

Nuclear Spin Physics via Polarization Measurements

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Contents

- **Three-nucleon force effects in few body systems**
 - Clear signature of three nucleon forces
 - Defects in spin-dependence
- **Pionic correlations in spin and isospin responses**
 - Precursor of pion condensation
 - Short-range tensor correlation effects
- **Gamow-Teller and Spin-Dipole Strengths**
 - Tensor force effects
 - Information on 2β -decay matrix elements

Emphasis on recent experimental data from RCNP, RIKEN, and KVI
(Mainly polarization observables)

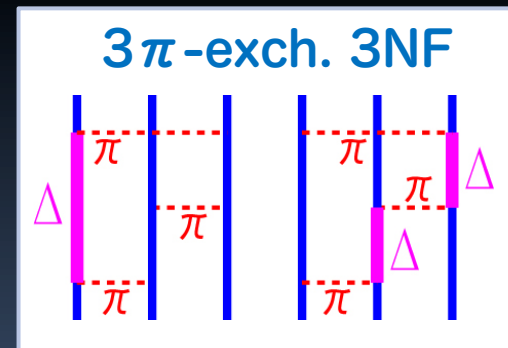
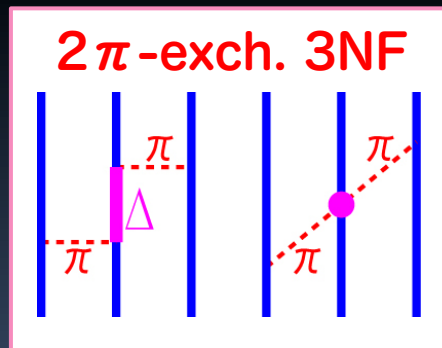
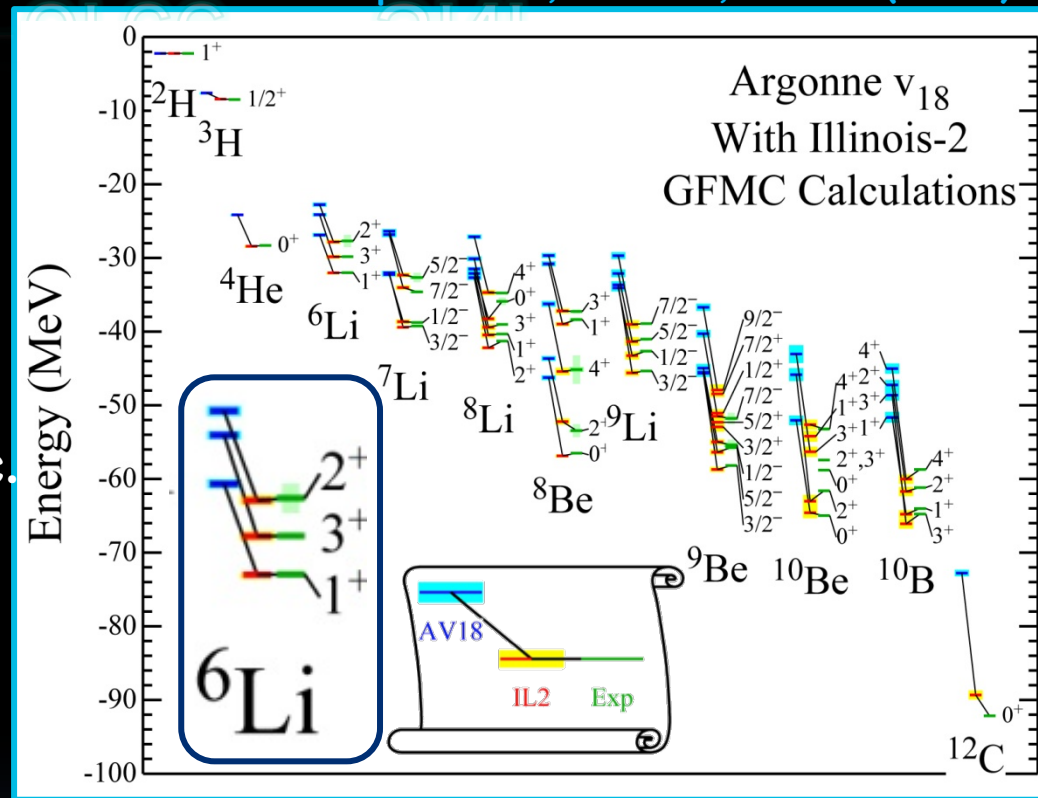
Three Nucleon Force Effects in Few Body Systems

