushu University

- M. Dozono — D
- T. Noro — P
- K. Sagara — P
- Y. Yamada — D
- S. Kuroita — M
- T. Imamura — M
- H. Shimoda — M
- T. Sueta — M

CYRIC

- Y. Sakemi — P
- T. Nagano — M

RCNP

- K. Hatanaka — P
- H. Okamura — P
- A. Tamii — AP
- K. Suda — R
- Y. Tameshige — D
- H. Matsubara — D
- D. Ishikawa — M

Dozono-san will take his doctorate in science with this experiment.

Study of Spin Dipole Strengths in ^{16}O via Complete Polarization Transfer Measurements
Y. Dozono
RCNP-E317 Collaboration

Kyushu-RCNP-CYRIC Collaboration

Figures in E317 Proposal

Figure 1

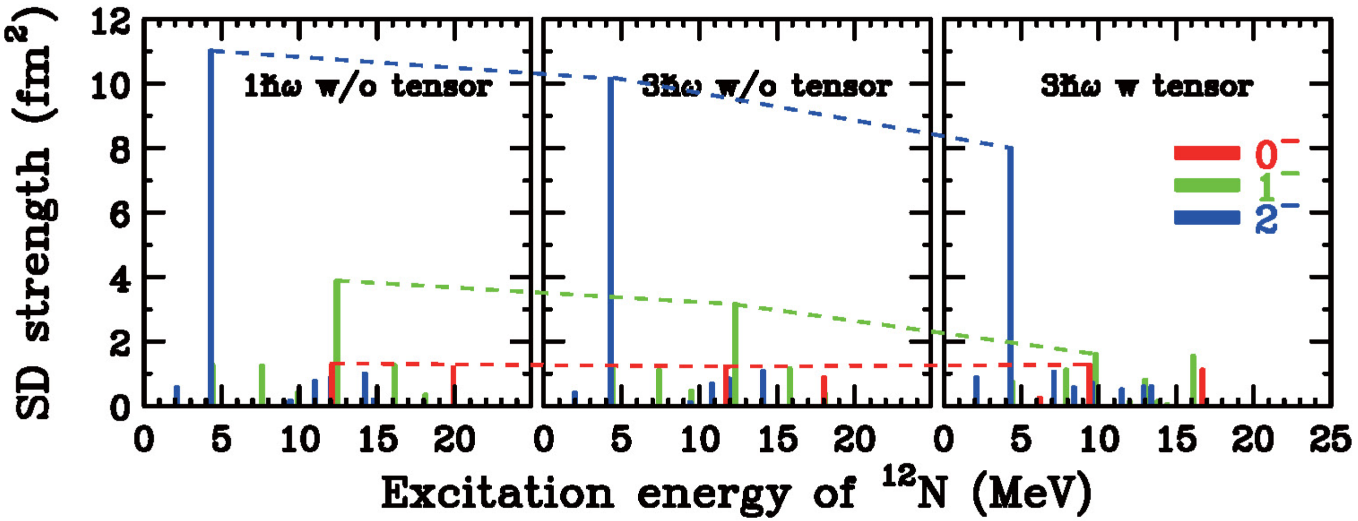


Figure 1: SD strengths of shell model calculations in ^{12}N with Michigan 3-range Yukawa (M3Y) interaction; (left) the $1\hbar\omega$ configuration space without tensor interaction. (middle) the $3\hbar\omega$ configuration space without tensor interaction. (right) the $3\hbar\omega$ configuration space with tensor interaction.

