

スピンで探る原子核の多体効果

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兼

九州大学・加速器ビーム応用科学センター

内容

- 九州大学・加速器ビーム応用科学センターの紹介
- 導入 一用語の説明や偏極に関して一
- アイソスピン $3/2$ の核子3体共鳴状態の研究
- 核力の核媒質効果の研究
- 核内中間子相関の研究
- 核内テンソル相関の研究

参考文献 (全て院生さんの仕事)

- 伊原エマさん (2008年修士修了)
 - *E. Ihara, T. W. et al., Phys. Rev. C 78, 024607 (2008).*
 - *T. W., E. Ihara et al., Phys. Rev. C 77, 054611 (2008).*
- 堂園昌伯君 (2007年修士修了・現在博士課程)
 - *M. Dozono, T. W. et al., J. Phys. Soc. Jpn. 77, 014201 (2008).*
 - *T. W., M. Dozono et al., Phys. Lett. B 656, 38 (2007).*
- 萩原洋右君 (2005年修士修了)
 - *T. W., Y. Hagihara et al., Phys. Lett. B 645, 402 (2007).*
 - *T. W., Y. Hagihara et al., Nucl. Instrum. Methods Phys. Res. A 547 (2005) .*

九州大学 加速器ビーム応用科学センターの 紹介

九州大学・新キャンパス（伊都キャンパス）

Seminar at CYRIC - スピンで探る原子核の多体効果 -



(新) 伊都
キャンパス

(現) 箱崎
キャンパス

博多駅

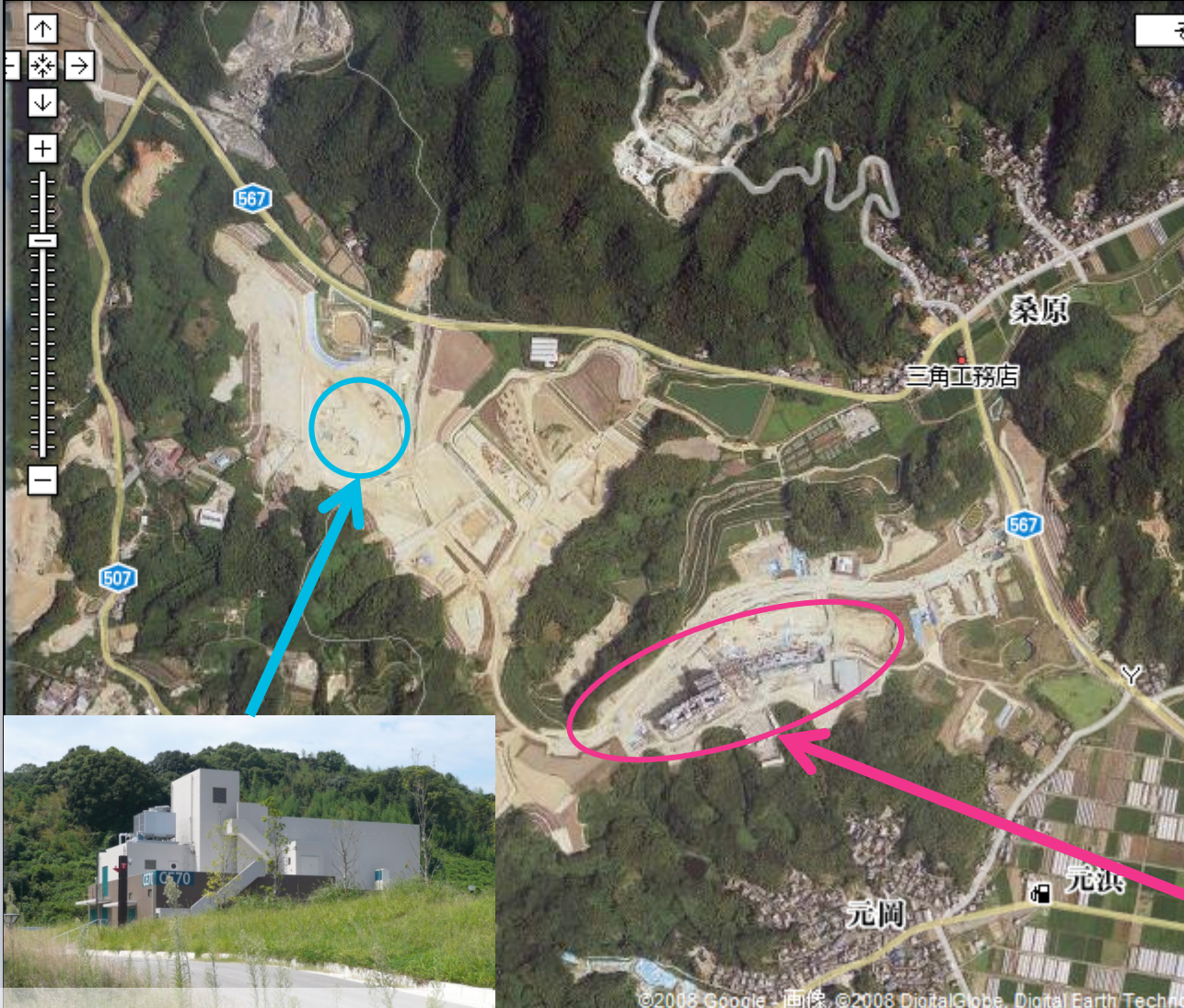
福岡空港

- ✓工学研究院（移転済）
- ✓全学教育（H21より）
- ✓理学研究院（H27より（？））



九州大学 加速器ビーム応用科学センター

Seminar at CYRIC - スピンで探る原子核の多体効果 -



センターから
工学研究院を眺める



4F 連絡通路 5F
← ウエスト3号館 →
West Zone Building III West Zone Building II



加速器センター



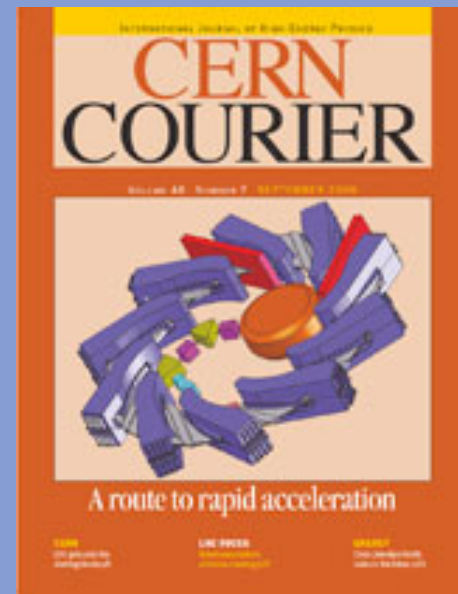
工学研究院

FFAG加速器

- 固定磁場強集束 (FFAG)
 - Fixed Field Alternating Gradient
 - サイクロトロン¹⁾の側面
 - ・ 時間的に一定な磁場
 - ・ 軌道が時間 (エネルギー) と共に変化
 - シンクロトロン²⁾の側面
 - ・ 空間的に磁場は変化 (強収束)
 - ・ 入射・加速・引き出しを繰り返す

サイクロとシンクロの間 (良いところ取り?)

- 日本発
 - 原理提唱・実証共に日本人
 - 国際的にも注目されている
- 特徴
 - アクセプタンスが広い
 - ・ 2次ビームなどの加速
 - ・ フェーズ・ローテーション



The University of Kyusyu also has a new accelerator facility under construction. The main machine will be a 150 MeV proton FFAG accelerator whose design closely follows the one at KEK described above. This will be available for various applications, such as nuclear physics and material science.

九大FFAG加速器

- KEKのFFAG加速器を九大に移設・整備
 - 工学研究院と理学研究院が共同
 - 目的
 - 粒子ビームを利用した教育や研究に資する
 - アジアの中核となる共同利用教育研究施設へ

学内共同教育研究施設
(教育が主目的)

- 整備スケジュール
 - 10月 入射サイクロ・ビーム調整
 - 11月 FFAG・設置アライメント
 - 12月 **FFAGへビーム入射・ビーム周回**
(加速はしない)
 - 来年 FFAGビーム加速
 - KEK実績の再現が目標
 - 1 nA @ 100 MeV



ご協力よろしく
お願いします
(制御系など)

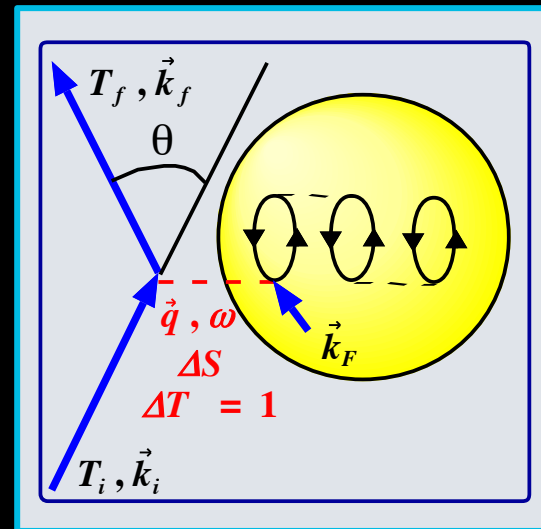


導入

—用語の説明や偏極に関して—

核子散乱と原子核の応答関数

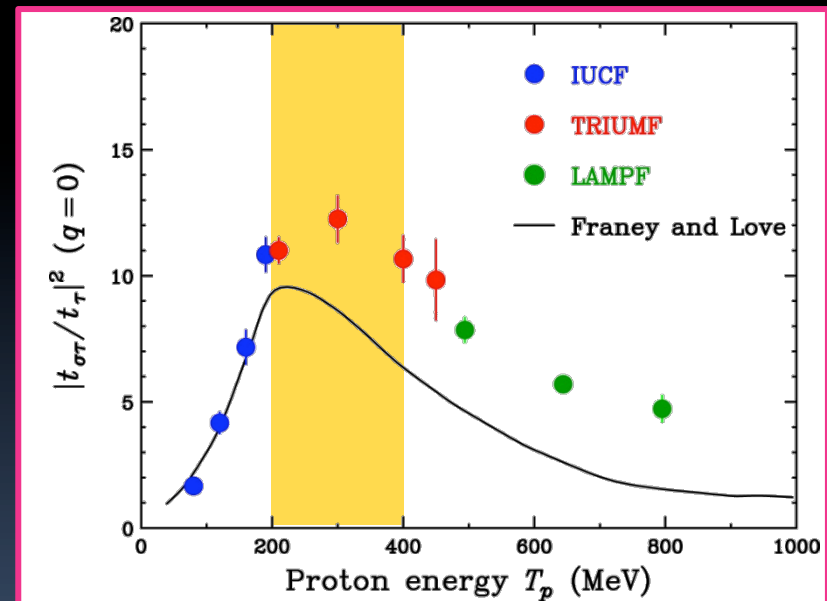
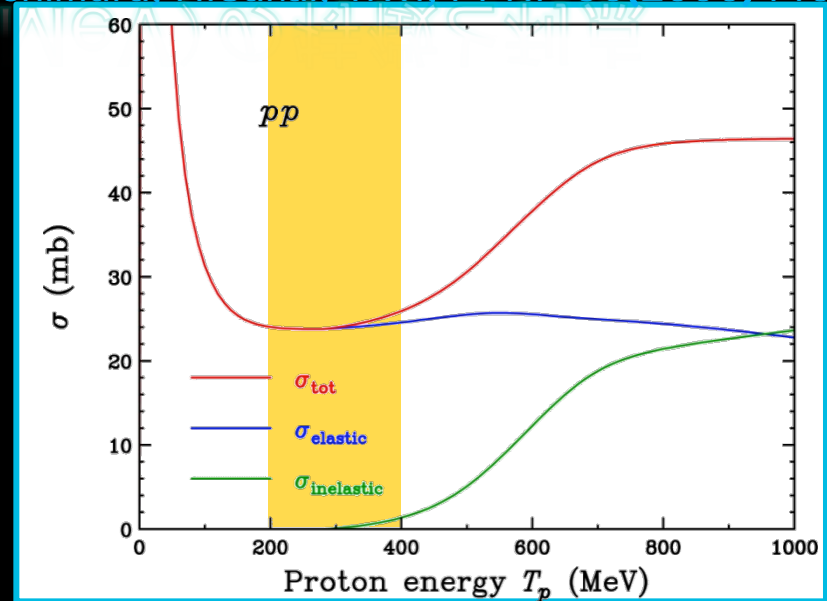
- 核子散乱で原子核にインパクト（衝撃）を与える
 - 運動量： q ，エネルギー： ω
 - スピン： ΔS ，荷電スピン： ΔT
 - (p,n)では $\Delta T=1$
- 中間エネルギー ($T_p > 100$ MeV) の特徴
 - インパクトは入射核子と核内核子の散乱による
 - 核子と原子核ではない
 - 第0近似では真空中の核子・核子散乱
- インパクトは実験的に制御（観測）可能
 - 核子は $s=1/2$ なので、 $\Delta S=0$ or 1
 - ΔS の向きも、スピン完全測定で観測可能
 - インパクトと同じ量子数を持った仮想粒子が核内にあり、それを核子が吸ったと考えてもよい
- 応答関数と相互作用
 - 応答関数：あるインパクトに対する原子核の励起されやすさ
 - $q, \omega, \Delta S, \Delta T$ …の関数
 - 相互作用：原子核内でのインパクトは真空中と同じか？
 - 応答関数が既知（他のプローブ(e,e')等）なら検証可能



中間エネルギー ($T_p > 100$ MeV) の特徴と利点

M. Ichimura, H. Sakai, T.W., PNP 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 ($\sigma \tau$)
> $10 \times$ 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



スピンに関して

- ΔS の向きを示す用語
 - **スピン縦 (Spin-longitudinal)**
 - ΔS と q が平行 ($\sigma \cdot q$)
 - 記号: L or q
 - **スピン横 (Spin-transverse)**
 - ΔS と q が直交 ($\sigma \times q$)
 - 直交方向は2方向ある \rightarrow p and n
 - 記号: T or p or n

- ΔS の向きと中間子 ($\Delta T=1$)
 - π 中間子: $J^\pi=0^- \Leftrightarrow \sigma \cdot q$
 - **スピン縦**
 - 原子核に仮想 π 中間子を渡す
 - 原子核中の仮想 π 中間子を吸う
 - ρ 中間子: $J^\pi=1^+ \Leftrightarrow \sigma \times q$
 - **スピン横**
 - 原子核に仮想 ρ 中間子を渡す
 - 原子核中の仮想 ρ 中間子を吸う

 π^\pm

$$I^G(J^P) = 1^-(0^-)$$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** 1 (1988).

 π^\pm MASS

| VALUE (MeV) | DOCUMENT ID | TECN | CHG | COMMENT |
|-------------------------------|-------------|------|-----|-------------------------------------|
| 139.57018±0.00035 OUR FIT | | | | Error includes scale factor of 1.2. |
| 139.57018±0.00035 OUR AVERAGE | | | | Error includes scale factor of 1.2. |

 $\rho(770)$

$$I^G(J^{PC}) = 1^+(1^{--})$$

A REVIEW GOES HERE – Check our WWW List of Reviews

 $\rho(770)$ MASS

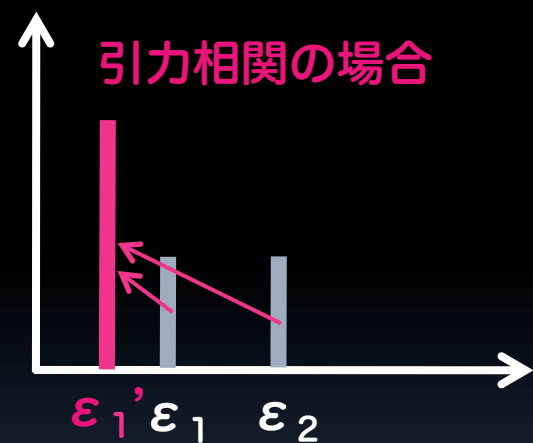
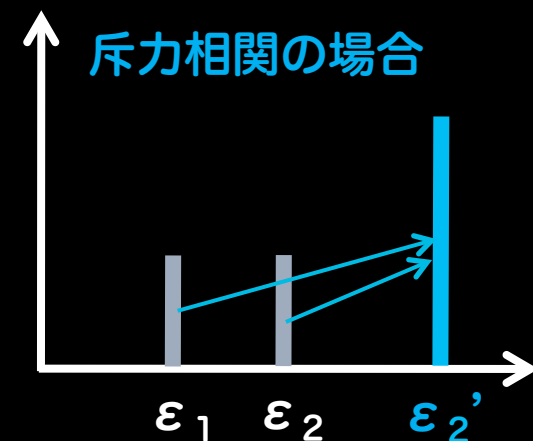
We no longer list S-wave Breit-Wigner fits, or data with high combinatorial background.

NEUTRAL ONLY, e^+e^-

| VALUE (MeV) | EVTS | DOCUMENT ID | TECN | COMMENT |
|-------------------------|------|-------------|------|---------|
| 775.49±0.34 OUR AVERAGE | | | | |

残留相互作用と巨大共鳴

- 2準位モデルで考える
 - ある J^π を持つ p-h の組が2つある場合
 - 各 ε を ε_1 及び ε_2 ($\varepsilon_1 < \varepsilon_2$) と置く
 - ε は適当な1体ポテンシャルを仮定すれば求まる
- 核内の残留相互作用により p-h 間に斥力が働く場合
 - 斥力相関により
 - $\varepsilon_1' > \varepsilon_1$
 - $\varepsilon_2' \gg \varepsilon_2$
 - 全ての強度が ε_2' に集中する (共鳴状態)
- 核内の残留相互作用により p-h 間に引力が働く場合
 - 引力相関により
 - $\varepsilon_1' < \varepsilon_1$
 - $\varepsilon_2' < \varepsilon_2$
 - 全ての強度が ε_1' に集中する (共鳴状態)
- p-h ($E \sim 0$ MeV) と Δ -h ($E \sim 300$ MeV) の2準位を考える
 - 引力であれば、 $E \sim 0$ MeV の領域の強度が増大
 - 斥力であれば、 $E \sim 0$ MeV の領域の強度が減少 (GT強度のクエンチングなど)

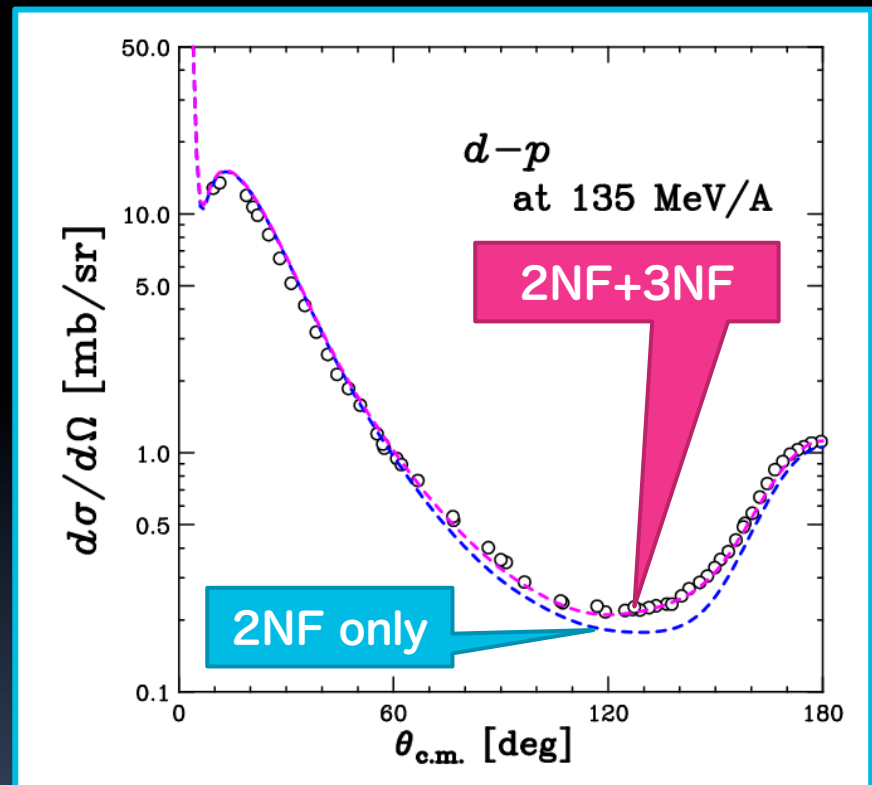
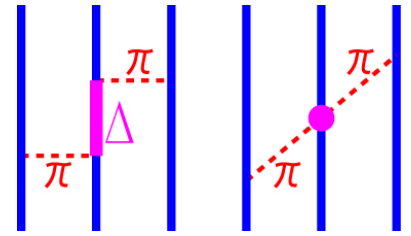


アイソスピン $3/2$ の 核子3体共鳴状態の研究

Many Nucleon Force – 3NF –

- First indication of 3 NF
 - Binding energies of ${}^3\text{H}$ and ${}^3\text{He}$
 - Smaller than exp. by 0.5–1 MeV
 - Need 2π -exch. 3NF
 - TM99, Urbana IX, etc.
- Further indications
 - **d+p elastic scattering**