Many Nucleon Force – 3NF –

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

- 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
 - B.E. and E_x for $A \leq 10$
 - Green's func. MC
 - No-core shell model
 - Need 2π -exch. 3NF
 - Also need 3π -exch. 3NF
 - Illinois 2, etc.

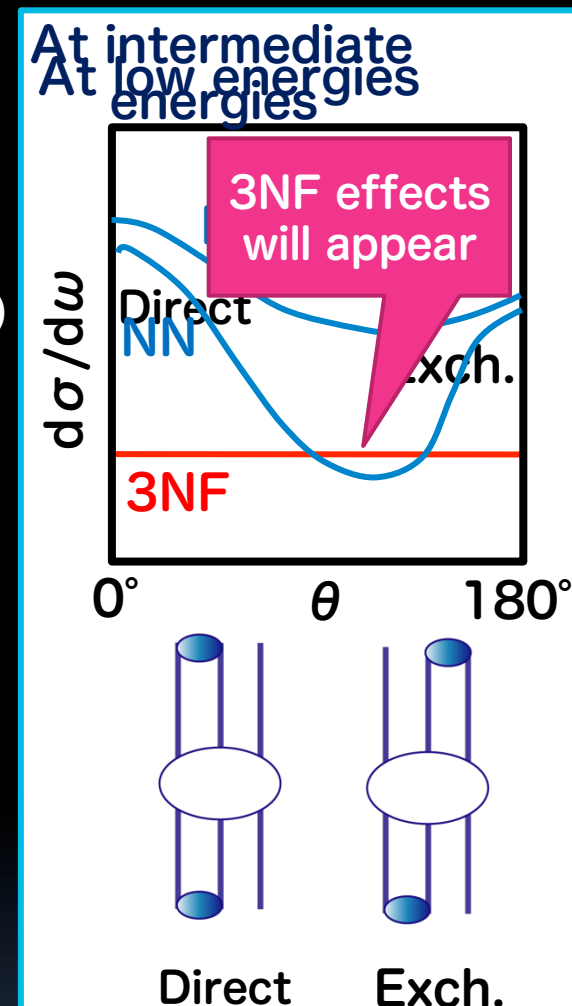


3NF Effects in Scattering States

- Dynamic properties of 3NF
 - Energy- and momentum dependence
 - Spin-dependence
 - Difficult to access by static properties (Ex. etc.)
 - **Can be accessed by reaction data**

- 3NF effects are expected to be small
 - Much smaller than 2NF
 - **Easily masked**

- 3NF effects in N-d elastic scattering
 - **2NF contributions become minimum at $\theta \sim 120^\circ$**
 - **2NF contributions become small with increasing energy**
 - **3NF contributions are less sensitive to energy and θ**