Figure 2

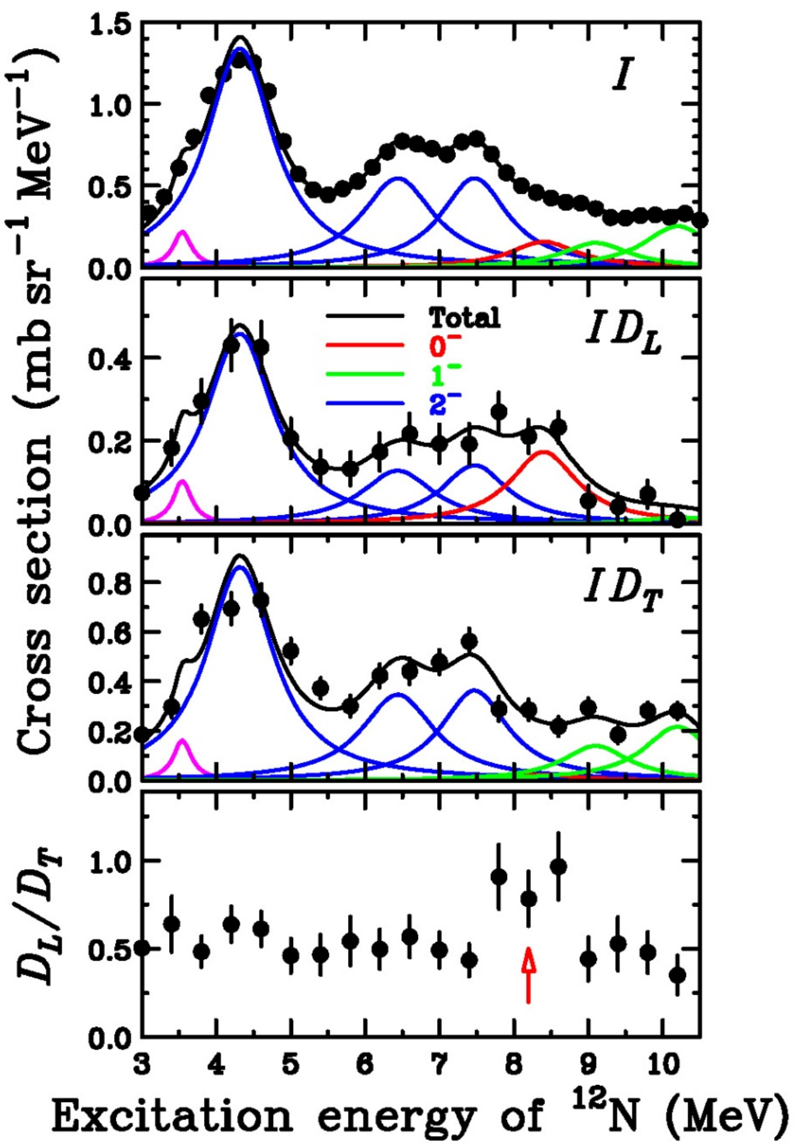


Figure 2: Measurements of $^{12}C(\vec{p},\vec{n})$ at T_p=296 MeV and $\theta_{\text{lab}} = 0°$; (top panel) the unpolarized cross section I. (2nd panel) the spin-longitudinal polarized cross section ID_L. (3rd panel) the spin-transverse polarized cross section ID_T. (bottom panel) D_L/D_T. The red, green, and blue curves are the results of fitting for 0^-, 1^-, and 2^-, respectively.

Figure 3

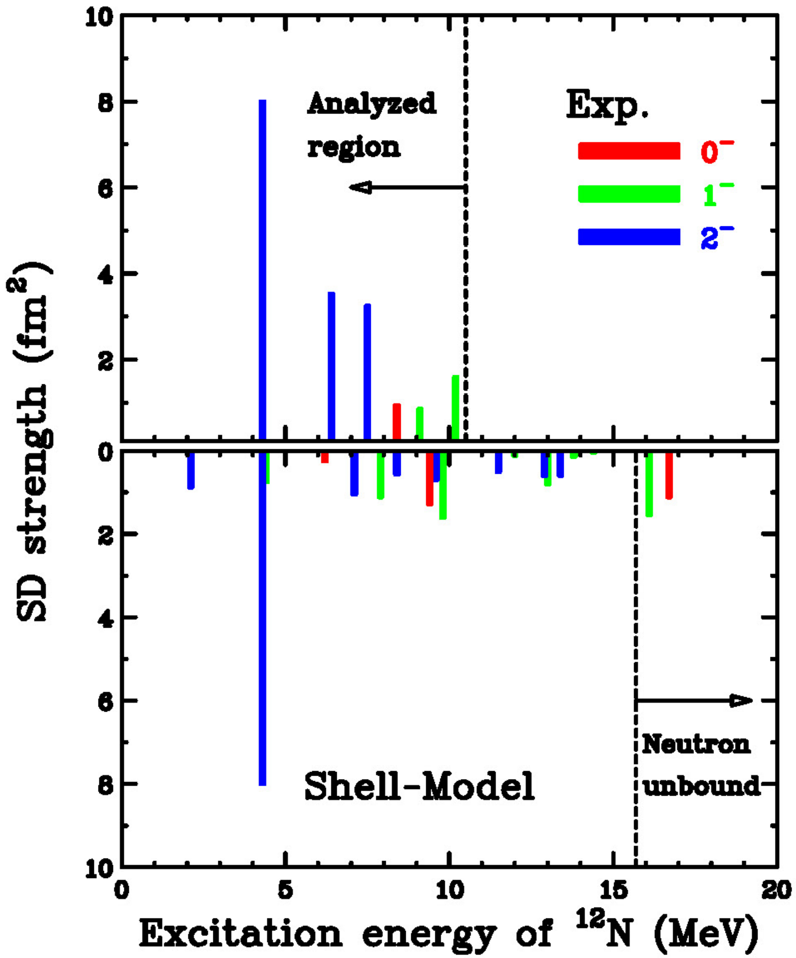


Figure 3: SD strengths in ^{12}N obtained from the ^{12}C$(\vec{p},\vec{n})$ reaction (top panel) compared with shell-model calculations with Michigan 3-range Yukawa (M3Y) interaction in the $3\hbar\omega$ configuration space.