2π -exch. 3NF



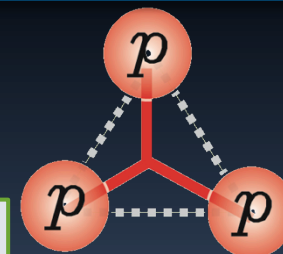
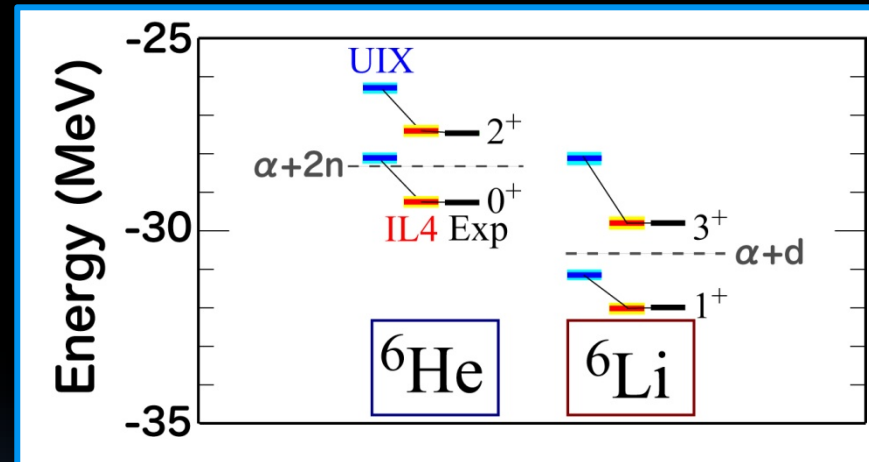
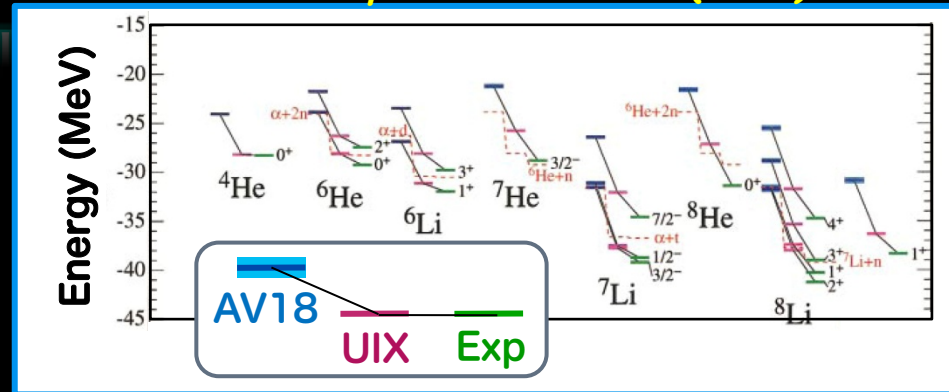
3NF effects are small
 → Seen at cross-section minima
 (Easily masked by 2NF effects)

Isospin Dependence of 3NF

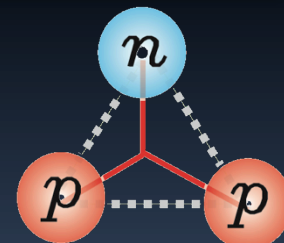
S.C. Pieper et al. PRC 64(2001)014001

- Evidence for 3NF
 - B.E. of ^3H and ^3He
 - Nd scattering/reaction
- Limited to $T=1/2$ system
- Binding energy for $A \geq 4$
 - Two-nucleon force only
 - Significant under-binding
 - **With UIX 3NF**
 - Close to exp. values
 - Still under-binding
 - Isospin-dependent 3NF
 - Illinois three-nucleon forces (IL4)
 - To describe neutron-rich system
 - Weaken in $T=1/2$
 - Strengthen in $T=3/2$

Experimental information on $A=3/2$ and $T=3/2$ systems are important



$T=3/2$



$T=1/2$

T=3/2 3NFs and Resonances

*A. Hemmdan, W. Glockle, and H. Kamada
PRC 66, 054001 (2002).*

- Recent Faddeev calculations for T=3/2 3N system (3n)
 - Only two-nucleon forces are considered
 - $J^\pi=3/2^-$ -12.13 -i 37.96
 - $J^\pi=3/2^+$ -10.30 -i 33.20
 - $J^\pi=1/2^-$ -20.38 -i 45.27
 - $J^\pi=1/2^+$ -14.29 -i 48.34
- “NO” three nucleon resonances
 - Existence of T=3/2 three nucleon resonances
⇒ Existence of T=3/2 three nucleon forces
(This work)
 - Information on T=3/2 three nucleon resonances
(Position and width)
⇒ Information on T=3/2 three nucleon forces
(Future theoretical work)

Far away from the
positive real-energy axis

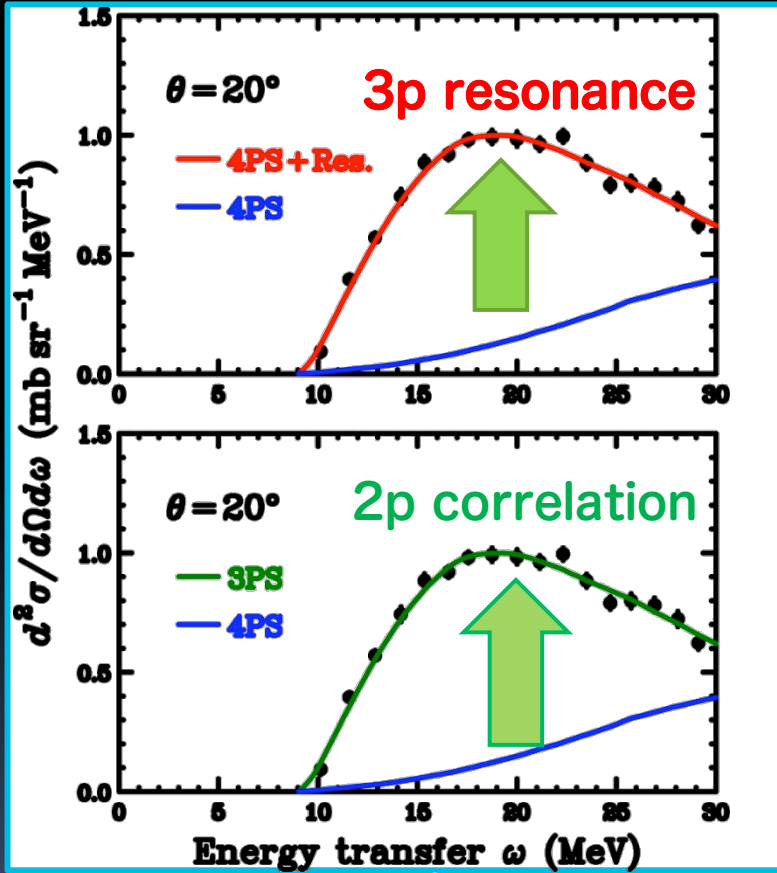
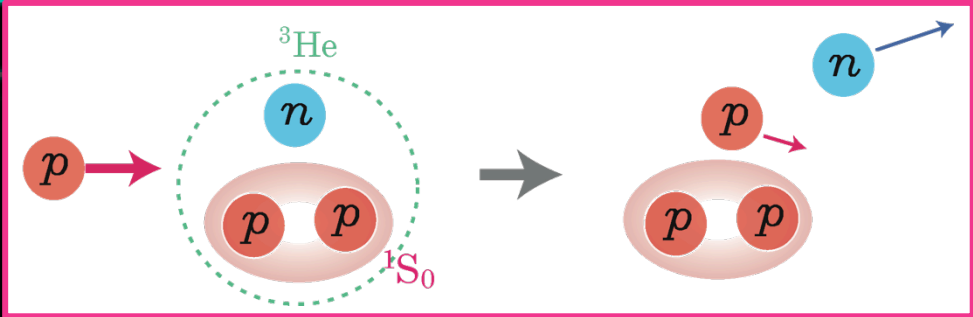
Previous Study of 3p Resonances and 2p Correlation Effects

- Production of 3p ($T=3/2$)
 - ${}^3\text{He}(p,n)3p$ at 48.8 MeV
- Comparison with 4-body phase-space calc. would be inappropriate
 - 2-protons in ${}^3\text{He}$ form 1S_0 state
 - Strongly correlated
 - Act as 1-body ${}^2\text{He}$
 - Final state consists of 3-particles

3-body phase space calc. would be appropriate



Excess from 4-body phase space
 \Rightarrow 2p correlation effects
 (NOT 3p resonance)



L.E. Williams et al., PRL 23(1969)1181.

M.Palarczyk et al., PRC 58(1998)645.

Power of Polarization Observables Filter 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

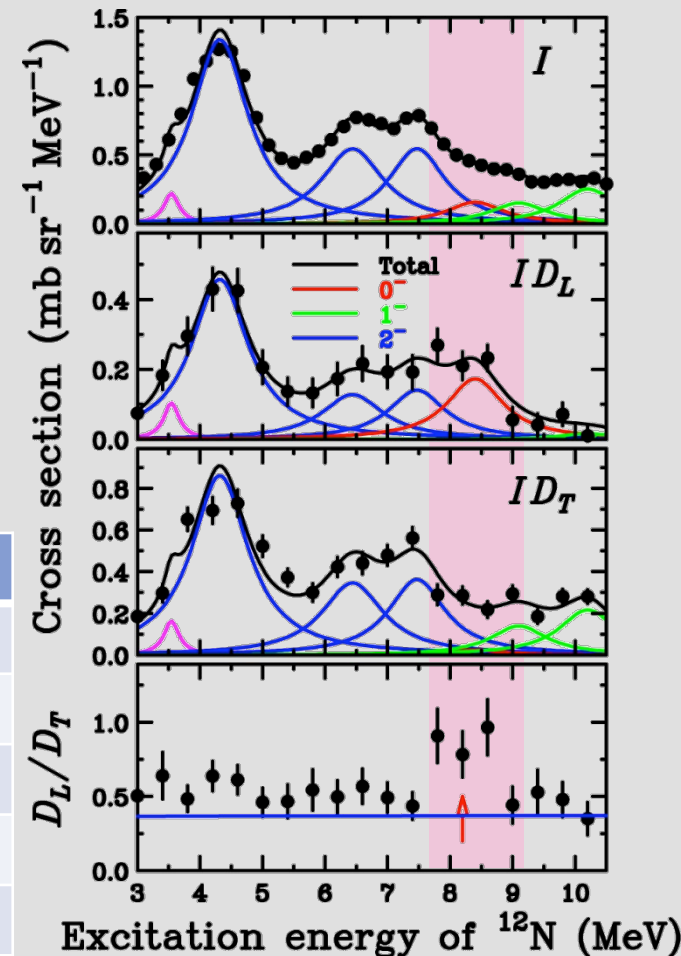
$$D_L = \frac{1}{2}(2S_{NN} - S_{LL}) = \frac{1}{4}(1 - 2D_{NN} + D_{LL})$$

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

| 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 |

Significantly different

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



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

Experiment -RCNP Ring Cyclotron Facility-

RCNP RING CYCLOTRON FACILITY

Polarized proton beam

- $T_p = 346 \text{ MeV}$
- $p = 60\%$

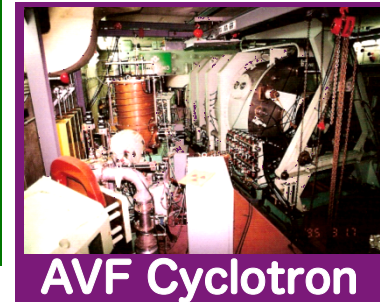
BLP1 &
BLP2



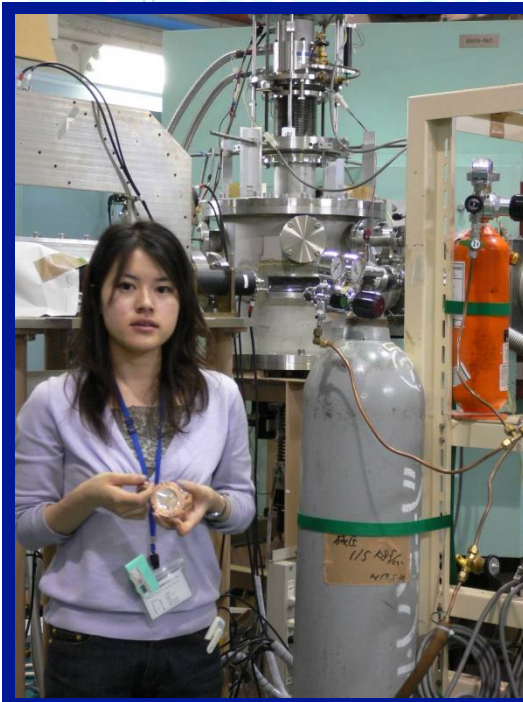
60 mm
Cooled Gas



Ring Cyclotron

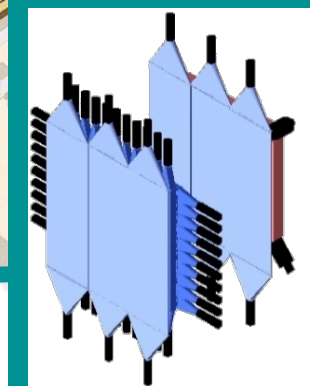


AVF Cyclotron



Cooled Gas Target (^3He)

$\sim 11 \text{ mg/cm}^2$
($T \sim 25 \text{ K}$, $P \sim 2.5 \text{ atm}$)

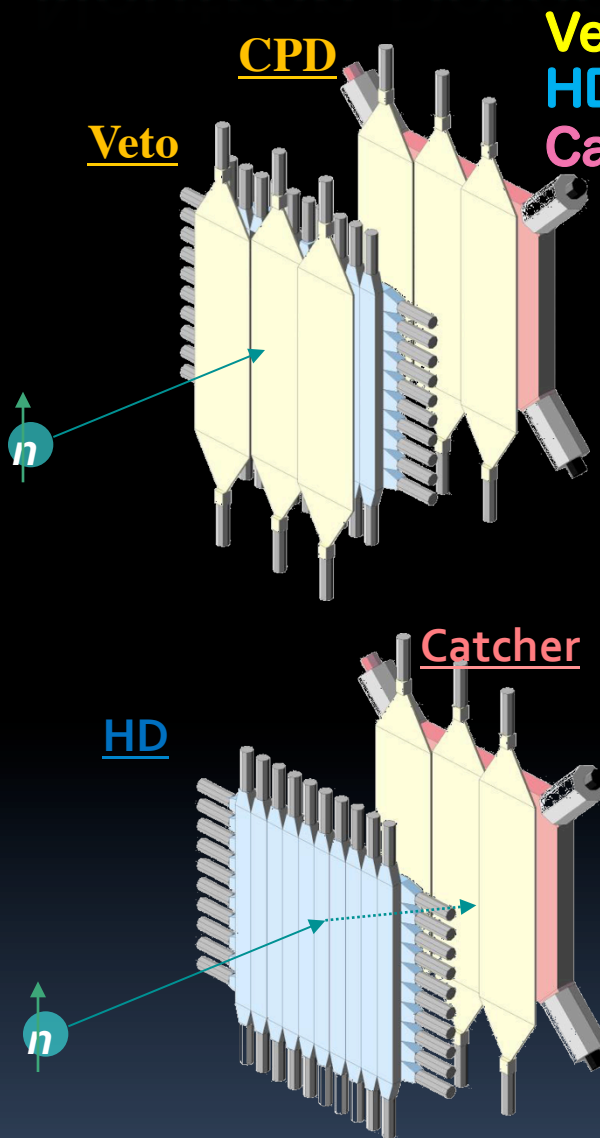


NPOL3
Kyushu
Univ.

SOL1 & SOL2

Neutron Detector/Polarimeter NPOL3

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



Veto/CPD

HD

Catcher

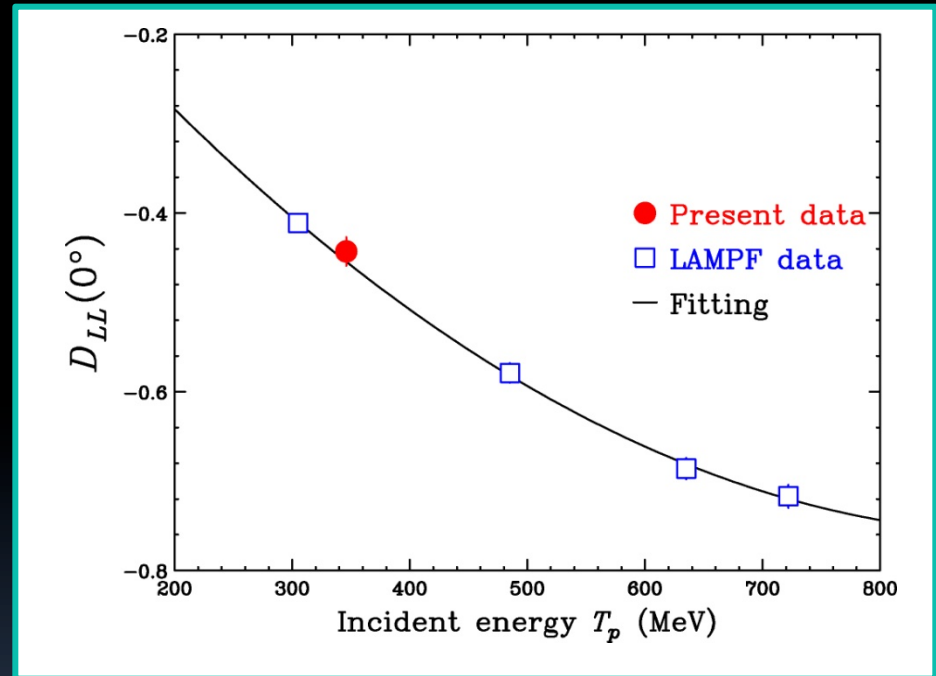
... Veto/Identify protons

... Neutron scatterer (analyzer)

... Detect recoil protons

Left/Right asymmetry

→ *Neutron polarization*

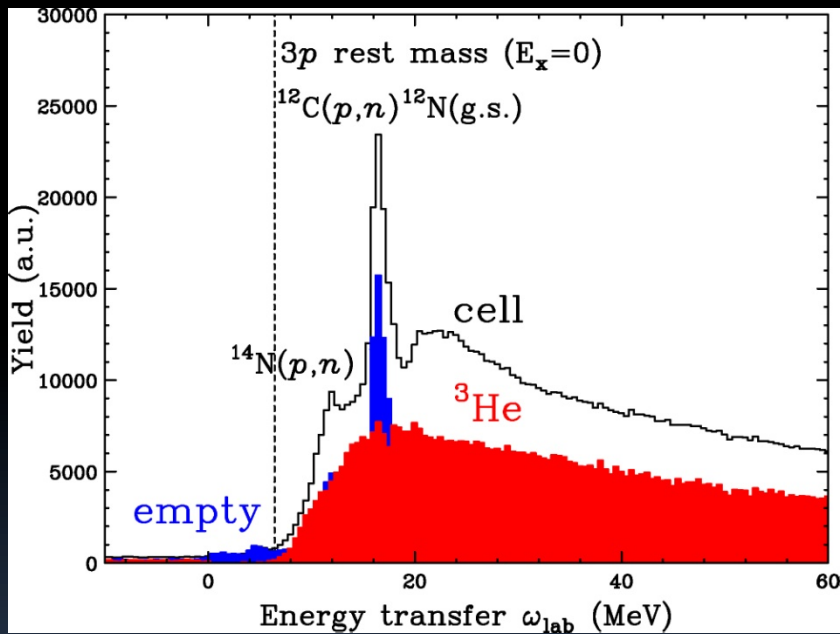


Consistent with previous data ⇒ High reliability

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

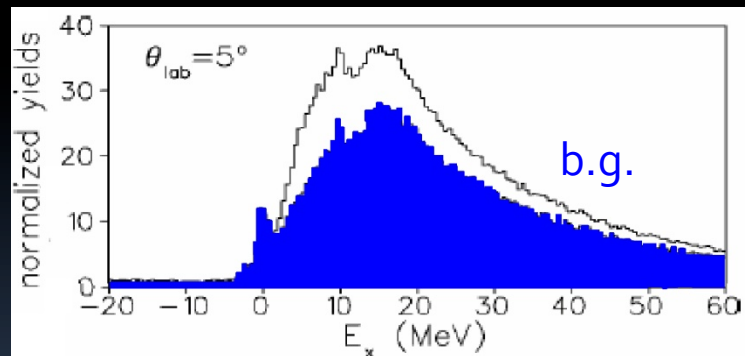
Results - *Background Subtraction* -

- **High S/N compared with Indiana data**
 - Thanks to relatively thin Alamid window
- **B.G. including narrow peaks and broad bump (SDR)**
 - Successfully subtracted **without adjusting relative normalization**
 - **Demonstrating reliability of our data**



Our data

$^3\text{He}(p,n)$ at 200 MeV at Indiana



Indiana data

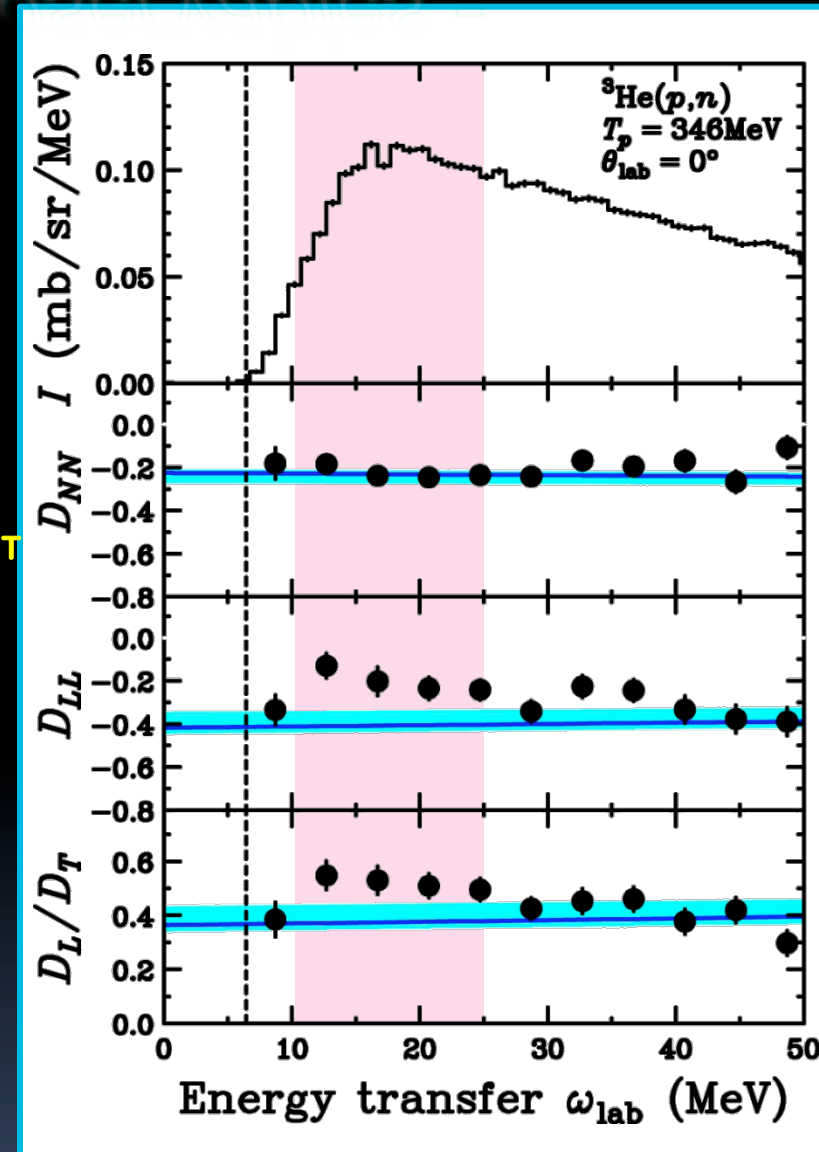
Results - Polarization Observables -

- Comparison with QES
 - Free NN values (w/o resonance effects)
 - Blue curve
 - Phase-shift solution FA07
 - Cyan band
 - Modern NN potential (AV18, CD-Bonn, Nij93, Paris)
 - Significant deviations in D_{LL} and D_L/D_T

Signature of resonance (?)