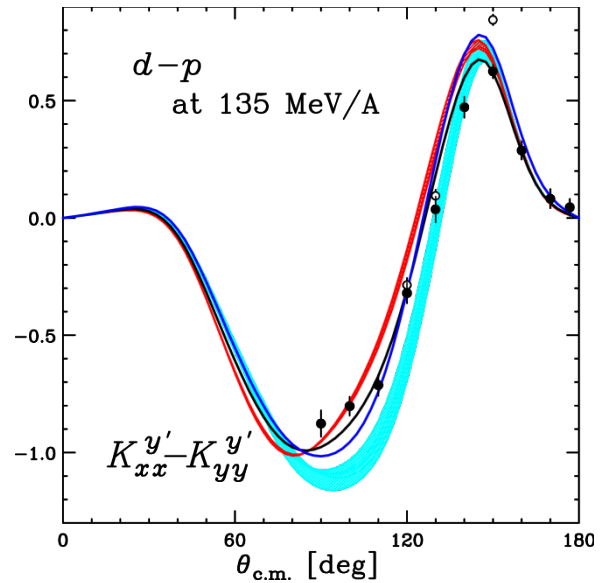
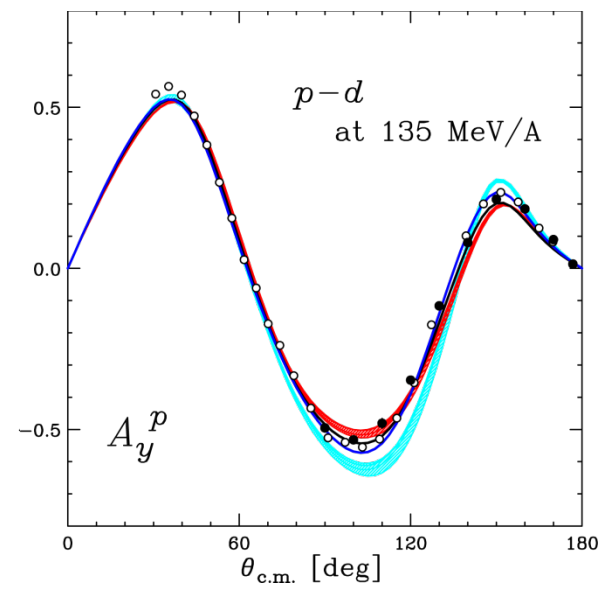
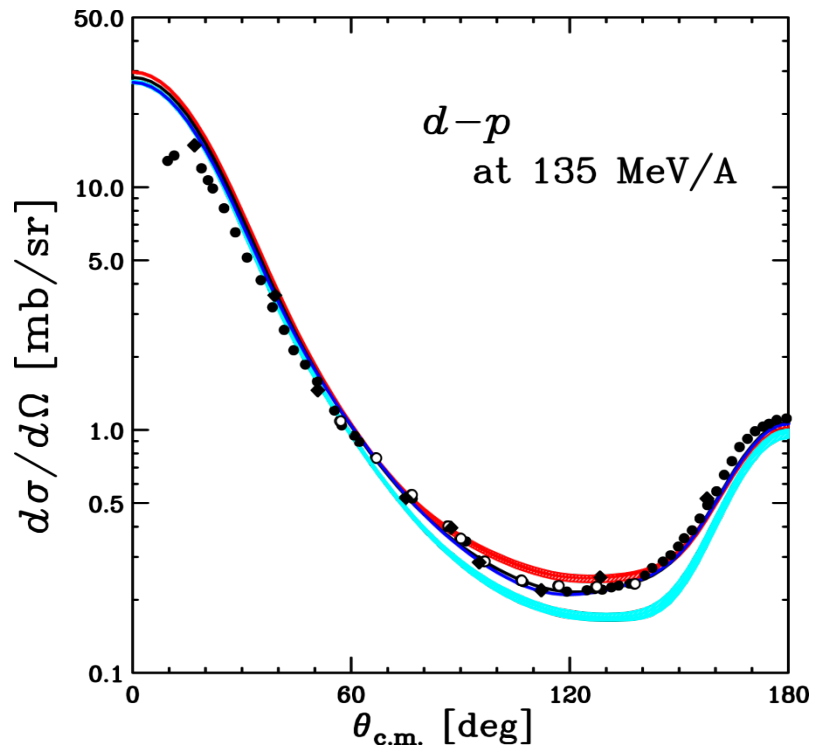


3NF effects will appear at **cross-section minima** and **intermediate energies**

3NF Effects in p-d Scattering at 135 MeV/A

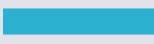



K.Sekiguchi et al., PRC 65,034003(2002).