Figure 4

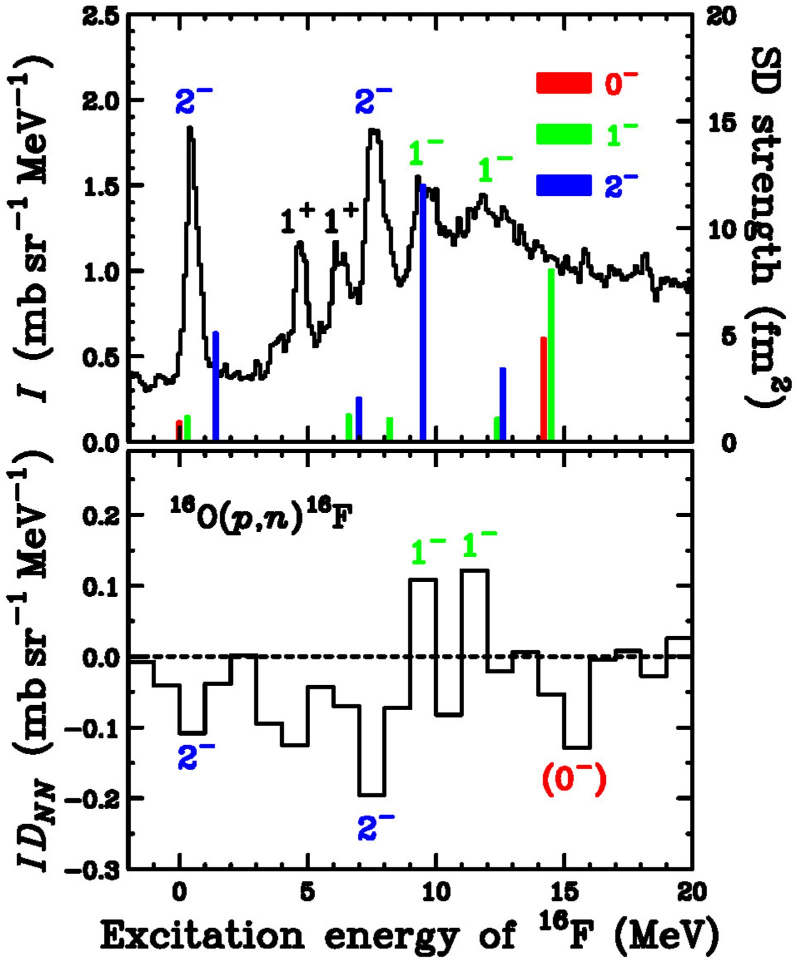


Figure 4: Measurements of $^{16}O(\vec{p},\vec{n})$ at T_p=135 MeV and $\theta_{\text{lab}} = 0°$; (top panel) the unpolarized cross section I. (bottom panel) $ID_{NN}(0°)$. The red, green, and blue curves are the results of the SM calculations for 0^-, 1^-, and 2^-, respectively.

Figure 5

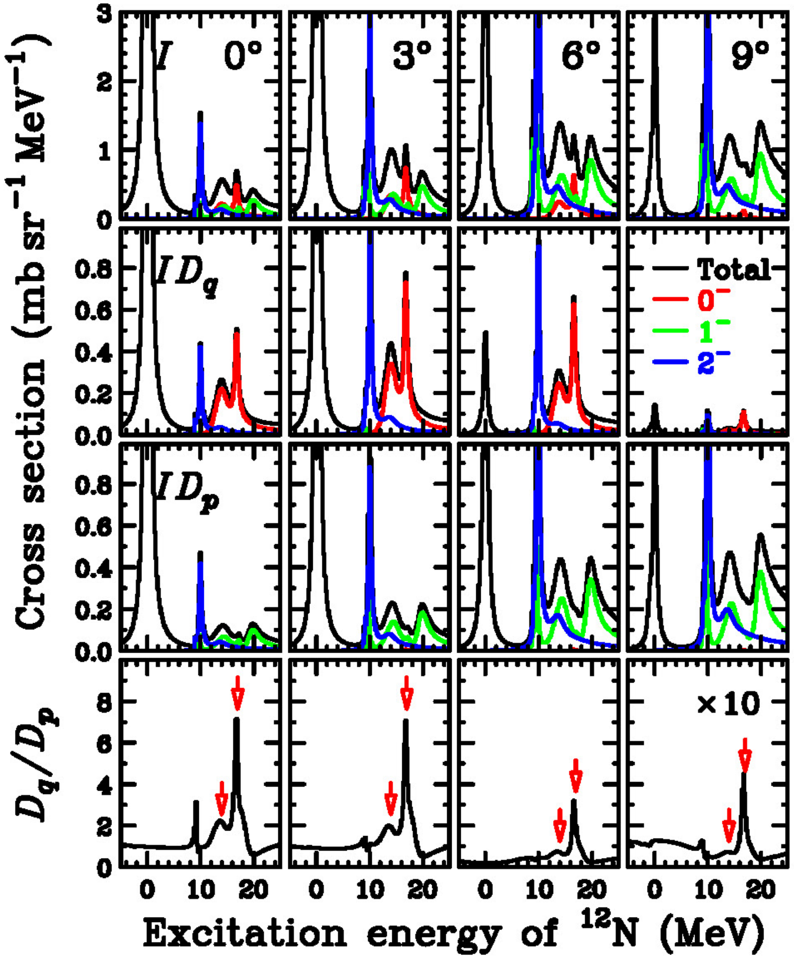


Figure 5: DWIA+RPA predictions for $^{12}C(p,n)$ at T_p=295 MeV and θ_{lab}=0°–9°. The red, green, and blue curves represent contributions from 0^-, 1^-, and 2^- SD excitations, respectively. The 0^- SD states are clearly observed in D_q/D_p as indicated by the red arrows.