- D_L/D_T for resonance
 - QES (B.G.) $D_L/D_T = 0.4$
 - Exp. (B.G. + Res.) $D_L/D_T > 0.5$

Resonance $D_L/D_T > 0.5$
 \Rightarrow Determination of J^π

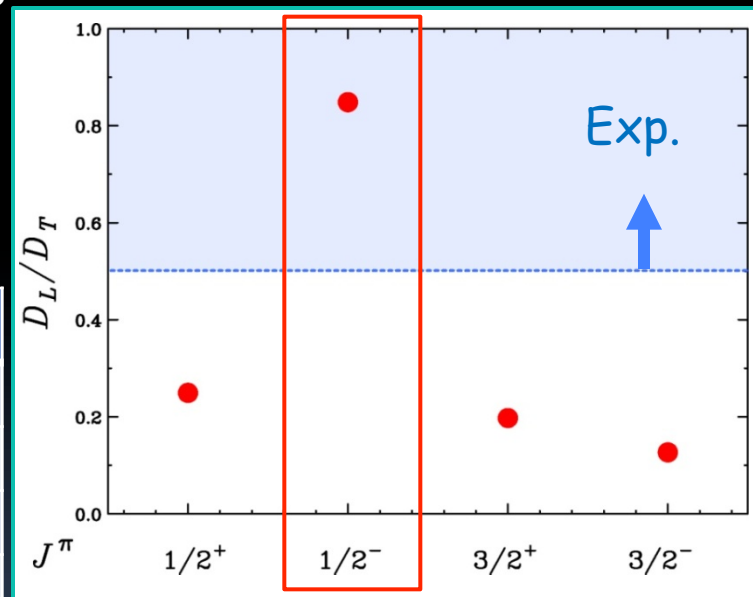
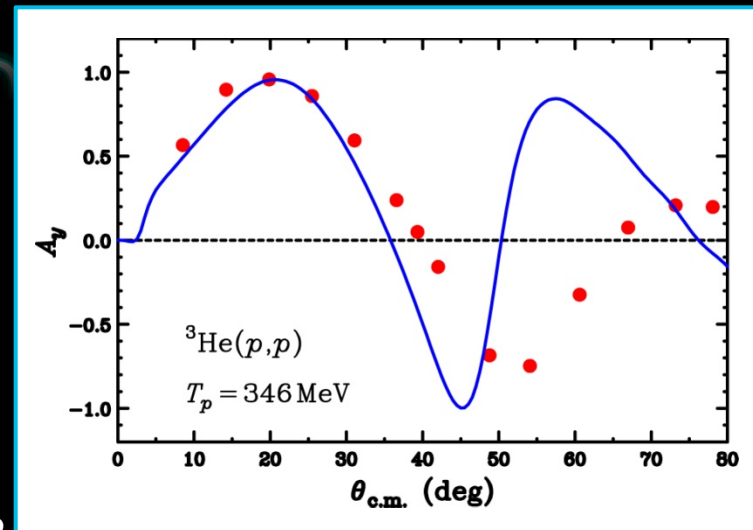


Spin-Parity of Resonance

- DWIA calculations with dw81
 - Optical potential
 - Global potential for ^4He
 - Reasonably reproduce our A_y data
 - NN t-matrix
 - Franey and Love at 325 MeV
 - Transition matrix element
 - G-matrix effective interaction for $A=3$
 - Hosaka et al., NPA 444, 76 (1985).
 - 0s-0p-1s0d-0f1p with OXBASH

DWIA results are insensitive to params.

| Final J^π | $D_{NN}(0^\circ)$ | $D_{LL}(0^\circ)$ | $D_L(0^\circ)$ | $D_T(0^\circ)$ |
|---------------|-------------------|-------------------|----------------|----------------|
| $1/2^+$ | -0.19 | -0.58 | 0.20 | 0.79 |
| $1/2^-$ | -0.11 | +0.18 | 0.35 | 0.41 |
| $3/2^-$ | -0.15 | -0.65 | 0.16 | 0.83 |
| $3/2^-$ | +0.16 | -0.33 | 0.09 | 0.67 |



Resonance $J^\pi = 1/2^-$

Energy and Width of Resonances

Assumption

- “Incoherent” sum of Res. (1/2-) and QES

$$\sigma^{\text{exp}}(0^\circ) = \sigma^{1/2^-}(0^\circ) + \sigma^{\text{QES}}(0^\circ)$$

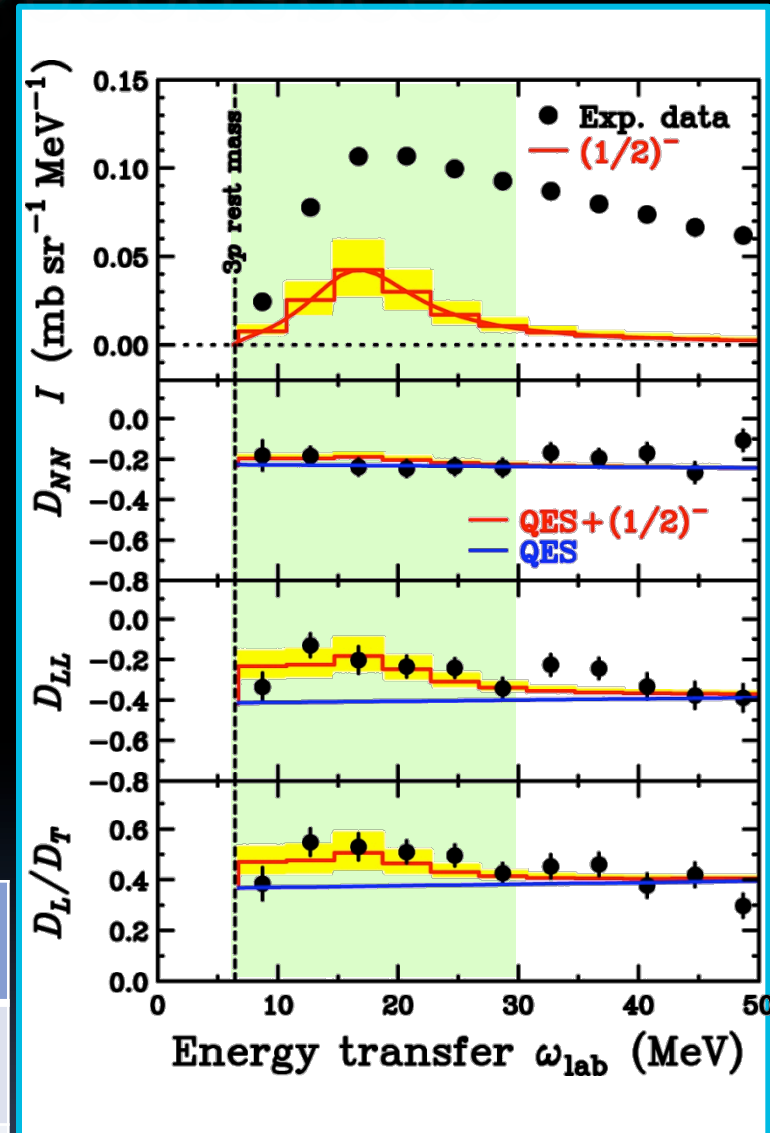
$$\sigma^{\text{exp}}(0^\circ) D_{NN}^{\text{exp}}(0^\circ) = \sigma^{1/2^-}(0^\circ) D_{NN}^{1/2^-}(0^\circ) + \sigma^{\text{QES}}(0^\circ) D_{NN}^{\text{QES}}(0^\circ)$$

$$\sigma^{\text{exp}}(0^\circ) D_{LL}^{\text{exp}}(0^\circ) = \sigma^{1/2^-}(0^\circ) D_{LL}^{1/2^-}(0^\circ) + \sigma^{\text{QES}}(0^\circ) D_{LL}^{\text{QES}}(0^\circ)$$

- Bright-Wigner func. (with Phase-space)

$$\sigma^{1/2^-}(0^\circ) = \frac{A}{\pi} \frac{\Gamma/2}{(\omega - \omega_0)^2 + (\Gamma/2)^2}$$

| Data | Fit (MeV) | Central (MeV) | E_x (MeV) | FWHM (MeV) |
|-----------------|---------------|---------------|-------------|--------------|
| This work | $\omega < 30$ | 16 ± 1 | 10 ± 1 | 11 ± 3 |
| Williams et al. | | | 9 ± 1 | 10.5 ± 1 |



Summary

- First measurement of complete polarization transfer D_{ij} measurements for ${}^3\text{He}(p,n)$ at 0°
 - Clean measurement with high S/N (~ 6)
 - Highly precise and reliable data
- Signature of $T=3/2$ resonance in D_{LL} and D_L/D_T
 - Spin-parity $1/2^-$
 - Energy $E_x = 10 \pm 1 \text{ MeV}$
 - Width $\Gamma = 11 \pm 3 \text{ MeV}$
- Future perspective
 - Detailed theoretical investigations are highly required

核力の核媒質効果の研究

Motivation - Medium modification of NN force -

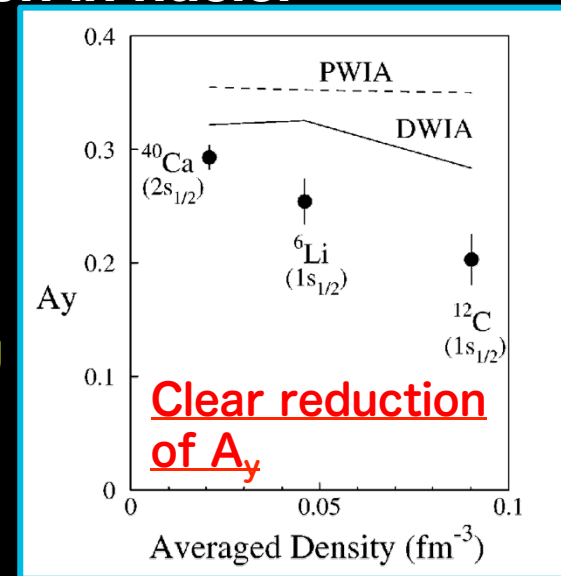
■ Nuclear medium effects on NN interaction in nuclei

□ Conventional medium effects

- Nuclear binding / Pauli blocking
- Relativistic mean field effects

□ Non-conventional medium effects

- Medium modifications of
 - Meson / Nucleon masses
 - Coupling constant
- ρ -meson mass scaling**



■ Experimental efforts to investigate these effects

- Exclusive (p,2p) reaction from s-shell
 - Direct comparison of NN in free space with NN in nuclear medium
 - Distortion effects of recoil nucleon are large ($T_p < 100$ MeV)
 - *Difficult to obtain absolute values of effective NN interaction*
- Stretched states via (p,p') and (p,n)
 - Reliable treatment for distortions ($T_p = T_n$)
 - Transition form factor is known from (e,e') scattering data

Enable us to assess the absolute size of NN interaction in nuclei

How to measure medium effects

- Factorize impulse approximation (FIA)

$$\sigma_{\text{FIA}}(q, \omega) = N_D \cdot \sigma_{\text{NN}}(q, \omega) \cdot R(q, \omega)$$

$$D_{ij} = (\text{Distortion}) \otimes (\text{NN interaction}) \otimes (\text{Response})$$

- Polarized cross sections and KMT NN amplitudes
 - NN scattering amplitude M in KMT notation

$$M = A + B\sigma_{0n}\sigma_{1n} + C(\sigma_{0n} + \sigma_{1n}) + E\sigma_{0q}\sigma_{1q} + F\sigma_{0p}\sigma_{1p}$$

- Experimental I and $D_{ij} \Rightarrow ID_0, ID_n, ID_q, ID_p$

$$ID_q = \frac{I}{4} [1 - D_{nn} + D_{qq} - D_{pp}] = N_D \cdot |E|^2 \cdot R_q$$

$$ID_p = \frac{I}{4} [1 - D_{nn} - D_{qq} + D_{pp}] = N_D \cdot |F|^2 \cdot R_p$$

If R is known

→ NN amplitudes (E, F, etc) can be studied separately

Stretched state - R is known from (e,e') -

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

R_p is given by the (e,e') data

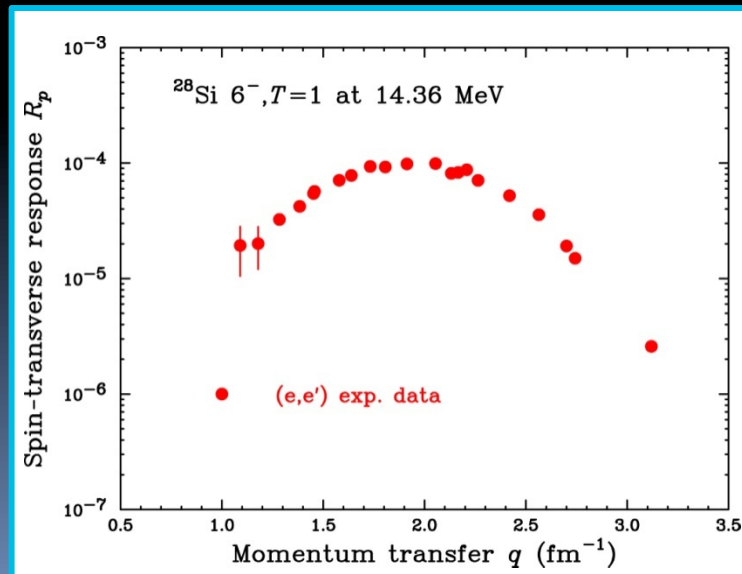
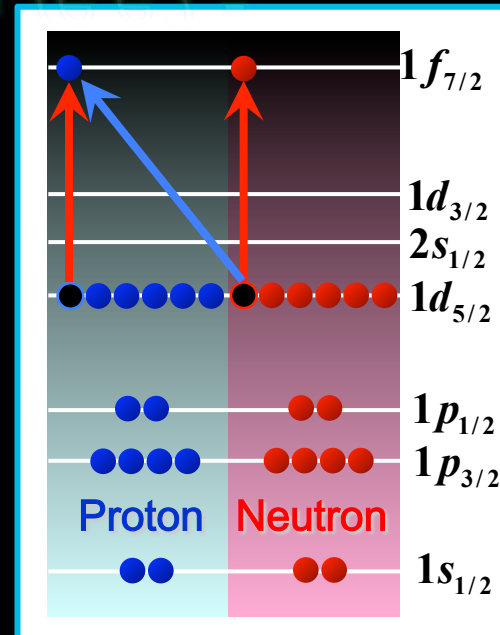
- Less ambiguity in theoretical calculations
- Reliable information on effective NN interaction

- 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



Results of $^{28}\text{Si}(p,p')$ at IUCF

- Motivation of this experiment -

Two controversial explanation

- **Medium modifications in nuclei**
 - Reduction of ρ -meson mass \Rightarrow 20%
 - (Density independent calc.)
- **Isospin mixing**
 - Mixing angle between $T=0$ and $T=1 \Rightarrow 13^\circ$

Later “density-dependent” DWIA

\rightarrow The effect is too small

(Surface peak of transition density)

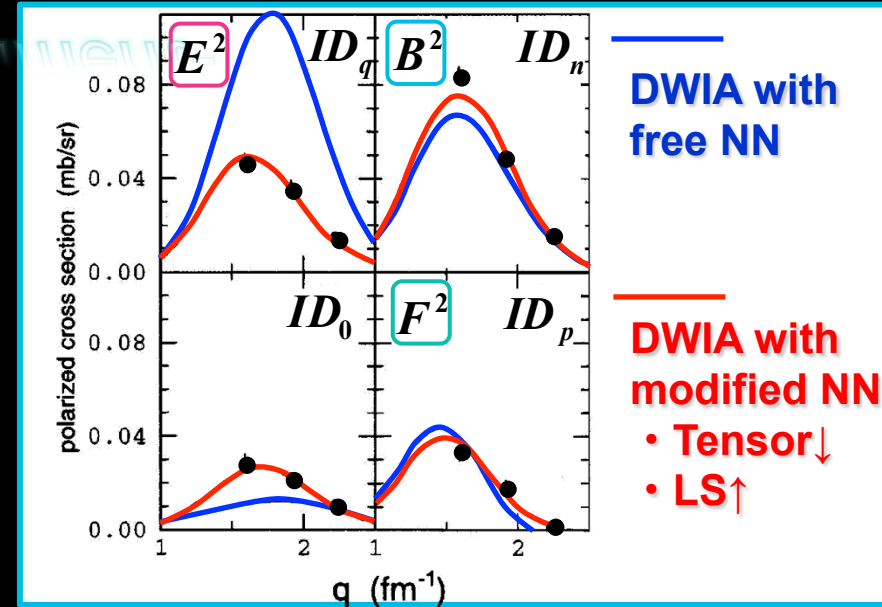
\Rightarrow Important to study isospin mixing effects

Advantage of (p,n)

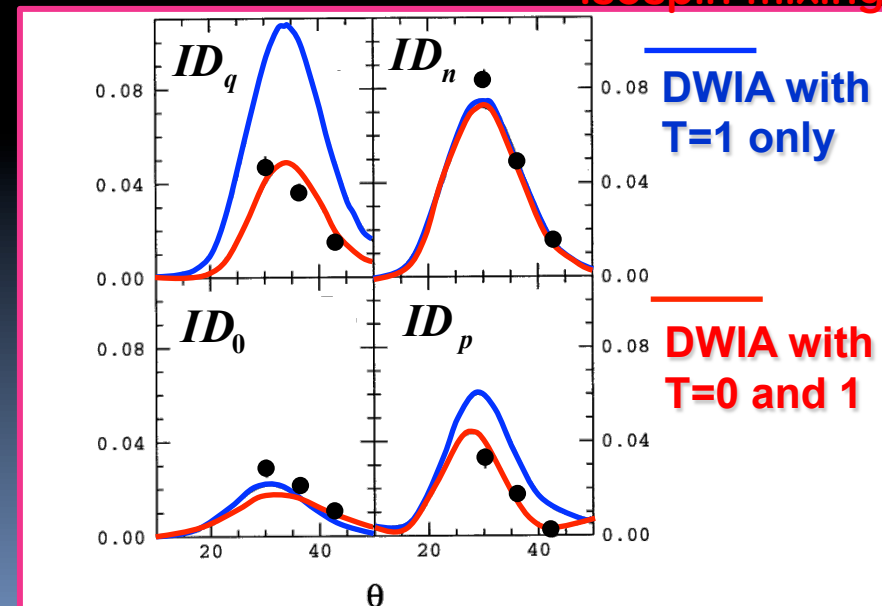
- **Pure isovector probe**
 - Excite only $T=1$ states
 - Exclude isospin mixing effects
- Ideal probe for medium effects