■ NN Only → Unsuccessful at cross section minima
■ with TM99 3NF
— with UIX 3NF
— with Δ -isobar
 } Successful

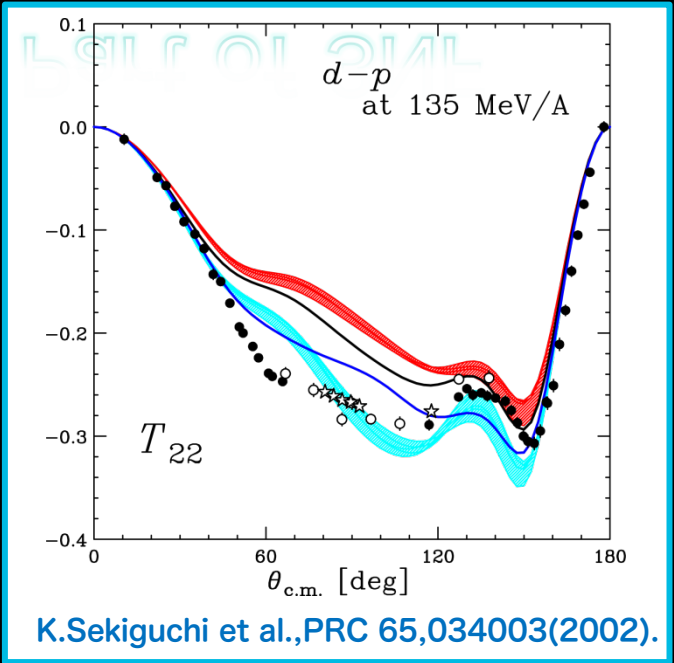


Defects in Spin Dependent Part of 3NF

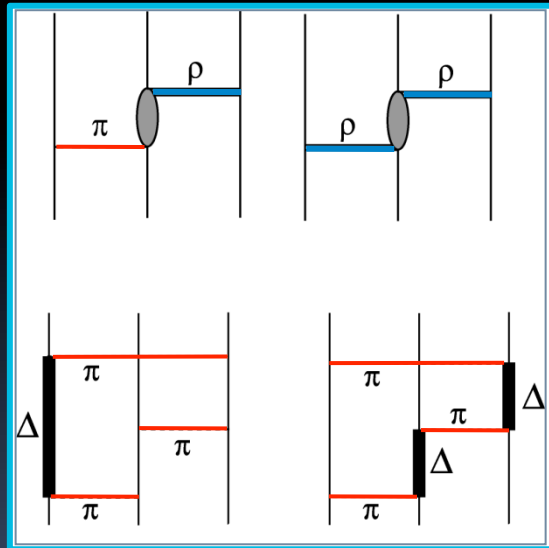
- Tensor analyzing power T_{22}

	NN Only → Unsuccessful at wide θ	} NOT improve
	with TM99 3NF	
	with UIX 3NF	
	with Δ -isobar	

→ Suggest defects in spin dependence



- Possibility for better description
 - New 3NF**
 - π - ρ and ρ - ρ exchange 3NF
 - Many Δ contributions with π -ring
 - Relativistic effects**
 - Limited at very backward angles
 - H.Witala et al., PRC 71, 054001(2005).
 - Systematic description of 3NF**
 - Chiral Effective Field Theory (χ EFT)

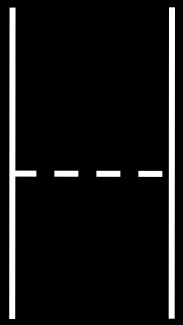


Progress in Theoretical Treatment

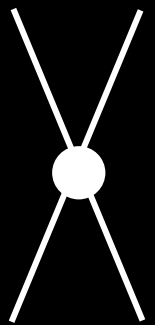
—Chiral effective field theory—

E.Epelbaum, PPNP 57,654(2006).

- Chiral Perturbation Theory
 - Systematic description of strong interactions at low energies