Figure 6

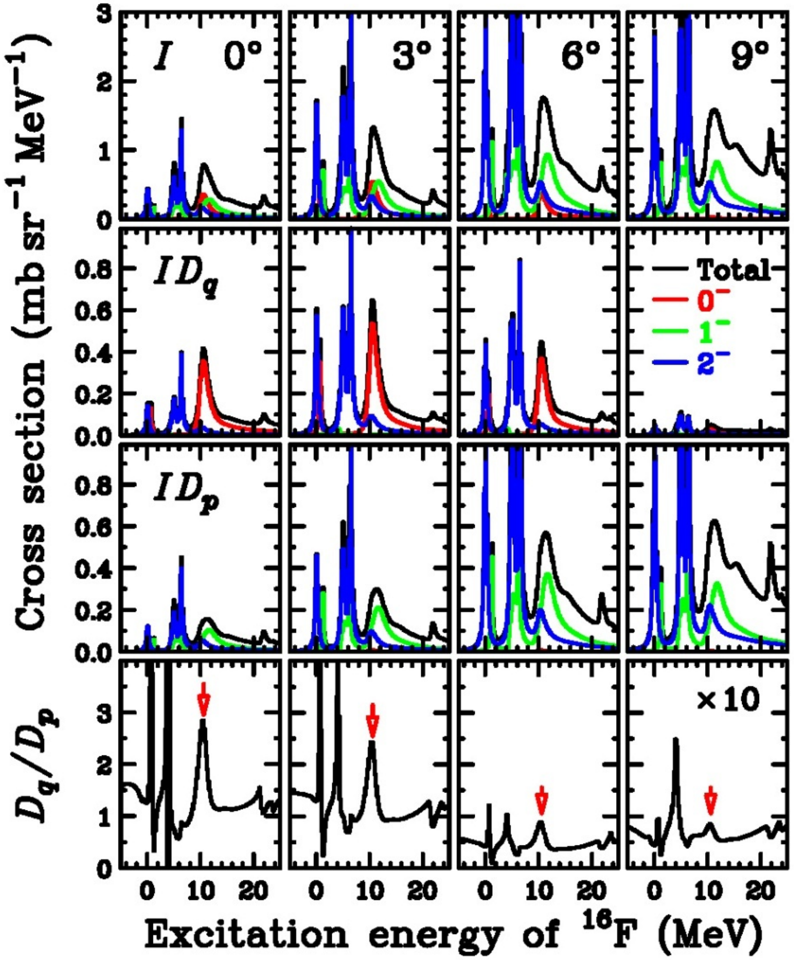


Figure 6: DWIA+RPA predictions for $^{16}O(p,n)$ at T_p=295 MeV and $\theta_{\rm lab}$=0°–9°. The red, green, and blue curves represent contributions from 0^-, 1^-, and 2^- SD excitations, respectively. The 0^- SD states are clearly observed in D_q/D_p as indicated by the red arrows.

Figure 7

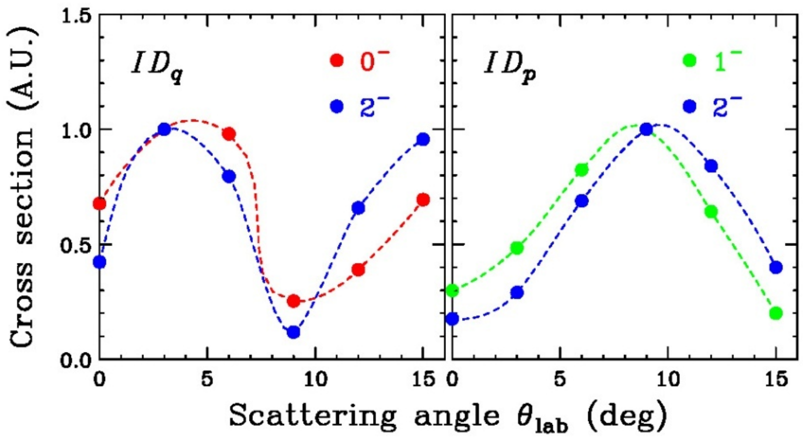


Figure 7: DWIA+RPA predictions for ID_q (left panel) and ID_p (right panel) of the $^{12}C(p,n)$ reaction at T_p=295 MeV. The red, green, and blue filled-circles are the results for 0^-, 1^-, and 2^- SD excitations, respectively.