E. J. Stephenson et al., PRL 78, 1636 (1997)

Medium modifications



Isospin mixing



Research Center for Nuclear Physics Osaka University

Thanks to M. Dozono



- **198 MeV Polarized protons**

- Same as (p,p') at IUCF (reliable DWIA)

- **Beam polarization**

- Control with 2-sets of solenoids
- Measure with 2-sets of BLP by p-p

- **Beam swinger**

- Cover $q=1.0-2.4 \text{ fm}^{-1}$

- **Neutron measurement**

- NPOL3 with 100 m TOF
- Complete measurement of neutron polarization with NSR

Neutron detector/polarimeter NPOL3

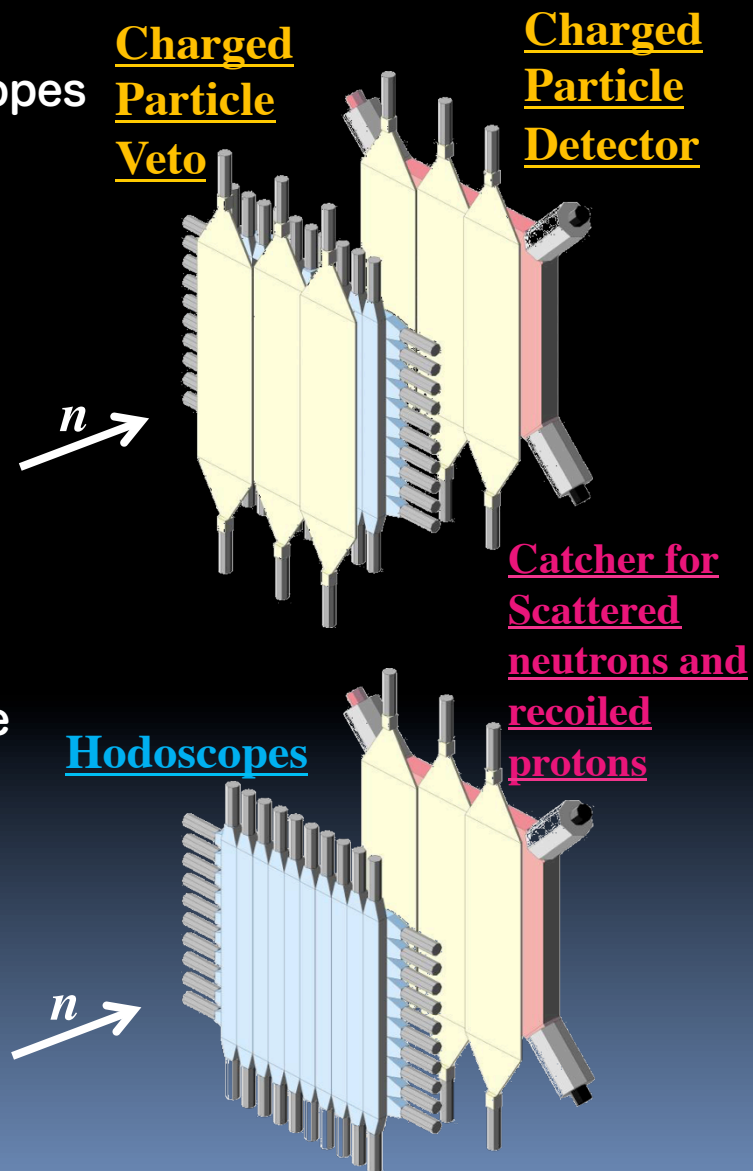
Thanks to E. Ihara

▪ Neutron detector

- 20 sets of 100cm×10cm×5cm hodoscopes
 - **Fast response PMT(rise time < 2ns)**
- Large solid angle : 0.1 msr at 100m
 - **Efficiency : $\epsilon \sim 0.03$**
- Energy resolution
 - **300 keV for 200 MeV neutrons**

▪ Neutron polarimeter

- **Polarimetry**
 - **n+p scattering in hodoscopes**
- Scattered neutrons/recoiled protons are detected with catcher
- Performance
 - **$A_{y;eff} = 0.13$ for 200 MeV neutrons**
 - **FOM = 1.0×10^{-4}**



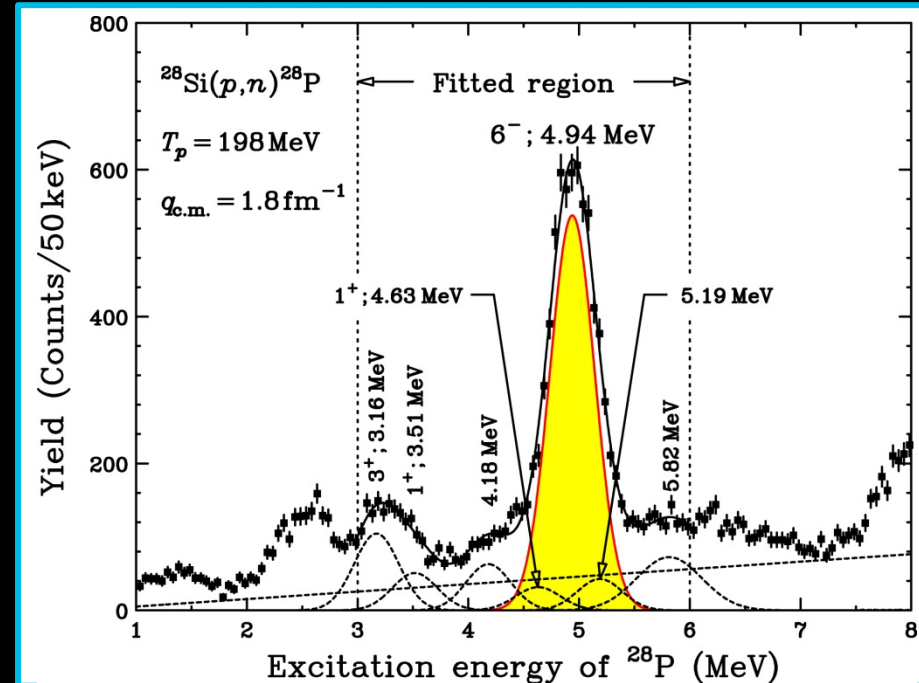
Energy spectrum and peak fitting

Energy spectrum

- Prominent 6^- peak at 4.94 MeV
- 480 keV FWHM
 - With thick 123 mg/cm^2 target

Peak fitting

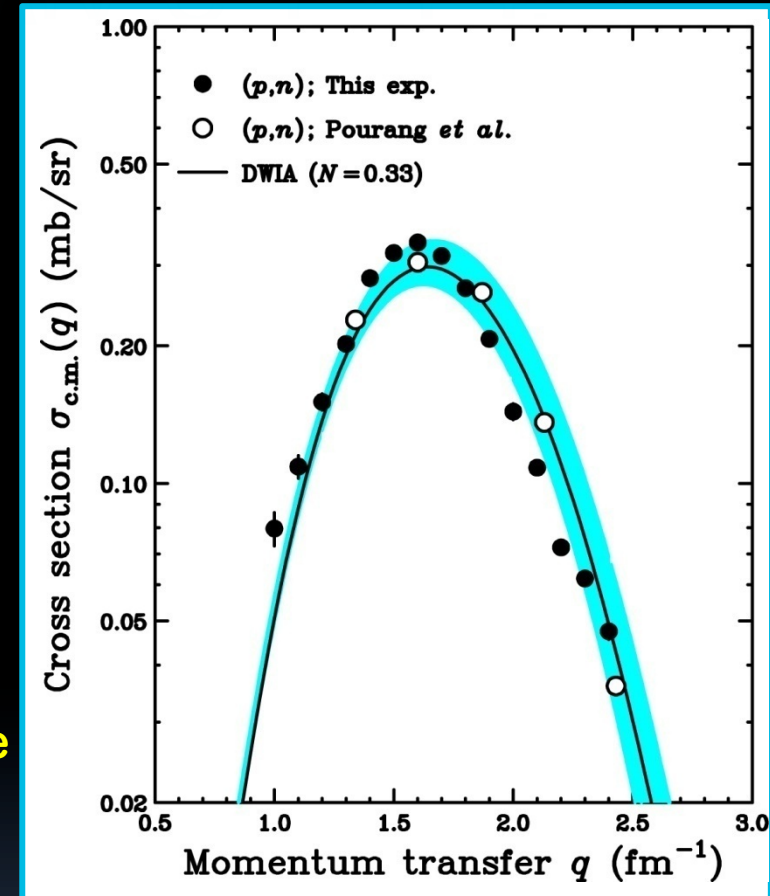
- With known 7 states in 3-6 MeV
 - 3.16, 3.51, 4.18, 4.63
 - **4.94(6^-)**, 5.19, 5.82 MeV
- Good reproduction of exp. data
 - **Reliable 6^- yield for $q=1.0\text{-}2.4 \text{ fm}^{-1}$**



Cross Section and DWIA Calculation

- Smooth q -dep. specified by $L=6$
 - Clear separation of 6^- from neighboring states with $\Delta E=500\text{keV}$
 - 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

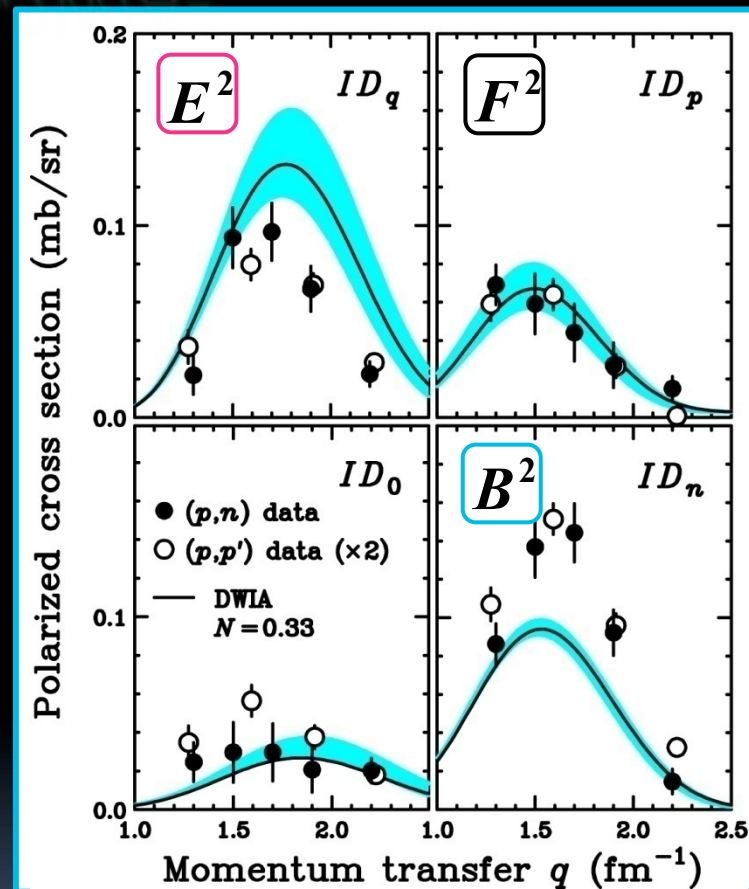
Results

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

- 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 : Reduction
- ✓ Normal spin-transverse B : Enhancement
- ✓ Other amplitude A, C, and F : No modification

Energy half-off-shell effects

Conventional medium effects

- Nuclear binding, Pauli blocking etc.

Sammarruca et al. show that these effects are **too small to explain (p,p')** data

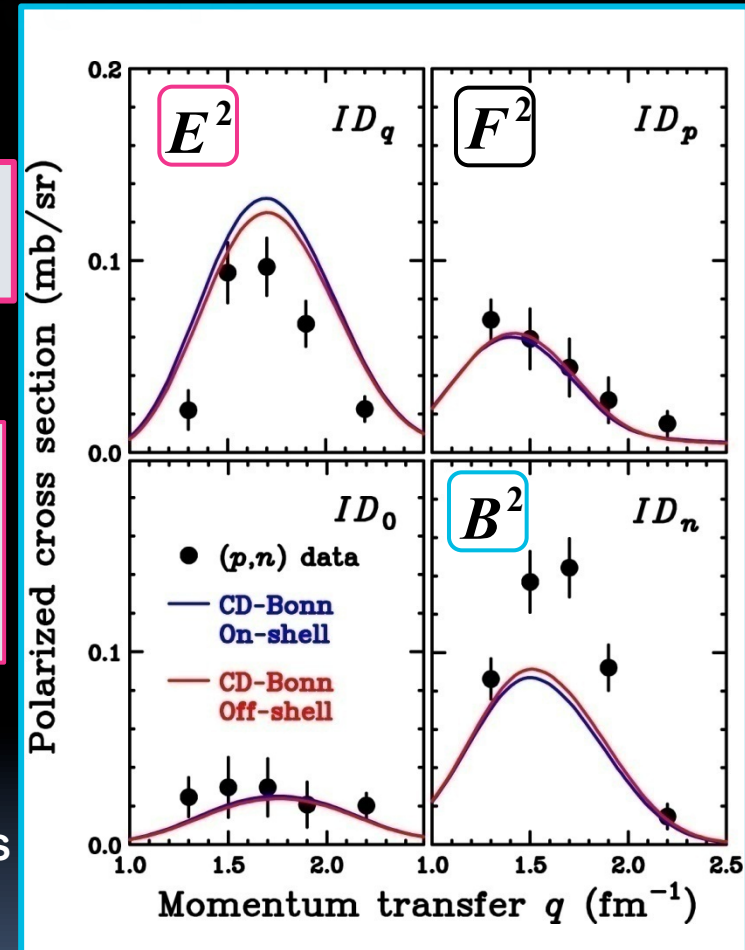
Non-conventional medium effects

- r-meson mass modification

- ✓ Density **independent** DWIA
→ Qualitatively: ○, Quantitatively: ×
- ✓ Density **dependent** DWIA
→ **Effect is too small (Surface peak)**

Energy half-off-shell effects

- **Reaction Q-value = -20.6 MeV \gg 0**
- Energy on-shell / half-off-shell t-matrixes are deduced from CD-Bonn



Partly explain the discrepancy in ID_q and ID_n → Effect is too small
More comprehensive and detailed theoretical analyses are required

Summary

- High resolution measurement of $^{28}\text{Si}(p,n)^{28}\text{P}(6^-)$ at 198 MeV
 - 500 keV FWHM → Clear separation from neighboring states
 - Good statistics for investigation of effective NN interaction
- Comparison with theoretical calculations and (p,p')
 - Consistent with (p,p') data
 - **Isospin-mixing is NOT responsible for discrepancy in (p,p')**
 - Reliable calculations with responses normalized to (e,e')
 - $ID_q (\propto E)$: Small quenching
 - $ID_n (\propto B)$: Significant enhancement
 - Enhancement of B is also observed in QES data
- Comparison with energy half-off-shell calculations
 - Effects are too small to explain the data

核内中間子相関の研究

Nuclear Correlations and Δ Effects

- Effective Interaction

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

Longitudinal (π)

Transverse (ρ)

- $\pi + \rho + g'$ 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

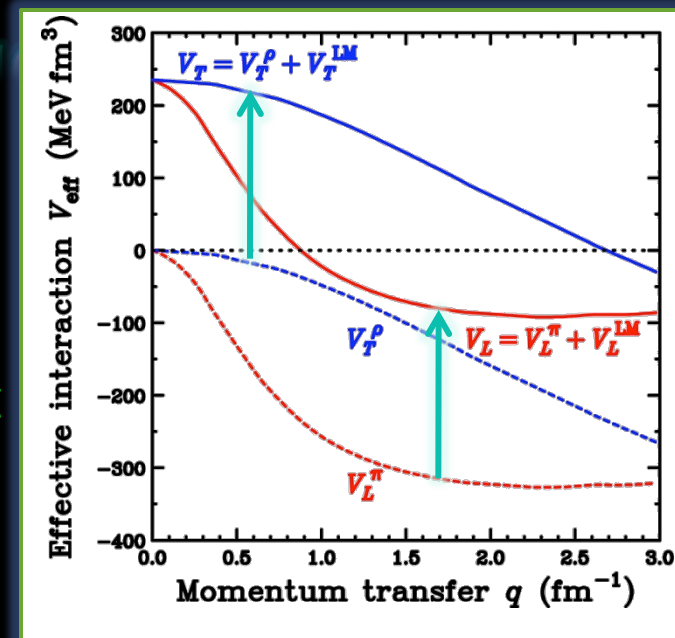
$$V_T(q, \omega) = \frac{f_{\pi NN}^2}{m_\pi^2} \left(\underbrace{\frac{q^2}{\omega^2 - q^2 - m_\pi^2} \Gamma_{\pi NN}^2}_{\pi\text{-exchange}} + \underbrace{g'_{NN}}_{\text{Short-range repulsion}} \right) (\tau_1 \cdot \tau_2) (\sigma_1 \cdot \hat{q}) (\sigma_2 \cdot \hat{q})$$

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

- Extension to N+ Δ system for LM interaction

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

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}

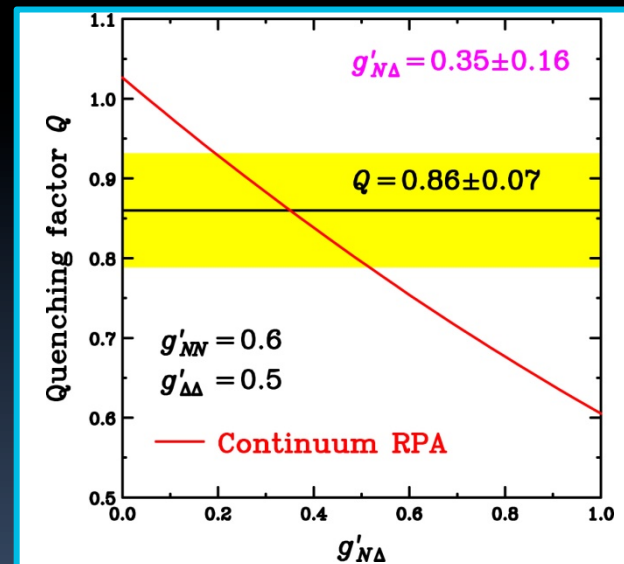
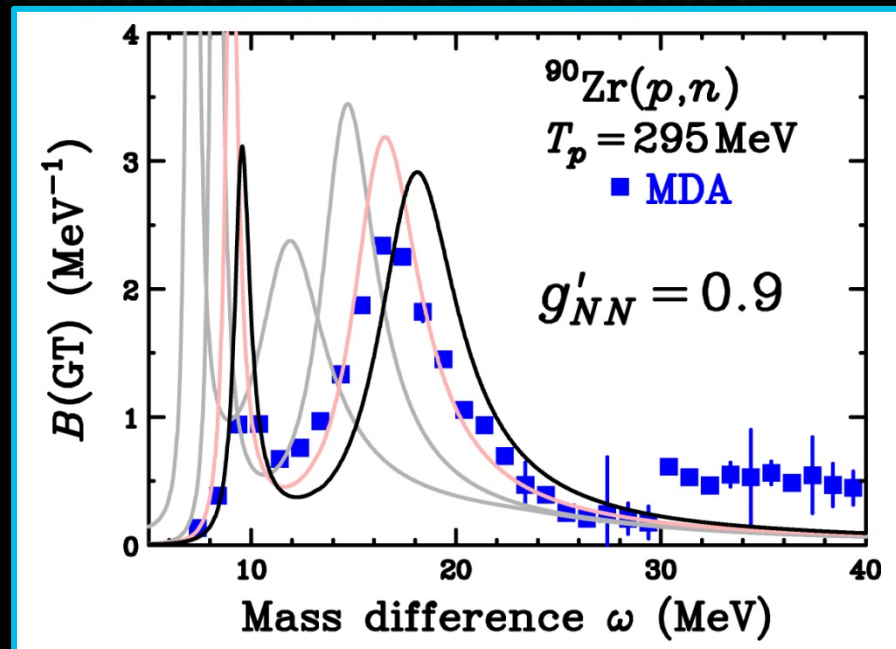
$$g'_{NN} = 0.6 \pm 0.1$$

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

- $g'_{N\Delta}$ Dependence of Q
 - $Q=0.86\pm0.07$ (quadratic sum of errors)
 - Q evaluated in RPA

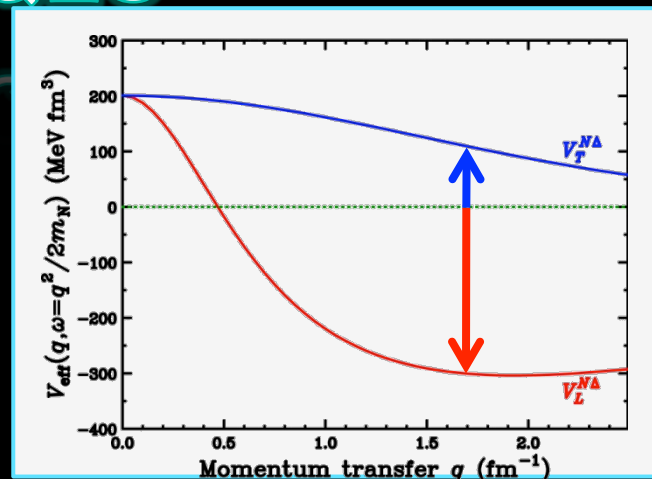
- Strongly depends on $g'_{N\Delta}$

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



Pionic Enhancement in QES

- Effective interaction at large q
 - Attractive spin-longitudinal V_L
 - Especially for $N\Delta$ 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.