$\pi + N$



$\Delta + \text{Heavy-meson}$

$\left(\frac{Q}{\Lambda}\right)^\nu$ expansion

→ nNF derived consistently

	2N forces	3N forces
LO $\nu=0$		—
NLO $\nu=2$		
N^2LO $\nu=3$		

=0 at non-rel. limit

FM-type 3NF

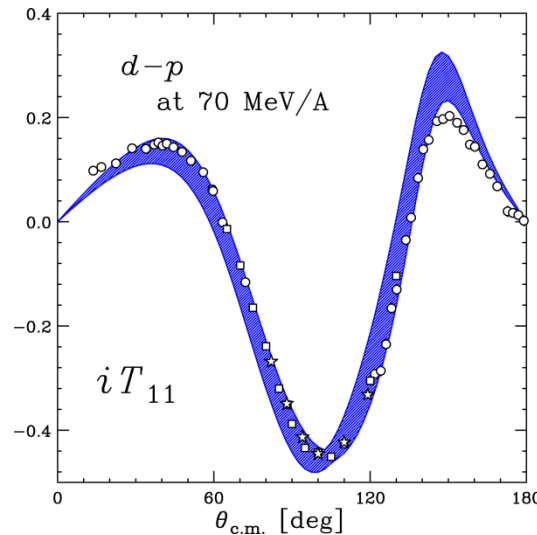
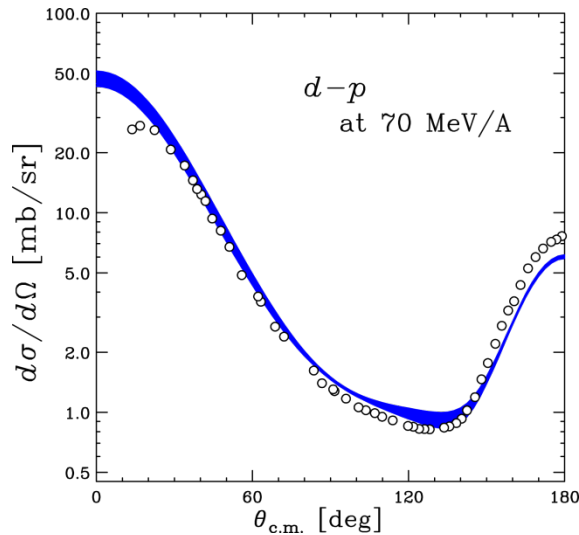
Faddeev Calc. with χ EFT Potential

E.Epelbaum, PNP 57,654(2006).

E.Epelbaum et al., PRC 66,064001(2002).

✓ χ EFT can be applied up to 100 MeV/A

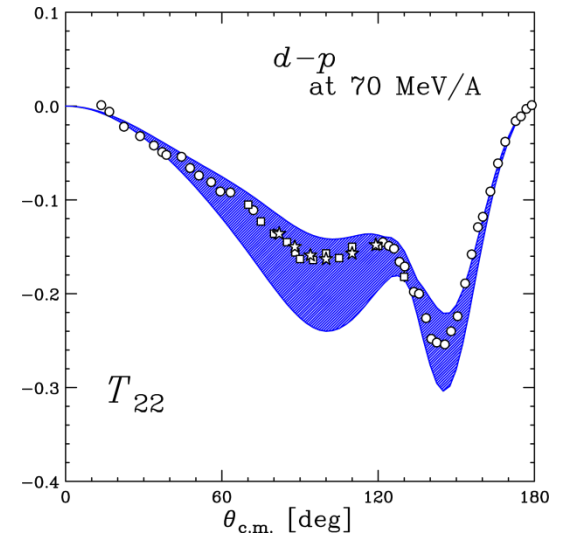
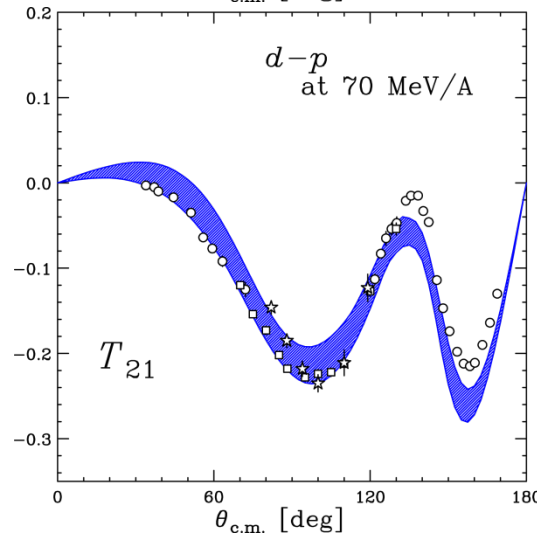
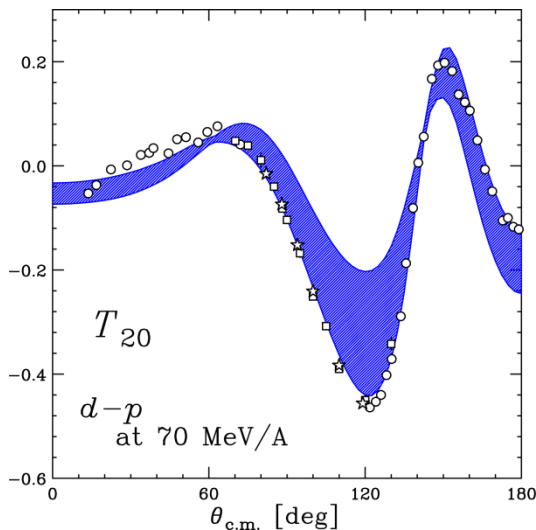
✓ Reasonable reproduction of data within theoretical uncertainty (Λ choice)