Figure 8

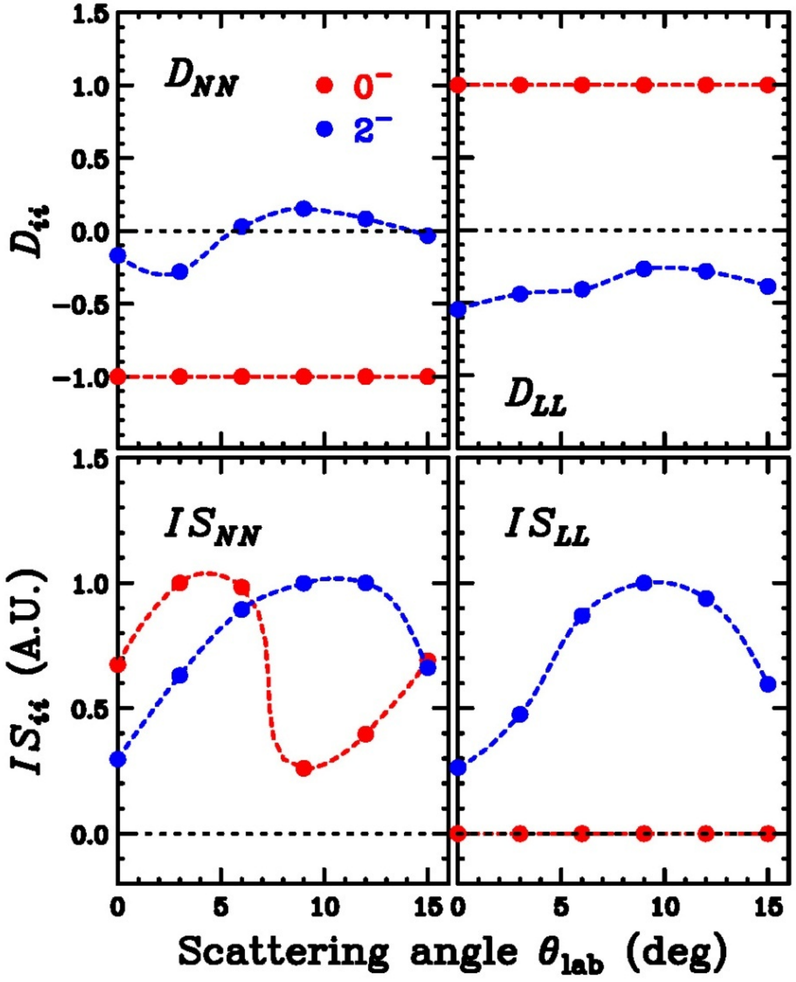


Figure 8: DWIA+RPA predictions for S_{ii} (top panels) and IS_{ii} (bottom panels) of the $^{12}C(p, n)$ reaction at T_p=295 MeV. The red and blue filled-circles are the results for 0^- and 2^- SD excitations, respectively.

Figure 9

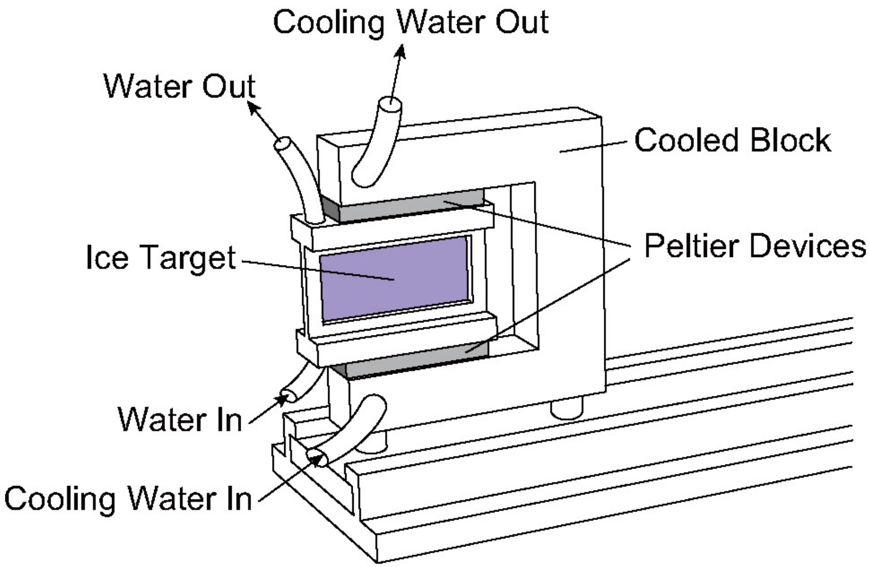


Figure 9: Illustration of the ice target system for this experiment.