Spin-longitudinal Spin-transverse

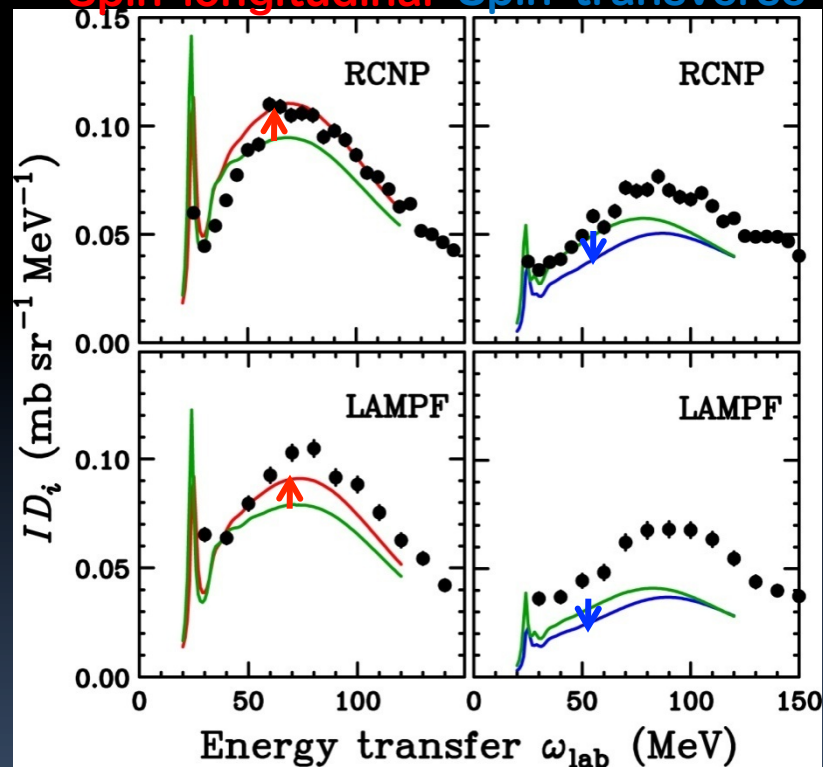
- RCNP/LAMPF data on ^{12}C at $q=1.7\text{fm}^{-1}$

- Spin-longitudinal mode
 - Exp. = RPA > Free (w/o corr.)

Pionic enhancement/correlations in nuclei

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

Attractive rho-mesonic correlations?



New Experiments at RCNP

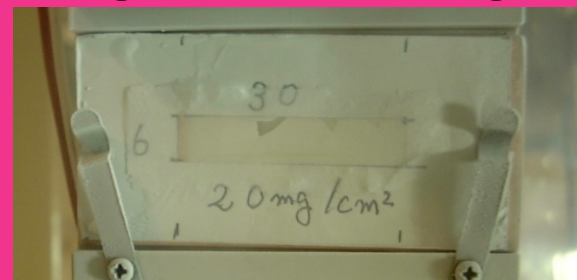
- **Results of quasi-elastic scattering**
 - Enhancement of spin-longitudinal **OK**
 - Quenching of spin-transverse **NG**
 - **Enhancement is really due to attractive pionic correlations ?**
 - Spin-longitudinal/transverse modes were separated with D_{ij}
 - Simple reaction mechanism was assumed
 -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

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

Grand Raiden Spectrometer

- ✓ Resolution: 37,000
- ✓ Acceptance: 5.6 msr

Large Area Ice Target

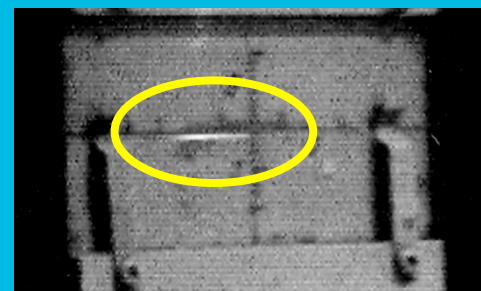


T.Kawabata et al., NIMA459('01)172.

Focal Plane Detector

- ✓ 2 VDC Systems
- ✓ 2 Trigger Scintillators

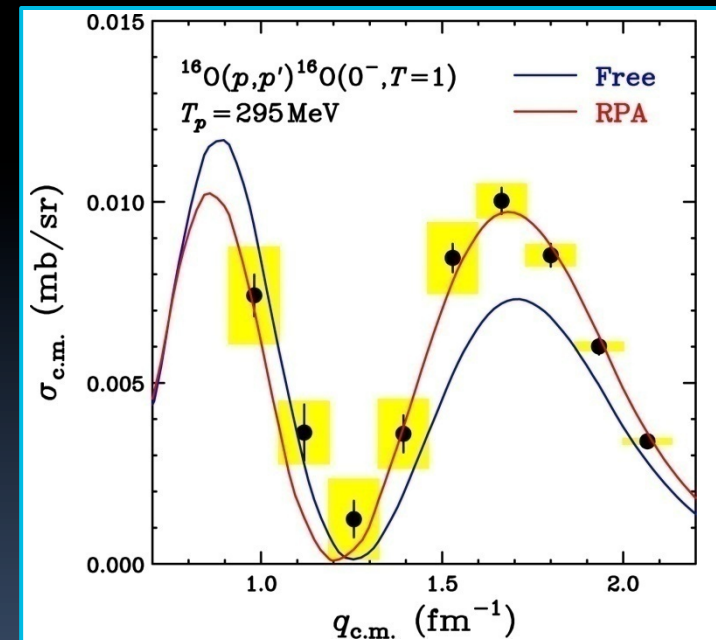
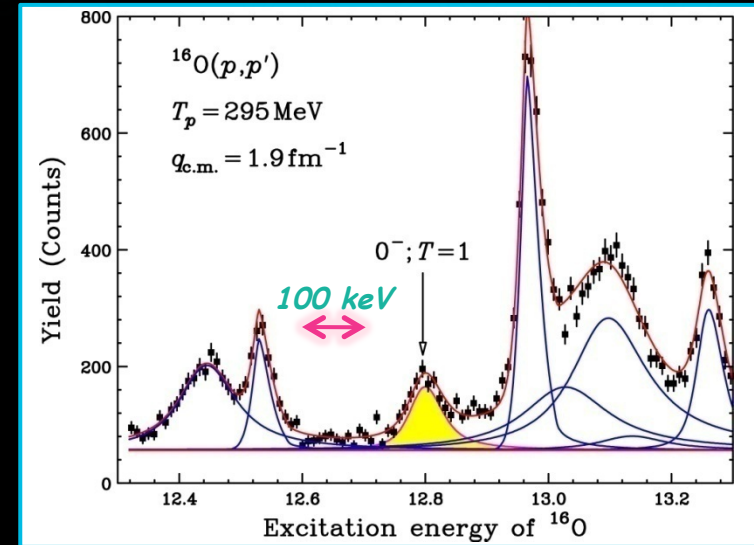
Dispersive Beam



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

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

- **Isvector $J^\pi=0^-$ excitations**
 - Carry π -like quantum number
 - Pure information on pionic mode
- **Experiment: $^{16}\text{O}(p,p')^{16}\text{O}(0^-,T=1)$**
 - $\Delta E=30$ keV with WS+GR
 - $q_{\text{c.m.}} = 0.9 - 2.1$ 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 ($q=1.7$ fm $^{-1}$)

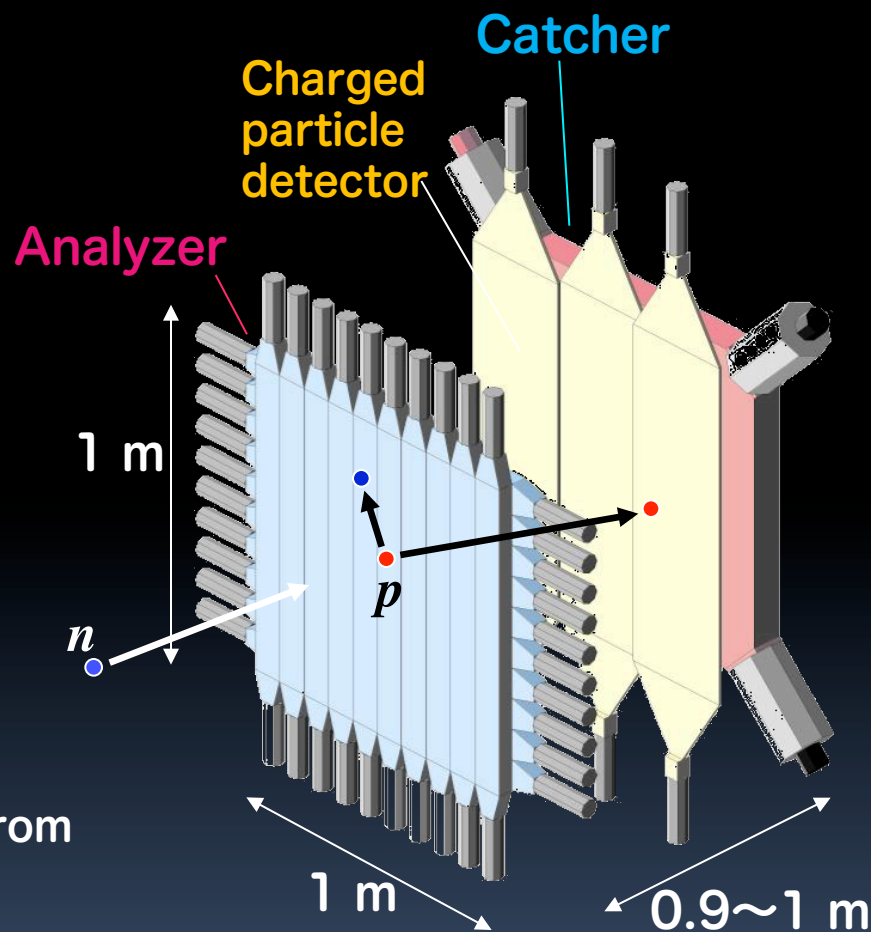
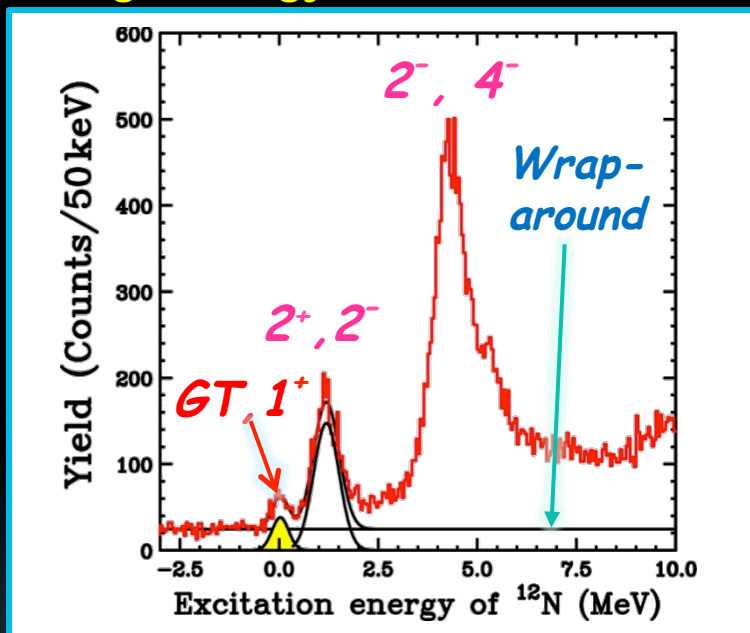


Our data support pionic enhancement
Signature of precursor for pion
condensation in pure pionic mode

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., PRC 77, 054611 (2008).

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

Benchmark reaction

⇒ accuracy of polarization data

- **Theoretical calculations**

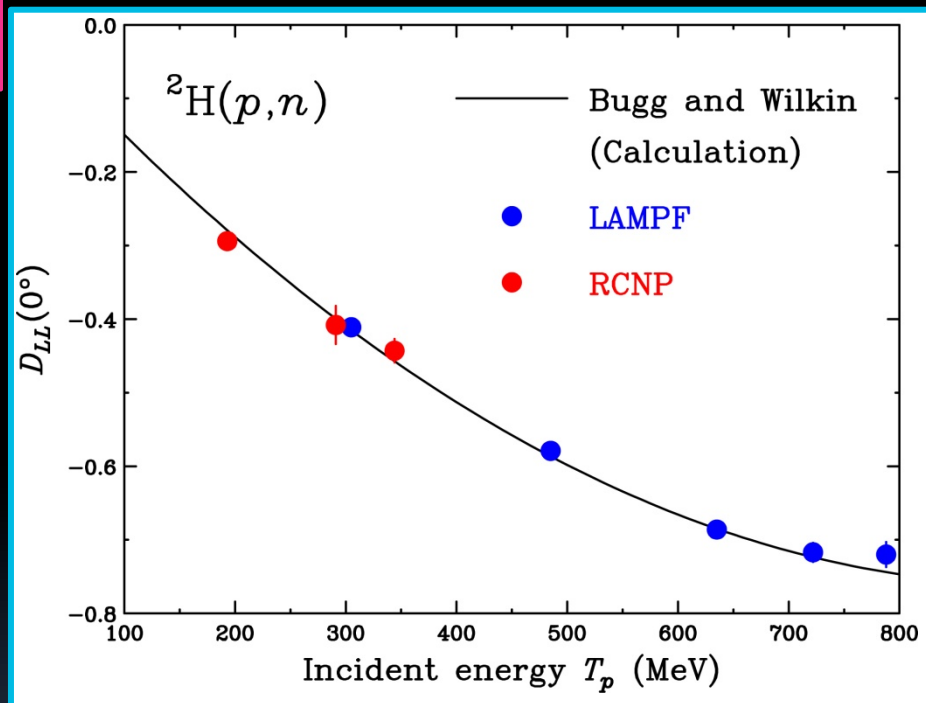
- Including deuteron D-state
- Including p-p FSI (^2He)

- **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)

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

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/ρ -mode
with PTO is reliable

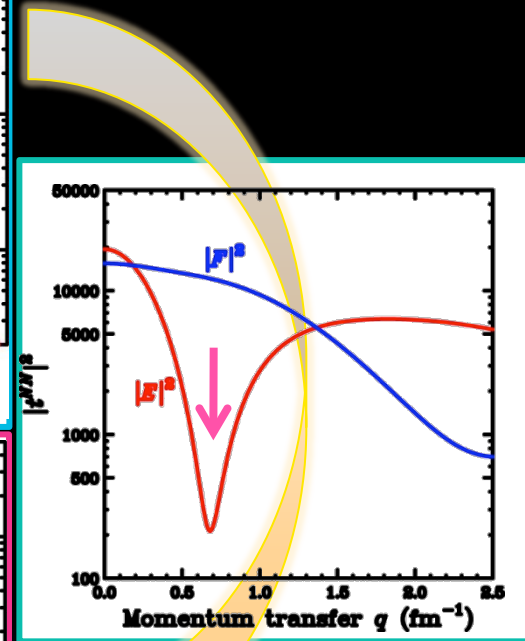
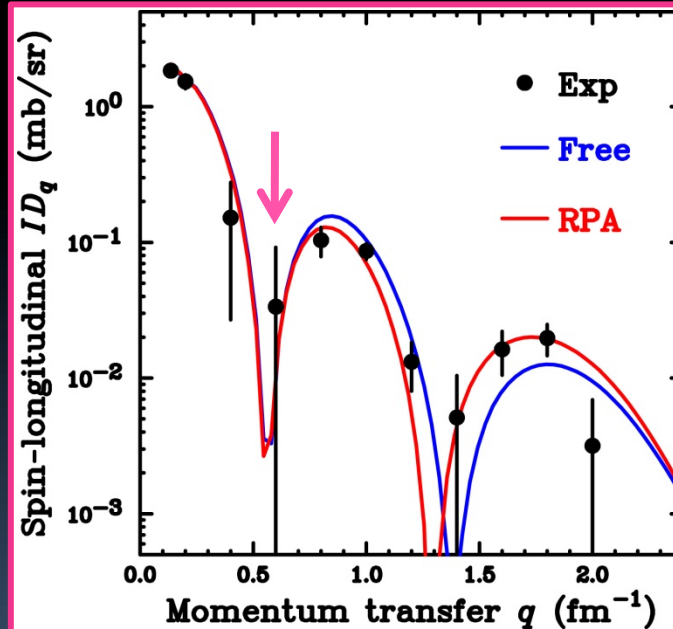
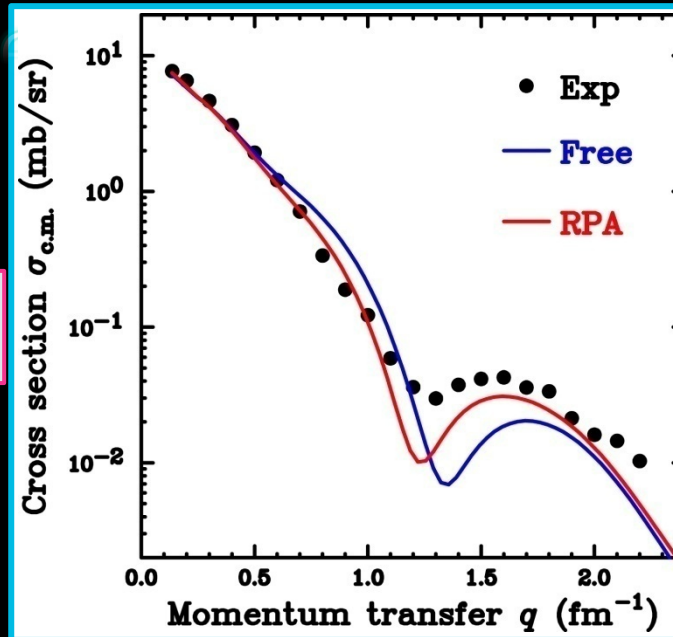
- Comparison with **Free**

- **Significant enhancement**

- Comparison 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?**



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

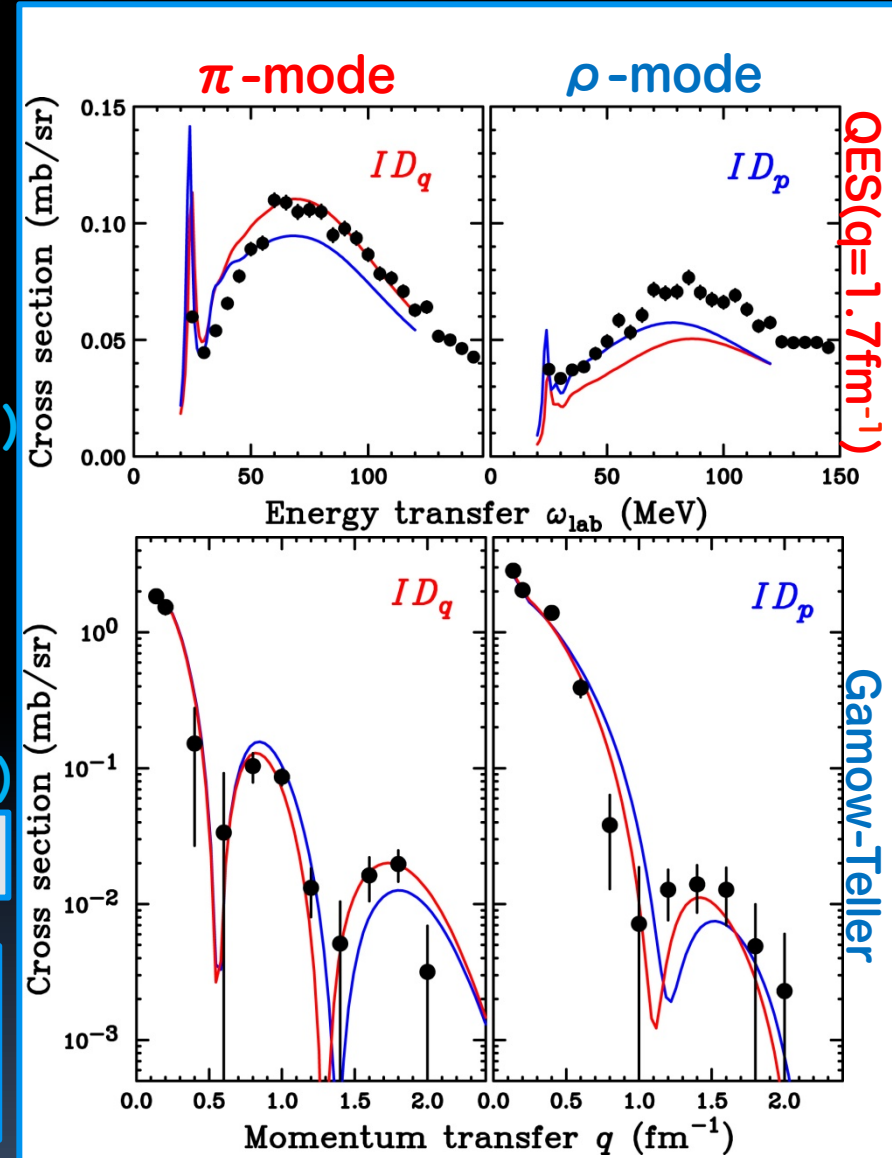
- Theoretical prediction for GT
 - B(GT) is normalized at $q=0$
 - **g' effects have been excluded**
- π -mode
 - At large q
 - Exp. = **RPA** > **Free(w/o corr.)**