$d-p$ at 70 MeV/A

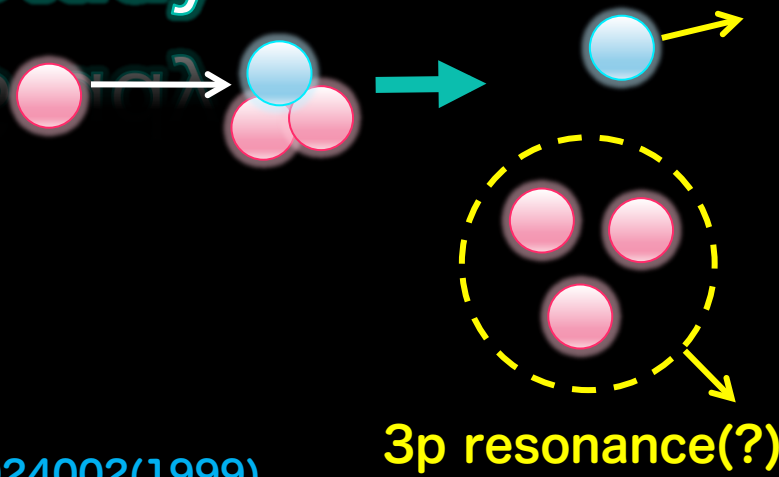
Calc. with χ EFT Pot.
(NNLO)

by E. Epelbaum et al.

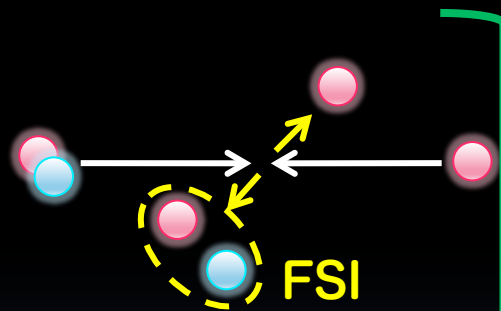


Extensions of 3NF Study

- $^3\text{He}(p,n)^3\text{p}$
 - Form $3p(T=3/2)$ system
 - $d+p \rightarrow T=1/2$ only
 - Existence of $3p$ resonance
 - Signature of $T=3/2$ 3NF
 - NO 3N resonance in Faddeev calc. with NN only
 - H.Witala and W.Glockle, PRC 60,024002(1999)
 - A.Hemmdan, W.Glockle, and H.Kamada, PRC 66,054001(2002)



- $d+p \rightarrow p+p+n$ [$d+p$ breakup]
 - Many kinematic config.
 - Check 3NF models
- $d+p \rightarrow d+p$ at higher energies [$d+p$ elastic]
 - Relativistic effects
- $d+p \rightarrow ^3\text{He} + \gamma$ [$d+p$ radiative capture]
 - Expected to be sensitive for short-range 3NF



Kalantar (KVI)
In parallel session
(Spin in Nuclei I)