Figure 10

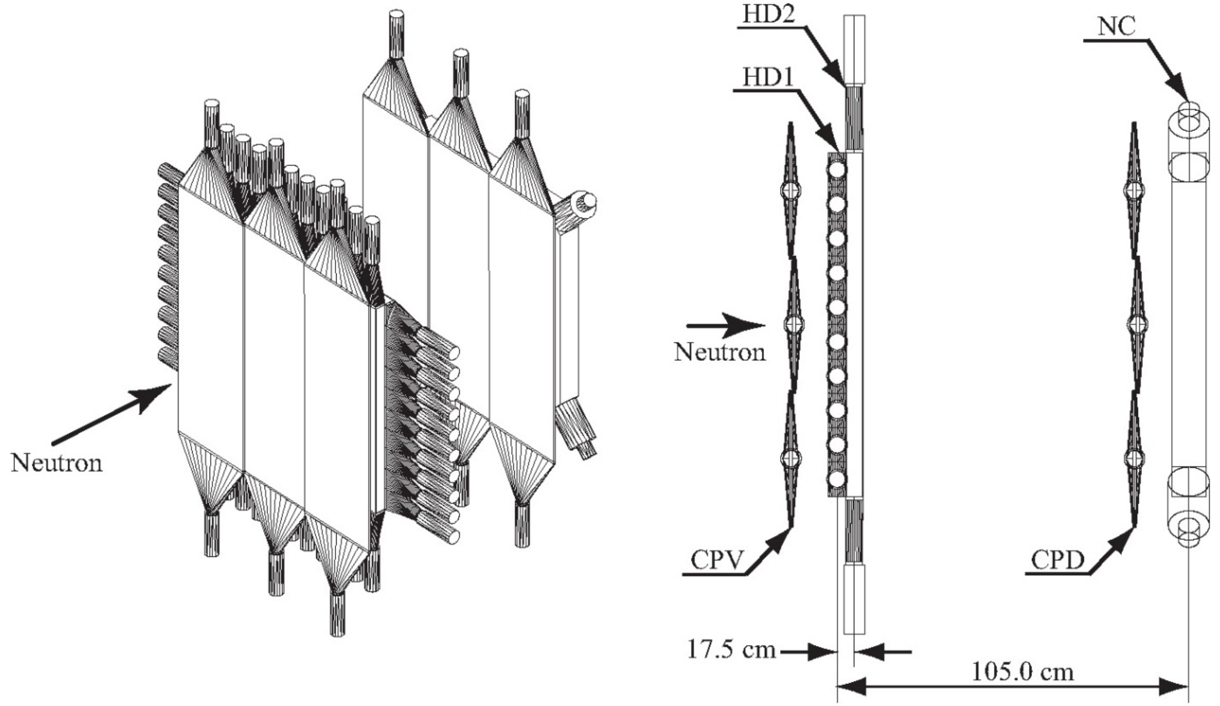
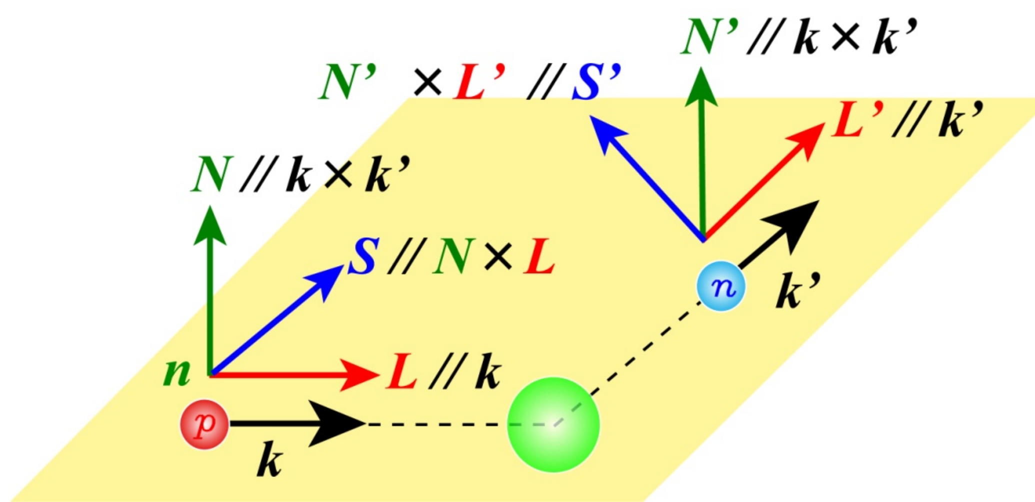


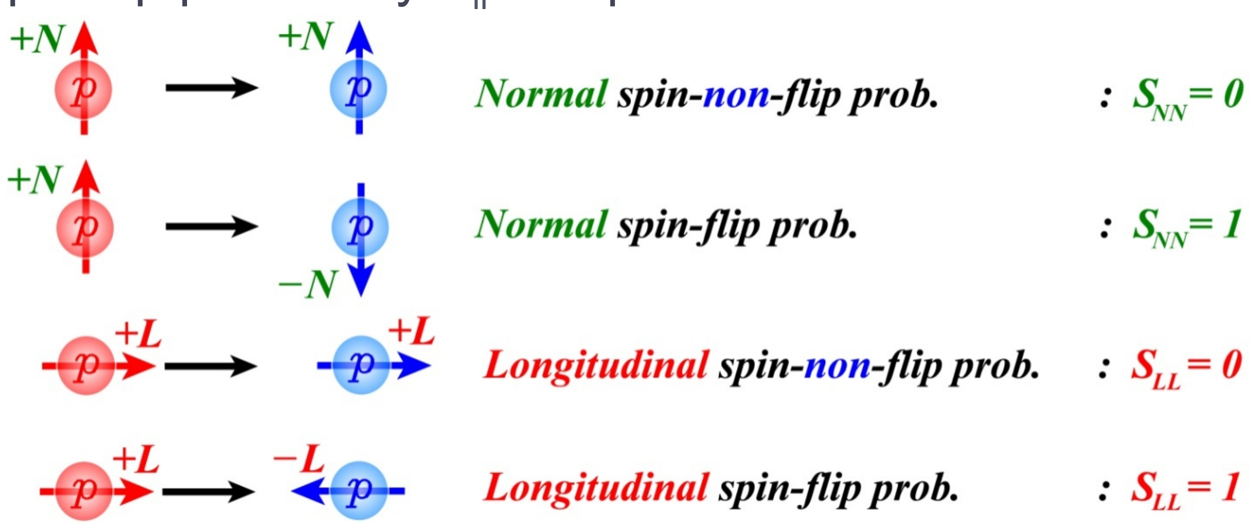
Figure 10: Schematic (left) and top (right) views of the NPOL3 system. In the polarimetry mode of NPOL3, HD1 and HD2 are the analyzer planes while NC is the catcher plane. Thin plastic scintillator planes are used to veto (CPV) or identify (CPD) charged particles.