Attractive π -corr. at large q

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

Suggest **attractive** ρ -corr. at large q

ρ -mode enhancement in QES
→ **NOT** due to ρ -corr. problem



Difference between Two Spin-Transverse Modes

Spin-transverse mode

In-plane

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

Normal

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

In intrinsic (target) frame, $p=n$

$$R_p = R_n$$

Experimental data

In-plane

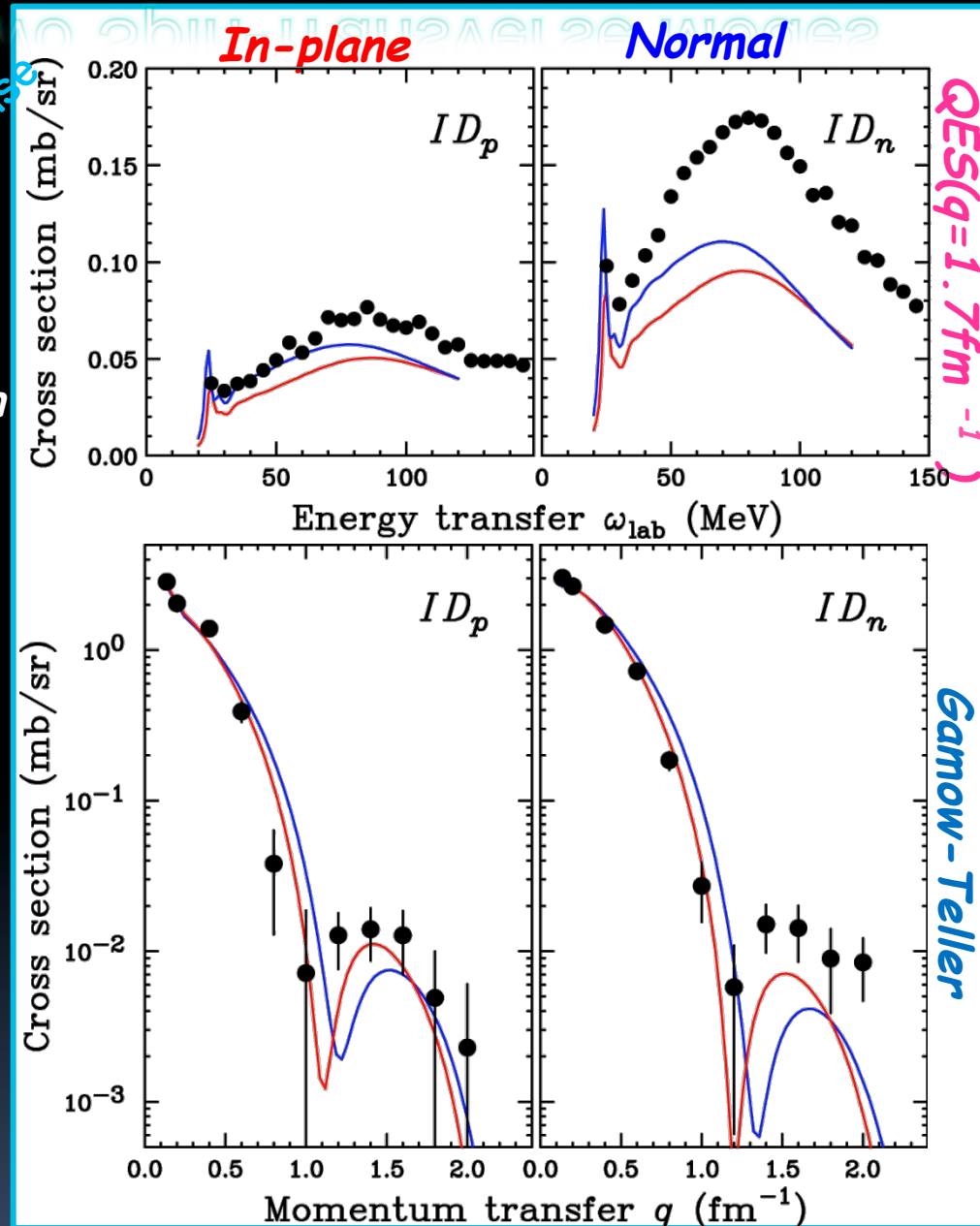
Exp. > RPA

Normal

Exp. >> RPA

Response function (R) and distortion/kinematic factors (KN) are common

⇒ NN *t*-matrices are modified?

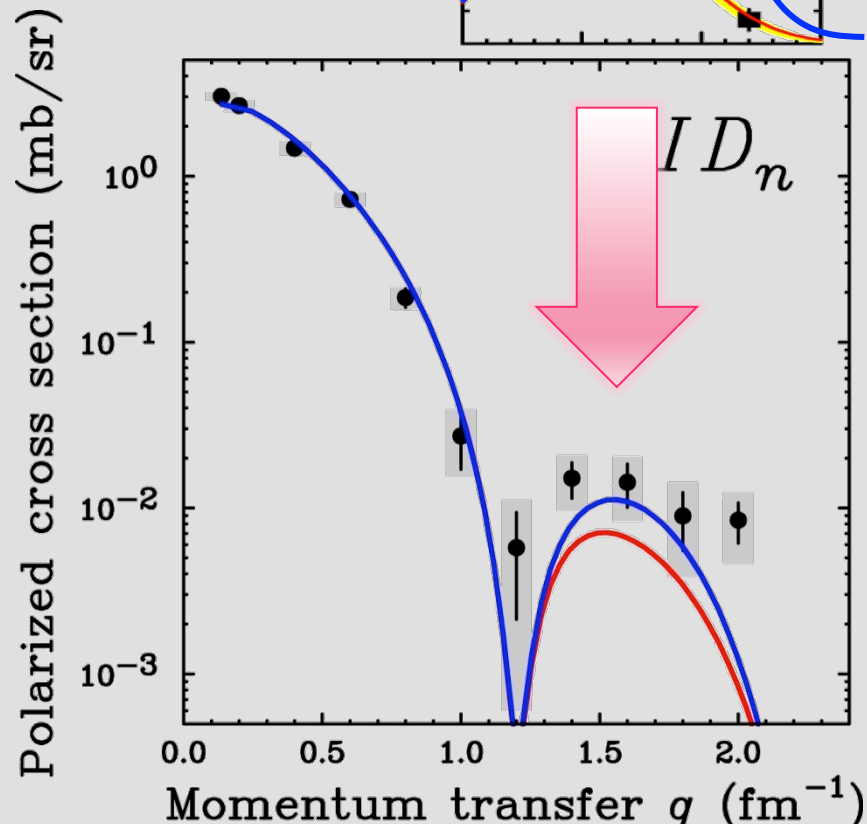
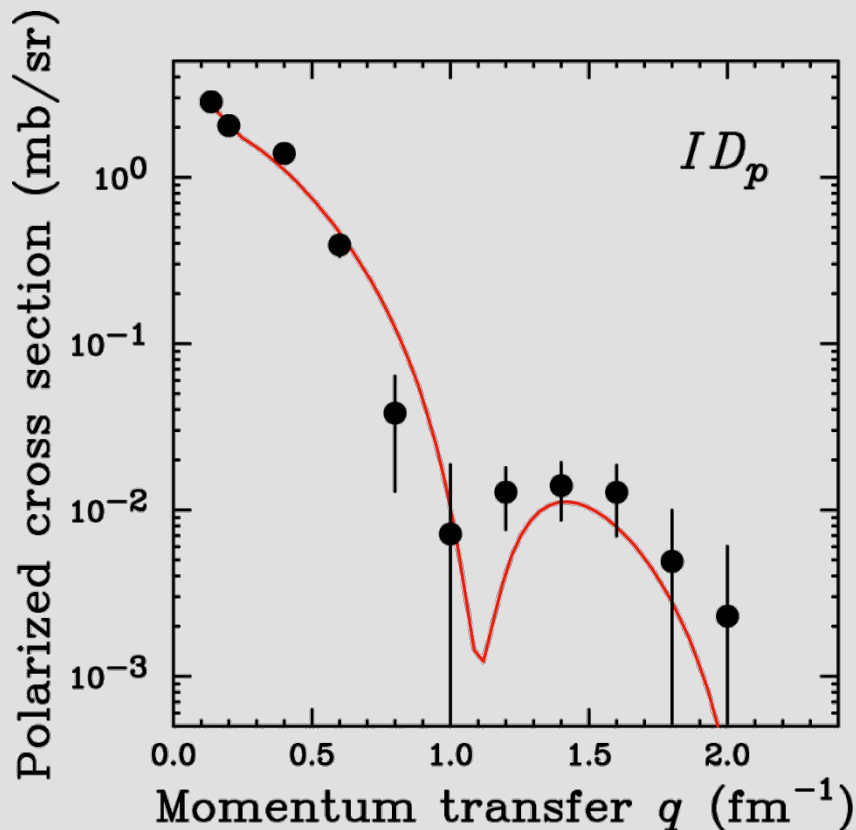


Toy-Model Calculation

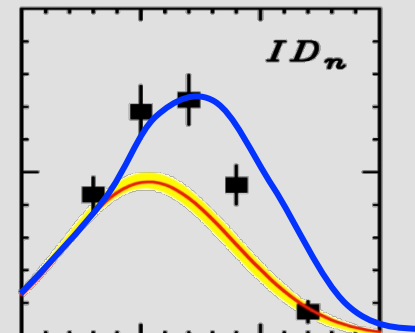
Normal spin-transverse B is enhanced in nuclei

✓ Red : DWIA + Free NN

✓ Blue : DWIA + Medium-modified NN



Stretched State



Summary and Future Perspective

▪ Results of recent experiments

- Measure s of $^{16}\text{O}(p,p')^{16}\text{O}(0^-, T=1) \cdots$ RCNP-E155
 - Pure pionic mode \rightarrow Separation with D_{ij} is not needed
 - **Observe the pionic correlations (enhancement)**
- Measure D_{ij} of $^{12}\text{C}(p,n)^{12}\text{N}(1^+, T=1) \cdots$ RCNP-E256
 - q -dependence of π - and ρ -exchange interactions
 - **Attractive contribution from both π -/ ρ -exchange at large q**

$\pi + \rho + g'$ model interaction is adequate for describing
spin-isospin responses of nuclei in wide (q, ω)

▪ Enhancement in spin-transverse ID_p and ID_n

- **Medium modification of NN t-matrix in normal-spin-transverse (B)**
- Short-range tensor effects should be also investigated

▪ New experiments at RCNP

- E313 (Yamada-san) : Medium effects of p-n interaction in nuclei via (p,pn) reactions

核内テンソル相関の研究

SD Sum Rules

Non-Energy-Weighted Sum Rule (NEWS)

- SD operator $\hat{O}_{\pm}^{\lambda,\mu} = \sum \tau_{\pm}^i r_i [Y_1(\hat{r}_i) \times \vec{\sigma}_i]_{\mu}^{\lambda}$ T.Suzuki and H. Sagawa, NPA 637, 547 (1998).

- 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 $1\hbar\omega$

- ^{12}C

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

$$S_{-}^0 : S_{-}^1 : S_{-}^2 = 1 : 2.7 : 3.5 \text{ for } jj\text{-closed nuclei}$$

- ^{16}O

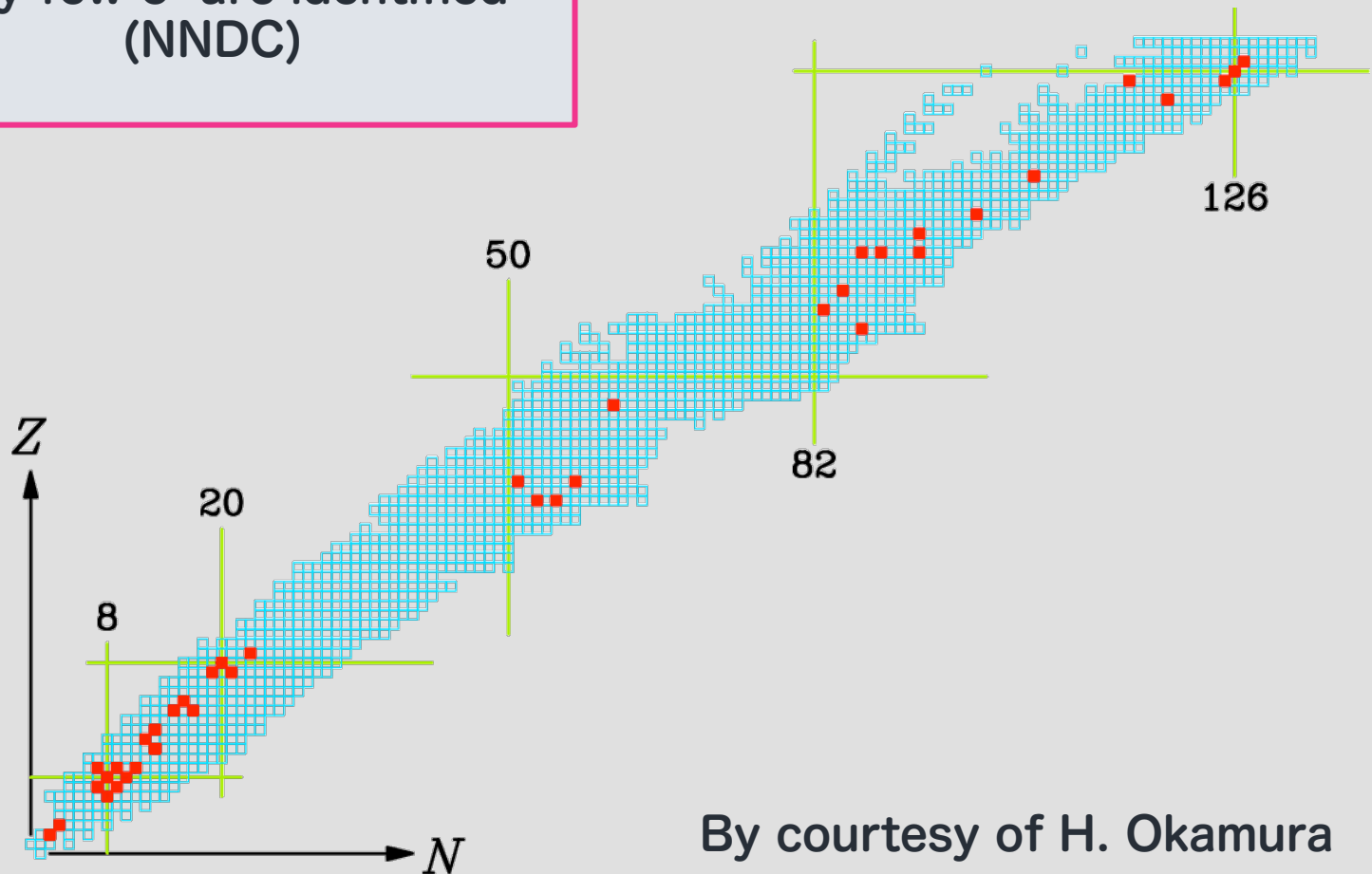
$$S_{-}^{\lambda} = \sum_{\mu} |\langle \lambda\mu | \hat{O}_{-}^{\lambda,\mu} | 0 \rangle|^2 = \begin{cases} \frac{3}{4\pi} 8b^2 = 5.98 \text{ fm}^2, & \lambda = 0^{-} \\ \frac{3}{4\pi} 24b^2 = 17.95 \text{ fm}^2, & \lambda = 1^{-} \\ \frac{3}{4\pi} 40b^2 = 29.92 \text{ fm}^2, & \lambda = 2^{-} \end{cases}$$

$$S_{-}^0 : S_{-}^1 : S_{-}^2 = 1 : 3 : 5 \text{ for } ls\text{-closed nuclei}$$

0⁻ strength is weak \Leftrightarrow 2⁻ strength is strong ($\times 3.5 \sim 5$)

Missing 0- States

Very few 0- are identified
(NNDC)



By courtesy of H. Okamura

Scientific Motivation for SD Resonance

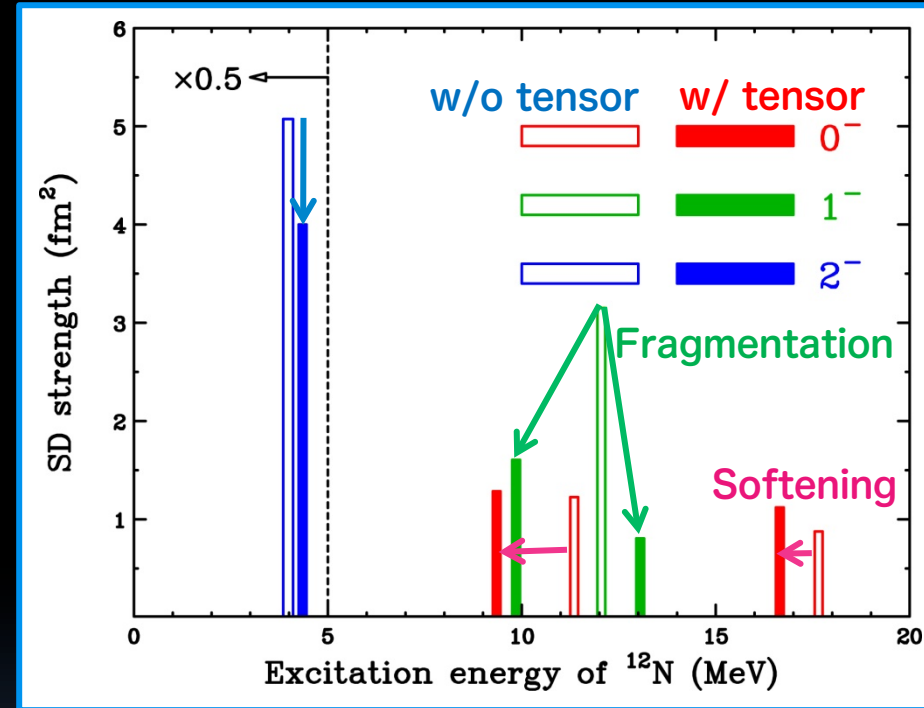
- **Search/Identify missing 0^- states**
 - **Model (roughly) independent sum-rule**
 - Missing strength is crucial problem in nuclear physics.
 - **0^- is the quantum number of pions**
 - 0^- strength is sensitive to pions in nuclei
 - Useful information on tensor correlations in nuclei
- **Search/Identify missing 1^- states**
 - Recent (p,n) and (d, ^2He) 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 is very important for astrophysics**



Tensor Effects in Spin-Dipole

- Shell-model calc. with M3Y
 - w/o tensor int.
 - w/ tensor int. (inherently neglected)
- **2⁻ strength**
 - Quenching
- **1⁻ strength**
 - Quenching and fragmentation
 - **Repulsive tensor correlation**
- **0⁻ strength**
 - Shift to lower E_x
 - **Attractive tensor correlation**

Shell-model calc for SDR in ^{12}N
(Major strengths)



Experimental challenge for observing tensor effects

- ✓ Identify 0^- state at lower E_x ($E_x \leq 10$ MeV)
- ✓ Confirm fragmentation of 1^- (= No-concentration)

J^π Components of SDR in ^{12}N

- Sensitive to J^π of SDR

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

- $E_x = 4.3 \text{ MeV}$ (known 2^-)

- ID_q and $ID_p \rightarrow 2^-$

- $E_x = 6.4$ and 7.5 MeV

- ID_q and $ID_p \rightarrow 2^-$ (dominant)
- Consistent with $(d, ^2\text{He})$, $(^{12}\text{C}, ^{12}\text{N})$

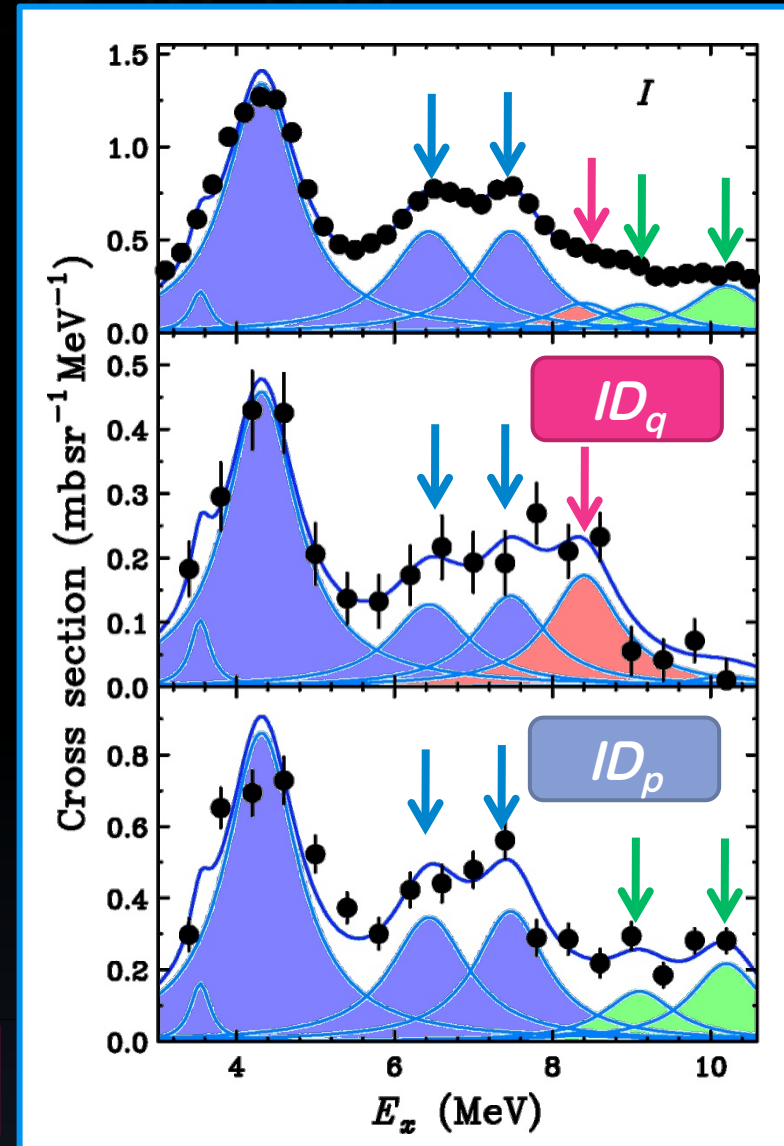
- $E_x = 8.4 \text{ MeV}$

- ID_q only $\rightarrow 0^-$ (dominant)
- 1st clear observation

- $E_x = 9.1$ and 10.2 MeV

- ID_p only $\rightarrow 1^-$ (dominant)

Consistent with calc. including tensor corr.