Search for 3-Nucleon $T=3/2$ Resonance

E. Iihara, T.W., et al.,
 PRC 78, 024607(2008).

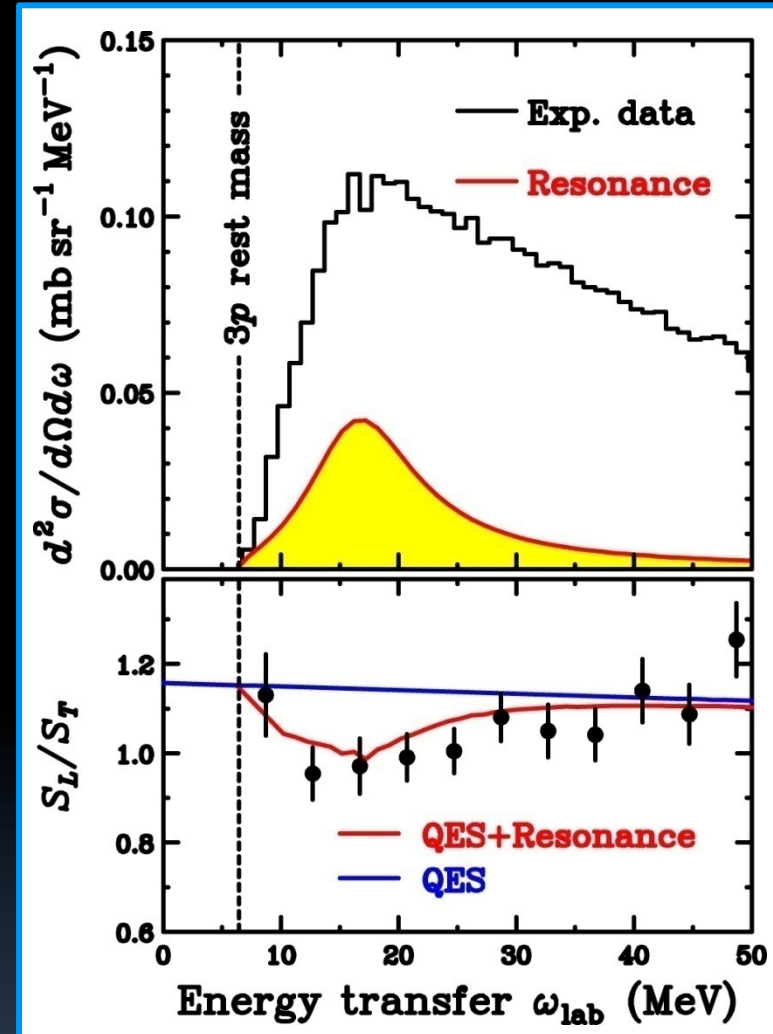
- Production of $3p(T=3/2)$ system
 - ${}^3\text{He}(p,n)3p$ at 346 MeV and 0°
 - Large physical B.G. from QES
 - **Non-resonant n-knockout from ${}^3\text{He}$**
 \rightarrow Free NN scatt.
- Spin-flip probabilities
 - Longitudinal S_L
 - Transverse S_T
 - $S_L/S_T < \text{QES (non-resonance)}$

- 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 $(1/2)^-$

Signature of $T=3/2$ 3N resonance
 \rightarrow Challenging data for $T=3/2$ 3NF
 and 4N system