Misc

Coordinate System and Polarization Observables

- Coordinate system
  - Longitudinal (k-direction)
  - Normal (to reaction plane)
  - Sideways
- At 0 degrees
  - L = L’
  - N = N’ = S = S’
  - Only L and N are meaningful
- Spin-flip probability S_{ii} and polarization transfer observables D_{ii}





✓ $S_{ii} \equiv \frac{1}{2}(1 - D_{ii})$

✓ S_{ii} depends on reaction

✓ $S_{LN} = S_{NL} = 0.5$ from symmetry

N Scattering and Polarization Observables

- NN t-matrix (scattering amplitude)
  - Franey-Love notation

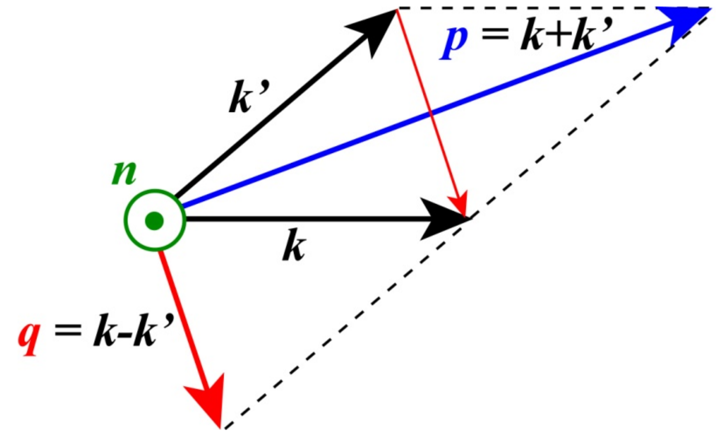
Central — Spin-orbit

$$t_{NN}(E,q) = A'P_S + B'P_T + C(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\hat{n}$$
$$+ E'S_{12}(\hat{q}) + F'S_{12}(\hat{p})$$

Tensor

  - Kerman-McManus-Thaler notation

$$t_{NN}(E,q) = A + B\vec{\sigma}_1\cdot\hat{n}\,\vec{\sigma}_2\cdot\hat{n} + C(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\hat{n}$$
$$+ E\vec{\sigma}_1\cdot\hat{q}\,\vec{\sigma}_2\cdot\hat{q} + F\vec{\sigma}_1\cdot\hat{p}\,\vec{\sigma}_2\cdot\hat{p}$$



$$S_{12}(\hat{u}) = 3\vec{\sigma}_1\cdot\hat{u}\,\vec{\sigma}_2\cdot\hat{u} - \vec{\sigma}_1\cdot\vec{\sigma}_2$$

- Cross section and polarization observables

$$\frac{d\sigma}{d\Omega}(E,q) = \mathrm{Tr}(t^+t) = 2(A^2 + B^2 + 2C^2 + E^2 + F^2)$$

$$D_{nn}(E,q) = D_{NN}(E,q) = \frac{\mathrm{Tr}(t^+\vec{\sigma}_1\cdot\hat{n}\;t\vec{\sigma}_1\cdot\hat{n})}{\mathrm{Tr}(t^+t)}$$

$$= \frac{A^2 + B^2 + 2C^2 - E^2 - F^2}{A^2 + B^2 + 2C^2 + E^2 + F^2}$$

$$\vec{\sigma}_1\cdot\hat{i}\,\vec{\sigma}_1\cdot\hat{j} = i\varepsilon_{ijk}\vec{\sigma}_k + \delta_{ij}$$
$$\{i,j,k\} = \{n,p,q\}$$

Scattering t-matrix (amplitude) ⇒ D_{ij} in NN scattering is calculable

ower of Polarization Observables
lter to Spin-Parity

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

- Resonance has definite spin-parity
  - J^π sensitive probe is useful to identify resonance
  - Polarization observables are powerful
    - Sensitive to spin-parity
- Example for $0^+ \rightarrow J^\pi$ ($\Delta S=1$) transition
  - PWIA with central only

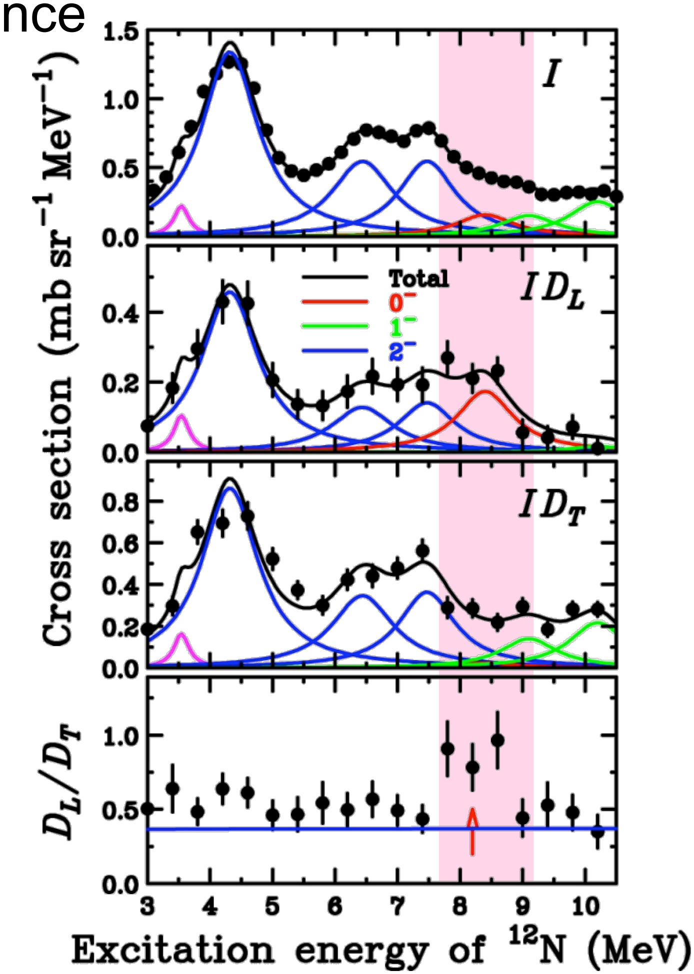
$$D_L = \frac{1}{2}(2S_{NN} - S_{LL}) = \frac{1}{4}(1 - 2D_{NN} + D_{LL})$$

$$D_T = S_{LL} = \frac{1}{2}(1 - D_{LL})$$

Significantly different

J^π	D_L	D_T	D_L/D_T
1^+	0.33	0.67	0.50
0-	**1.00**	**0.00**	**∞**
1-	0.00	1.00	0.00
2-	0.40	0.60	0.66
QES	**0.20**	**0.70**	**0.29**