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

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

$E_x = 4.3, 6.4, \text{ and } 7.5 \text{ MeV}$

□ ID_q and $ID_p \rightarrow 2^-$ (dominant)

$E_x = 8.4 \text{ MeV}$

□ $ID_q \rightarrow 0^-$ (enhancement in D_q/D_p)

$E_x = 9.1 \text{ and } 10.2 \text{ MeV}$

□ $ID_p \rightarrow 1^-$

• 2^- strength

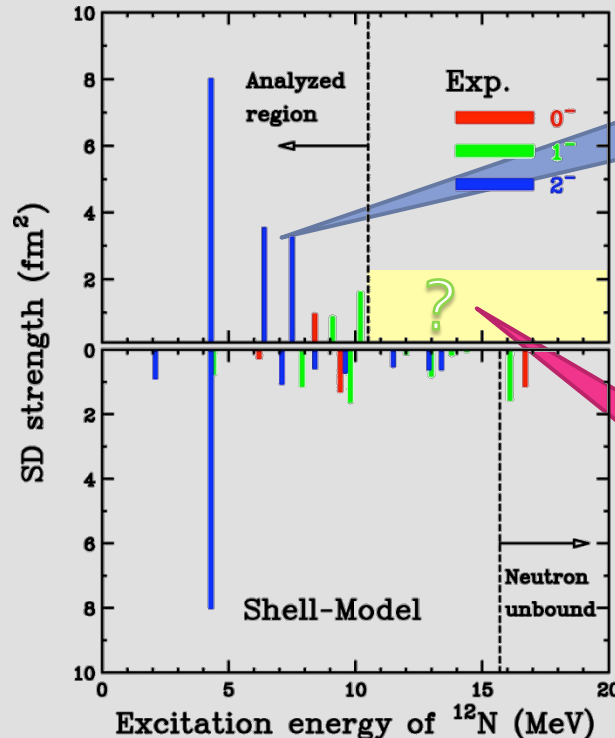
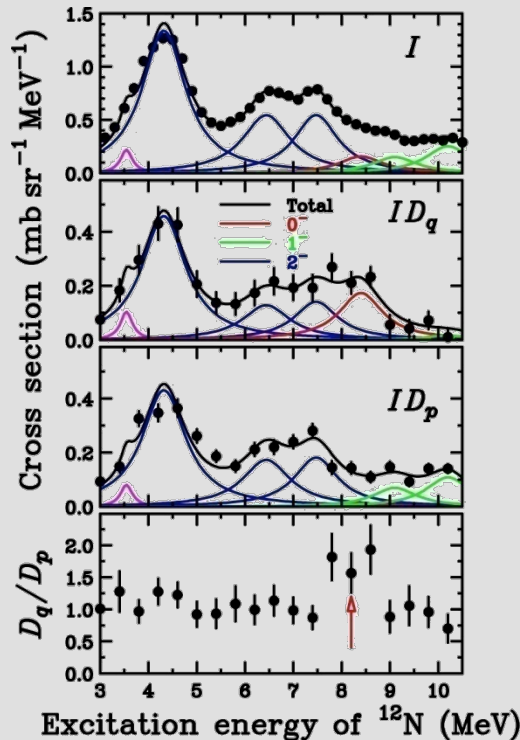
• $\sim 100\%$ NEWS

• $E_x=6.4$ and 7.5 MeV have other J^π
 \rightarrow High quality data is required

• 0^- and 1^- strengths

• Consistent with SM including tensor

• Large strengths in high E_x in SM

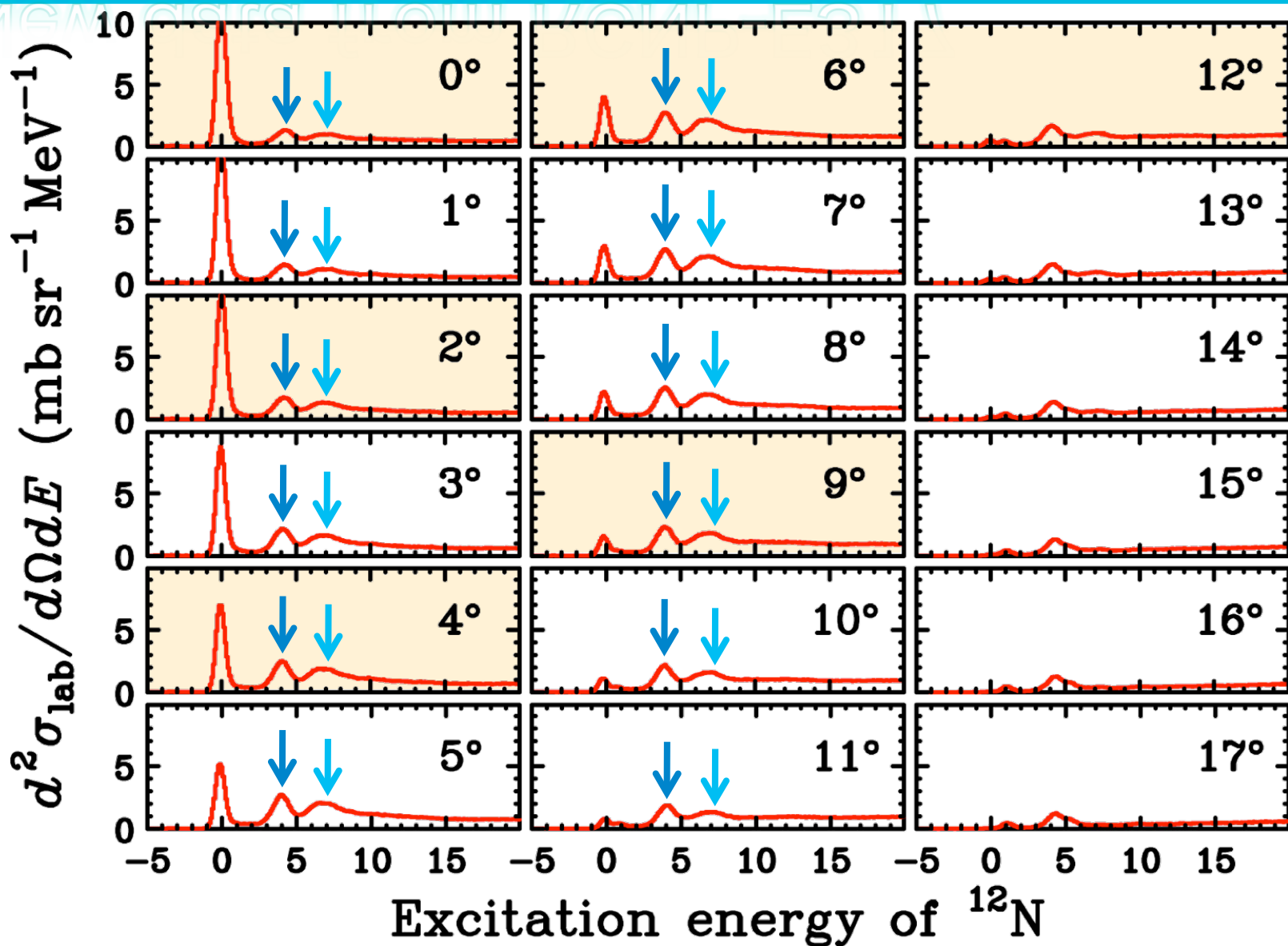


Including other J^π ?

New E317

Fragmented SDR ?

New data from RCNP-E317



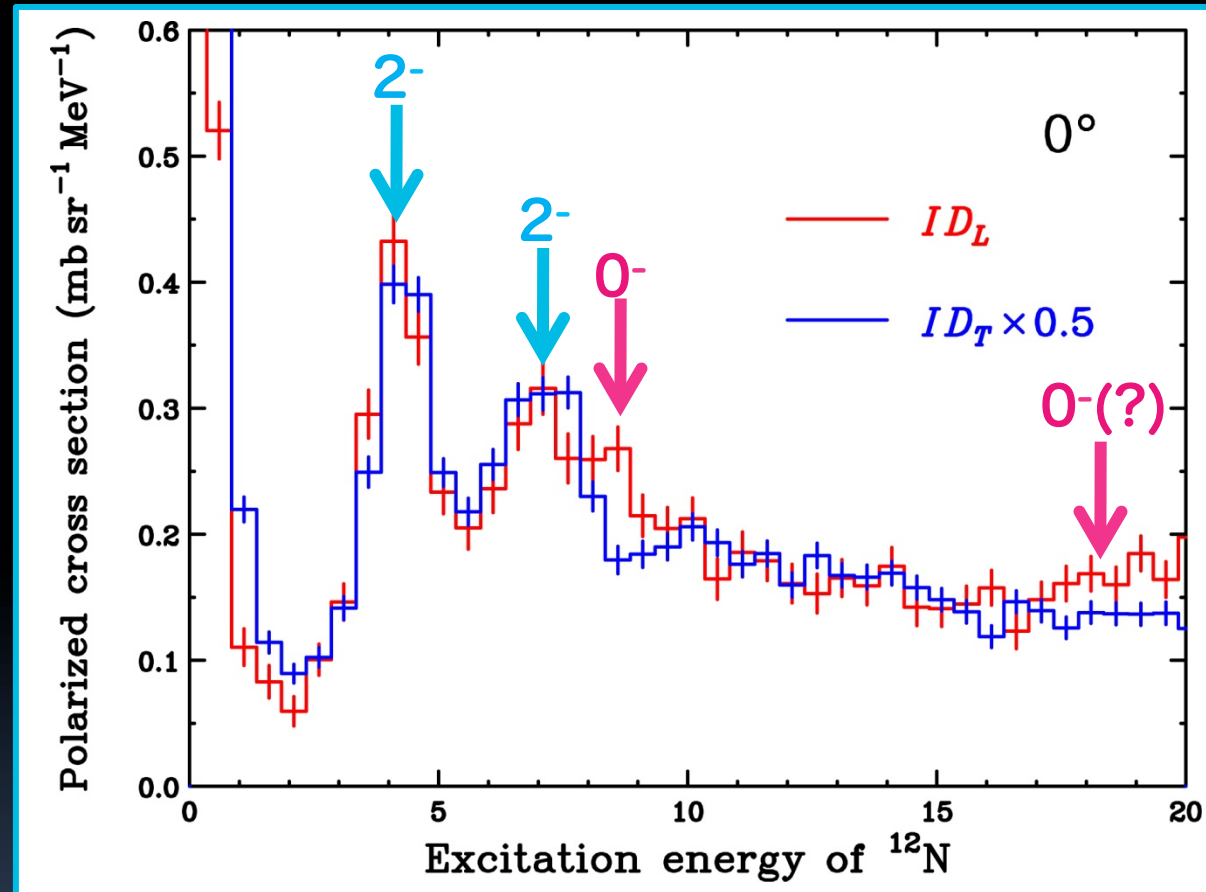
Preliminary Results of RCNP-E317

Spin-parity assignment

- 0^- : $- > -$
- 1^- : $- < -$
- 2^- : $- = -$

- ✓ 0^- : Confirmed
- ✓ 1^- : Not observed (fragmented?)

$^{12}\text{C}(\vec{p}, \vec{n})^{12}\text{N}$ at 0°



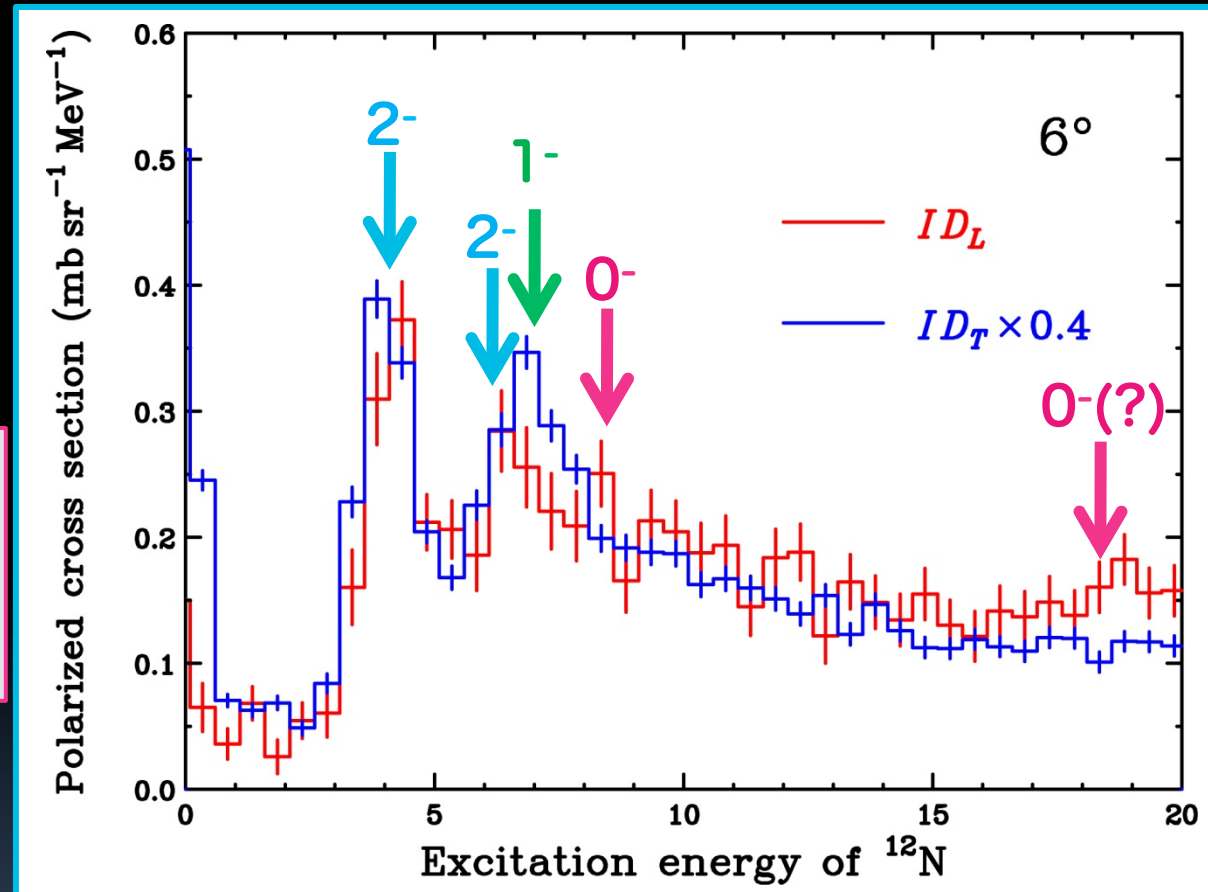
Preliminary Results of RCNP-E317

Spin-parity assignment

- 0^- : — > —
- 1^- : — < —
- 2^- : — = —

$^{12}\text{C}(\vec{p}, \vec{n})^{12}\text{N}$ at 6°

✓ 1^- : Observed at 7MeV
 ✓ 0^- : Fragmented at 15-20 MeV ?



Summary

- **SDR strength distribution in ^{12}N**
 - High resolution $^{12}\text{C}(p,n)$ measurement with $\Delta E=500-700$ keV
 - Measure complete spin observables
 - **Enable J^π assignment of SDR**
- **Experimental results**
 - SDR at $E_x \sim 4$ MeV
 - $J^\pi = 2^-$ (consistent with previous results)
 - SDR at $E_x \sim 7$ MeV
 - **2^- is dominant (1^- is also included)**
 - SDR at $E_x = 8.4$ MeV
 - **First observation of 0^- in ^{12}N**
 - SDR at $E_x \sim 10$ MeV
 - **1^- is dominant and fragmented**
- **Comparison with theoretical calculations**
 - **Consistent with shell-model calculations with tensor correlations**
 - Softening for 0^-
 - Fragmentation for 1^-

Systematic data (6 angles) have been collected
→ **SDR in continuum would be deduced**

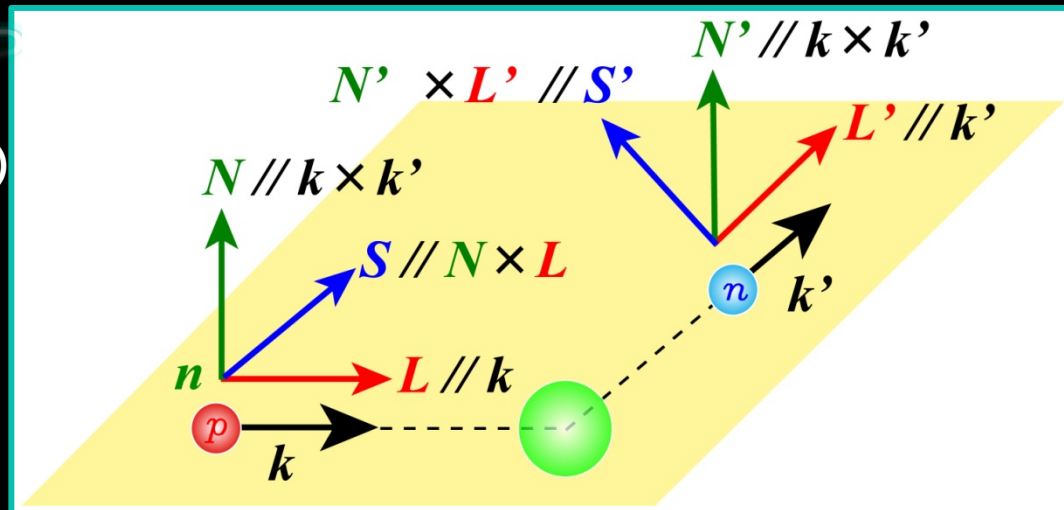
Thank you for your attention

本日はありがとうございました

予備スライド

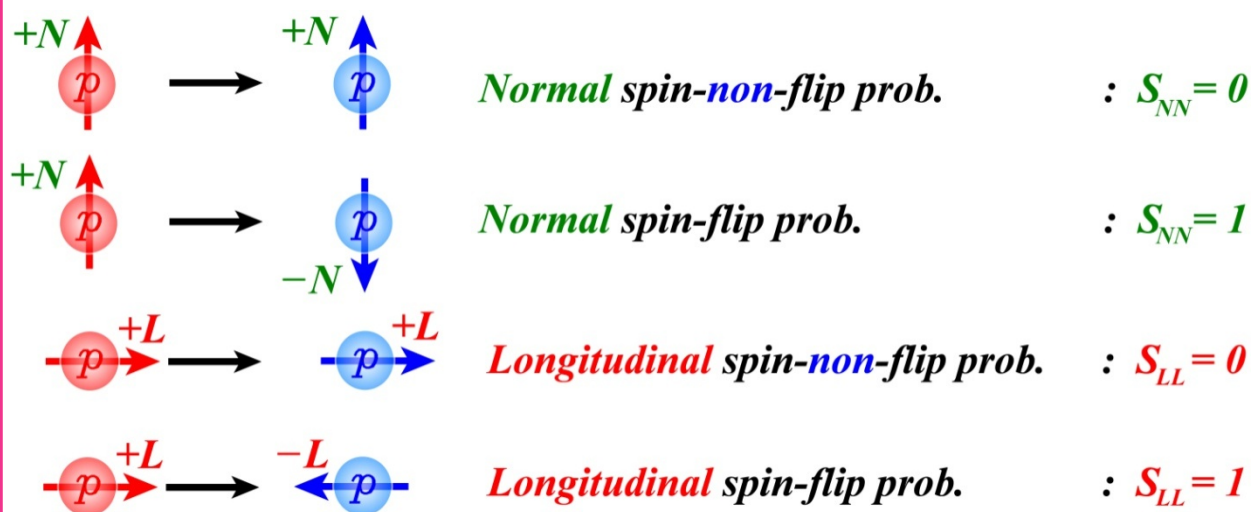
Coordinate System and Polarization Observables