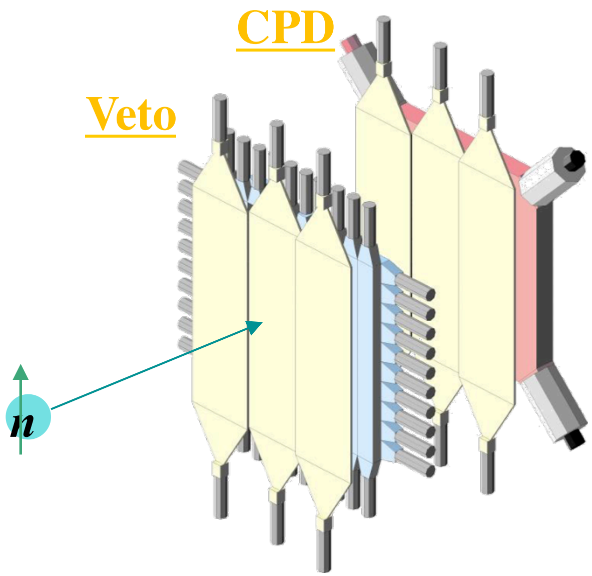
$^{12}C(p,n)^{12}N$ at 296 MeV and 0°



Measure D_{ii} (D_L/D_T) for $^3He(p,n)$ → Identify resonance and its J^π

eutron Detector/Polarimeter NPOL3

T.W., Y.Hagihara et al.,NIM A 547(2005)569.



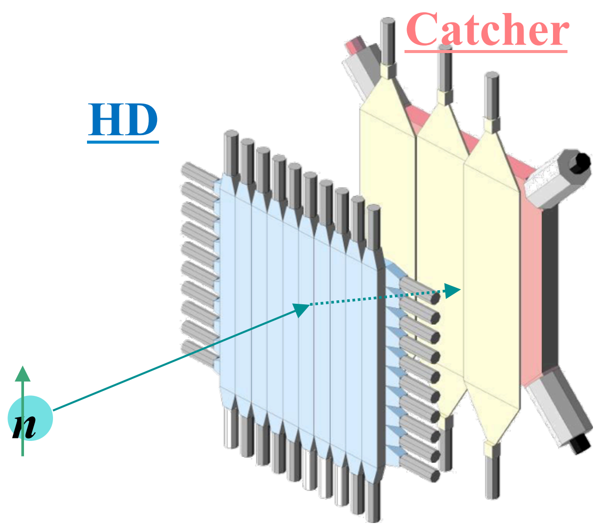
Veto/CPD …. Veto/Identify protons

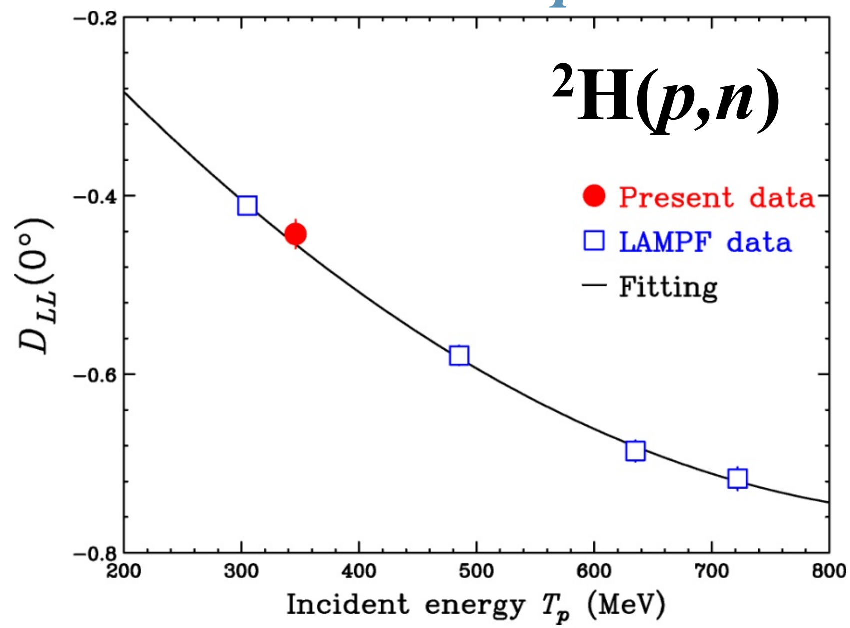
HD …. Neutron scatterer (analyzer)

Catcher …. Detect recoil protons

Left/Right asymmetry

→ Neutron polarization





Consistent with previous data ⇒ High reliability

M. W. McNaughton et al., Phys. Rev. C 45 (1992) 2564.