- 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_{ij} and polarization transfer observables D_{ij}



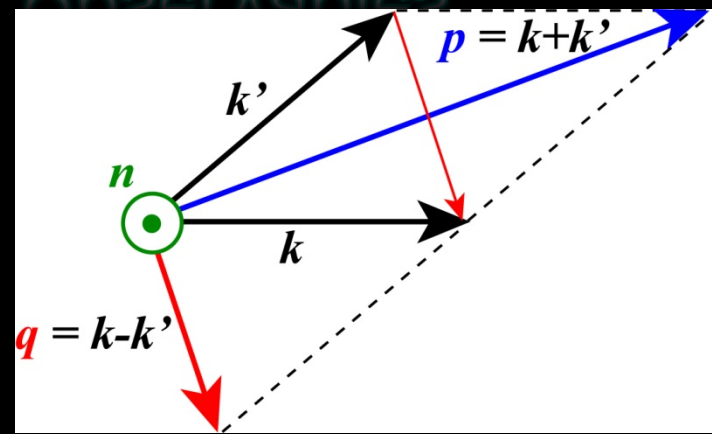
- ✓ $S_{ii} \equiv \frac{1}{2}(1 - D_{ii})$
- ✓ S_{ii} depends on reaction
- ✓ $S_{LN} = S_{NL} = 0.5$ from symmetry

NN Scattering and Polarization Observables

- NN t-matrix (scattering amplitude)

- Franey-Love notation

$$t_{NN}(E, q) = \underbrace{A'P_S + B'P_T}_{\text{Central}} + \underbrace{C(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{n}}_{\text{Spin-orbit}} + \underbrace{E'S_{12}(\hat{q}) + F'S_{12}(\hat{p})}_{\text{Tensor}}$$



- 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

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

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

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

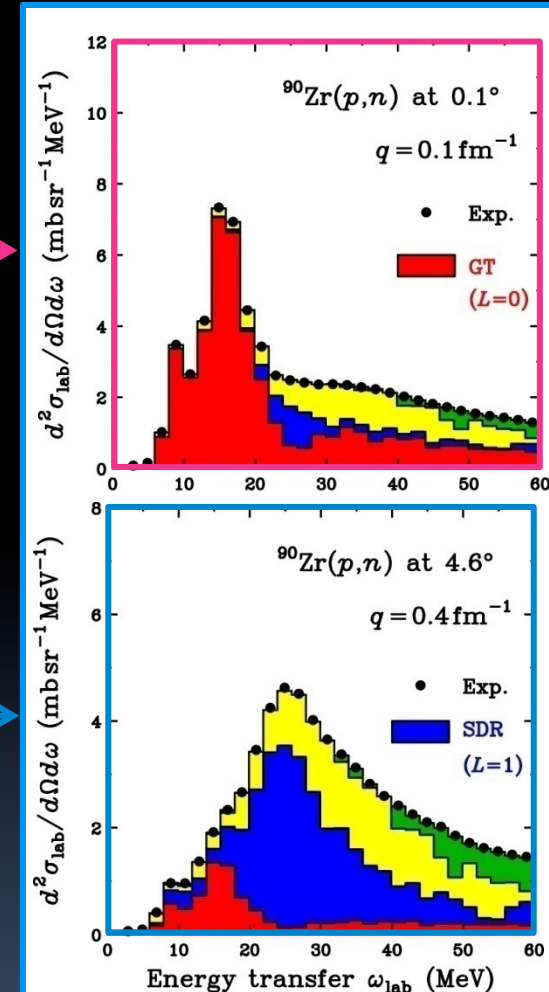
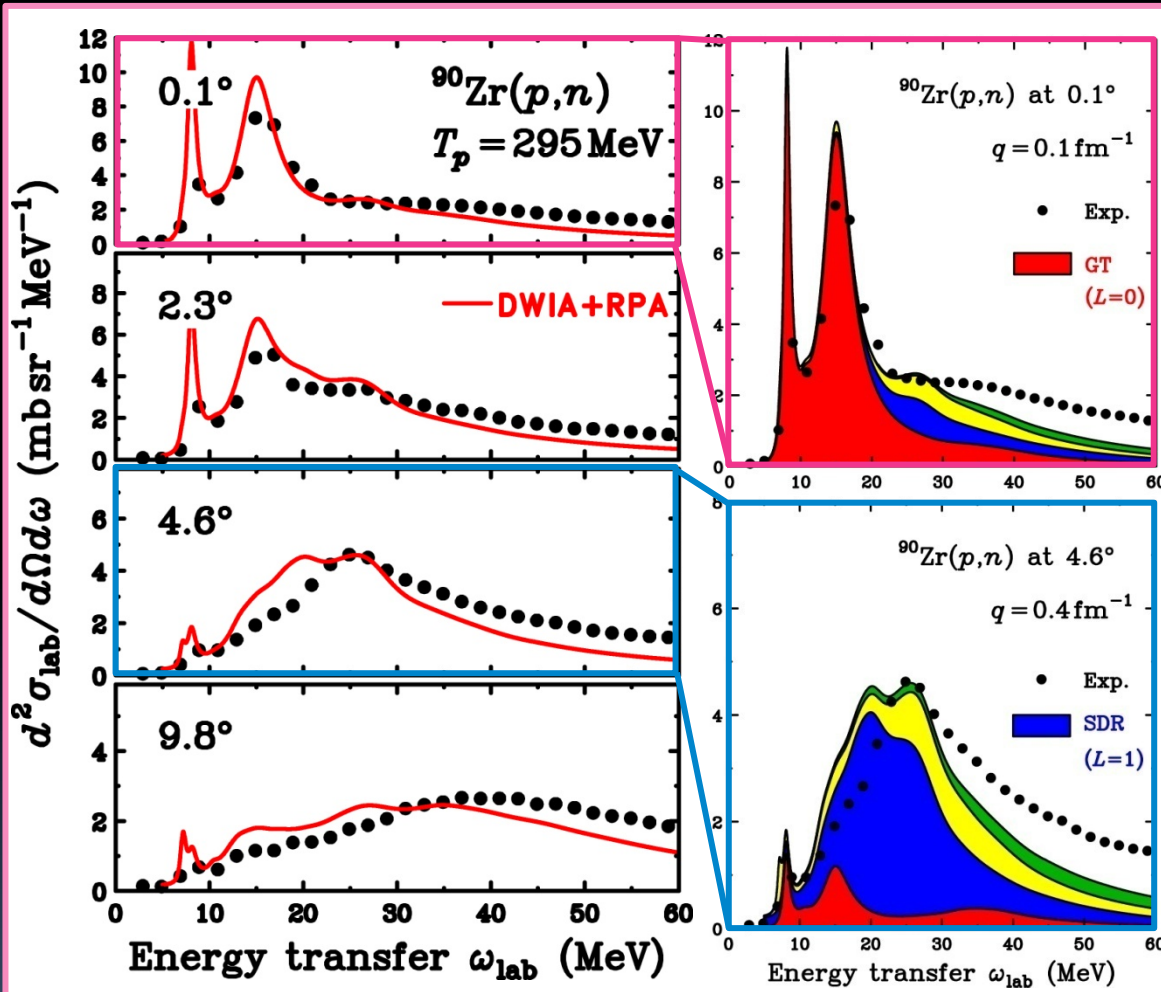
$$\vec{\sigma}_1 \cdot \hat{i}\vec{\sigma}_1 \cdot \hat{j} = i\varepsilon_{ijk}\vec{\sigma}_k + \delta_{ij}$$

$\{i, j, k\} = \{n, p, q\}$

Scattering t-matrix
 $\Rightarrow D_{ij}$ is calculable

DWIA Analysis for $^{90}\text{Zr}(p,n)$ at 295 MeV

- Reasonable description of absolute σ and each L contributions
 - Consistent with MDA
- Underestimation at large $\omega \rightarrow$ Lack of 2p2h effects



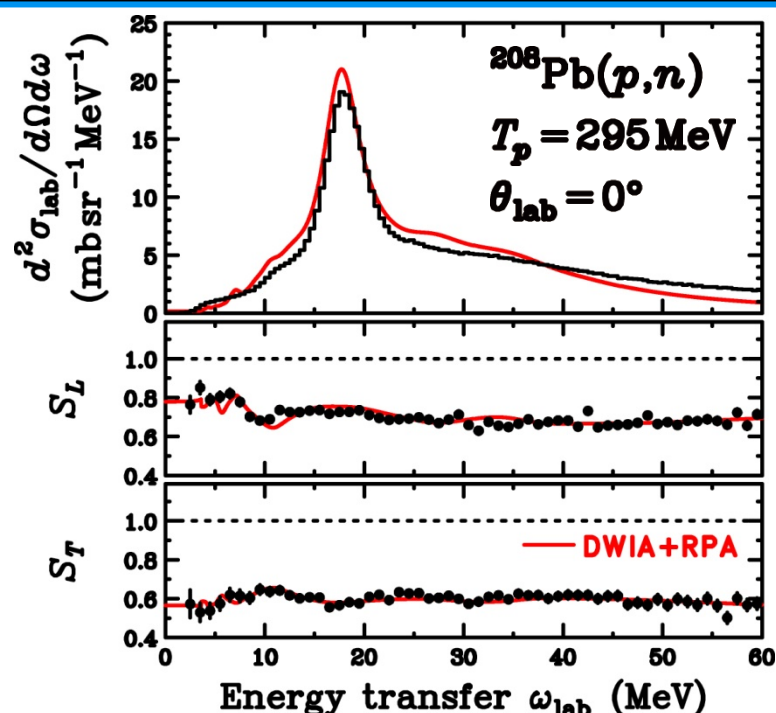
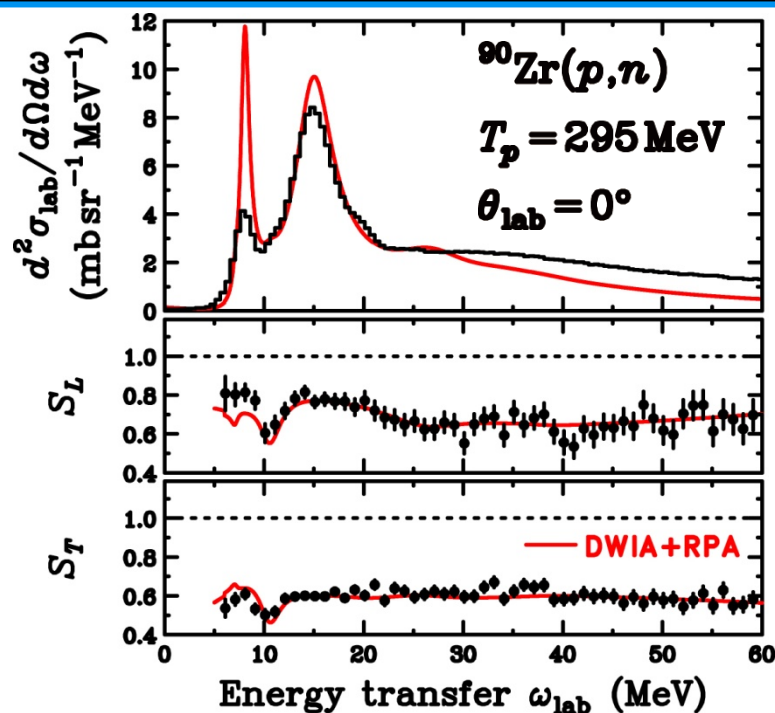
DWIA Analysis for Polarization Observables

- Longitudinal and transverse spin-flip S_L and S_T
 - Sensitive to spin-parity J^π
- Good reproduction of S_L and S_T
 - J^π composition in DWIA+RPA is appropriate**

PWIA
Prediction

| J^π | S_L | S_T |
|----------|-------|-------|
| 1+ (GT) | 0.67 | 0.67 |
| 0- (SDR) | 0.00 | 1.00 |
| 1- (SDR) | 1.00 | 0.50 |
| 2- (SDR) | 0.60 | 0.70 |

Lacking 2p2h would have same J^π composition
 → **Information for challenge including 2p2h**



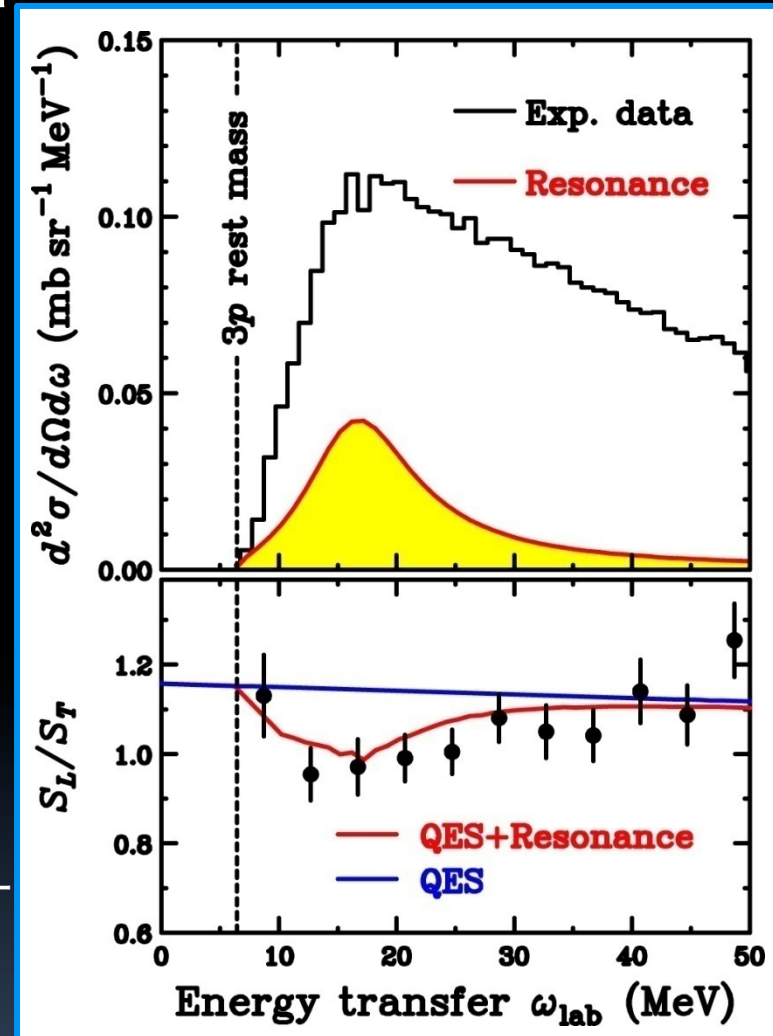
Search for 3-Nucleon T=3/2 Resonance

- Production of $3p(T=3/2)$ system
 - ${}^3\text{He}(p,n)3p$ at 346 MeV and 0°
- Spin-flip probabilities
 - Longitudinal S_L
 - Transverse S_T
 - $S_L/S_T < \text{QES (non-resonance)}$

- Sensitivity of S_L/S_T for J^π

| J^π | S_L/S_T |
|----------------------------|------------------------|
| $(1/2)^-$ | $0.7 < \text{QES}$ |
| $(1/2)^+$, $(3/2)^\pm$ | $1.3-1.6 > \text{QES}$ |

- Reproduce exp. S_L/S_T with $(1/2)^-$



Isospin Dependence of 3NF

- Evidence for 3NF
 - B.E. of ${}^3\text{H}$ and ${}^3\text{He}$
 - Nd scattering/reaction

Limited to $T=1/2$ system

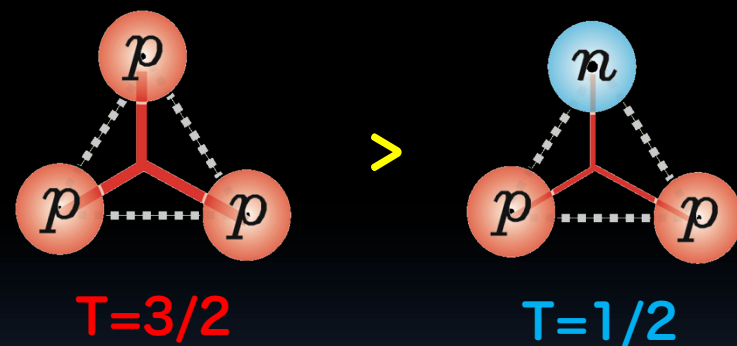
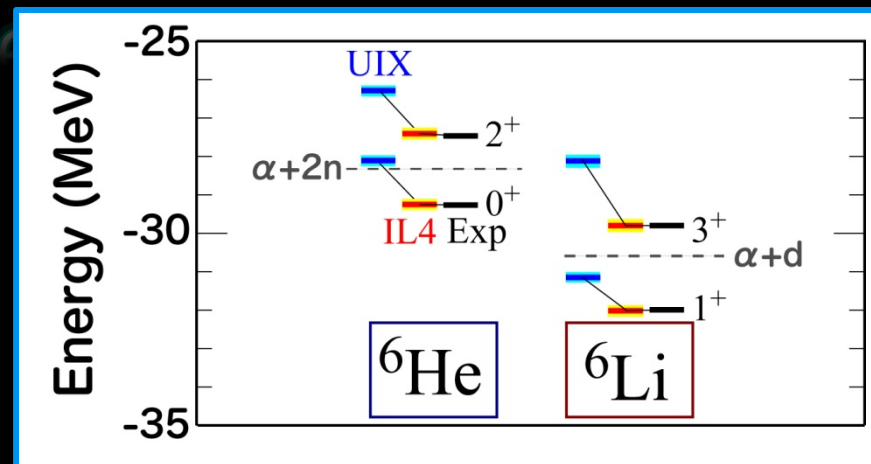
- Signature of $T=3/2$ 3NF

- B.E. and Ex for $A \geq 4$
 - Include 3p and/or 3n ($T=3/2$) system
- Neutron-rich system
 - $T \gg 1$

Illinois 3NF (Isospin-dependent 3NF)
 (3NF in $T=3/2$) > (3NF in $T=1/2$)

- “Experimental” search for $T=3/2$ 3NF
 - Faddeev calc. with 2NF only
 - $T=3/2$ 3N resonance does NOT exist

Existence of $T=3/2$ 3N resonance
 → Existence of $T=3/2$ 3NF



Isospin Dependence of 3NF

Evidence for 3NF

- B.E. of ${}^3\text{H}$ and ${}^3\text{He}$
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Limited to $T=1/2$ system

Signature of $T=3/2$ 3NF

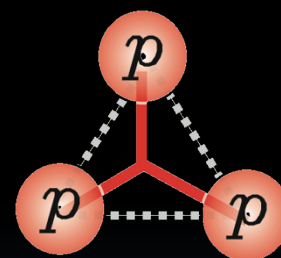
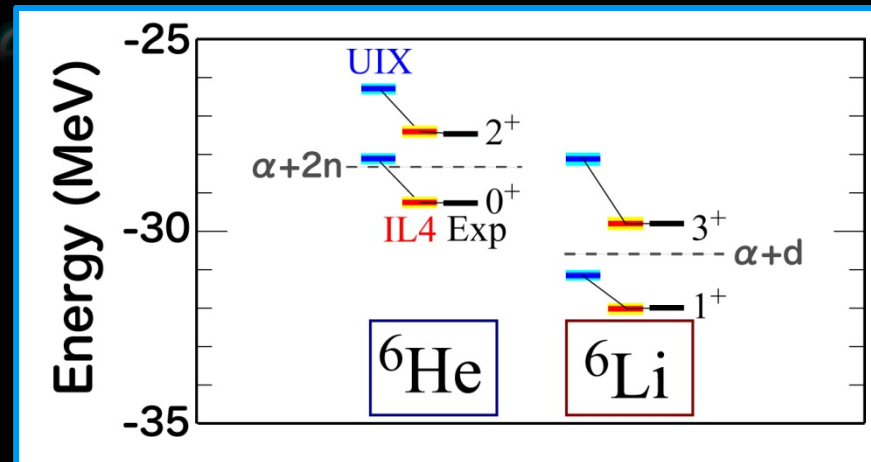
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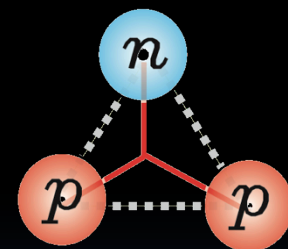
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Existence of $T=3/2$ 3N resonance
 → Existence of $T=3/2$ 3NF



$T=3/2$

>



$T=1/2$