Pionic Correlations in Spin and Isospin Responses

Spin-Isospin Modes in Nuclei

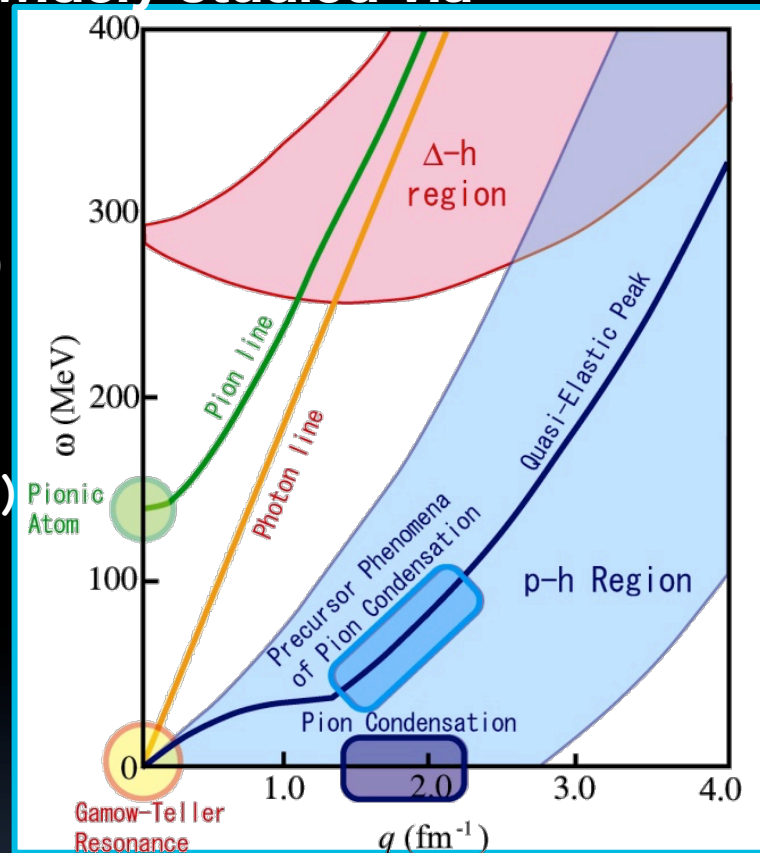
M.Ichimura, H.Sakai, T.W., PPNP 56(2006)446.

Spin-isospin responses have been widely studied via

- GT/M1 at $q \sim 0$ and small ω
 - (p,n) , $({}^3\text{He},t)$, (p,p')
- SDR at small q and small ω
 - (p,n) , $(d,{}^2\text{He})$
- QES at large q ($1\text{-}2\text{ fm}^{-1}$) 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)
 - $(d,{}^3\text{He})$, $(p,{}^2\text{He})$

In progress

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



Goal: Understand spin-isospin responses in wide (q, ω) in a unified way

✓ *Pionic and rho-mesonic correlations in nuclei*

✓ *Tensor correlations in nuclei*

Nuclear Correlations and Δ Effects

- Effective Interaction

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

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

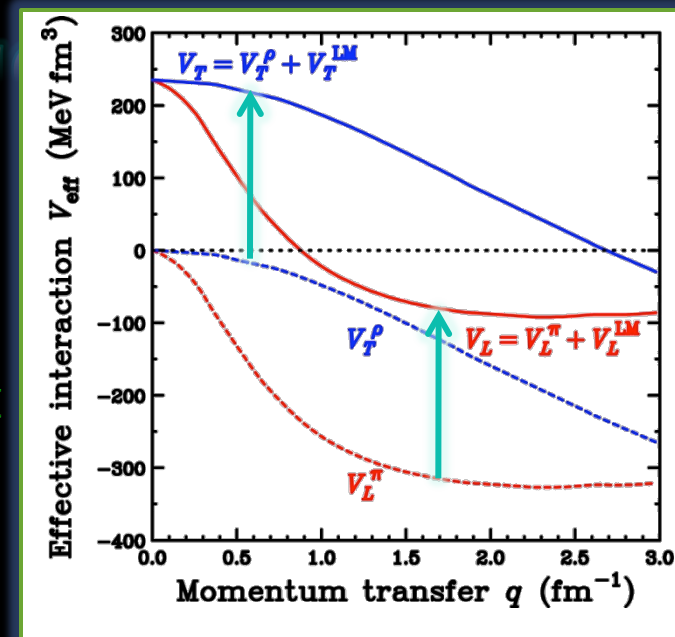
$$V_L(q, \omega) = \frac{f_{\pi NN}^2}{m_\pi^2} \left(\underbrace{\frac{q^2}{\omega^2 - q^2 - m_\pi^2} \Gamma_{\pi NN}^2}_{\pi\text{-exchange}} + \underbrace{g'_{NN}}_{\text{Short-range repulsion}} \right) (\tau_1 \cdot \tau_2) (\sigma_1 \cdot \hat{q}) (\sigma_2 \cdot \hat{q})$$

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

- 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.
T.W. et al., PRC 72(2005)067303.

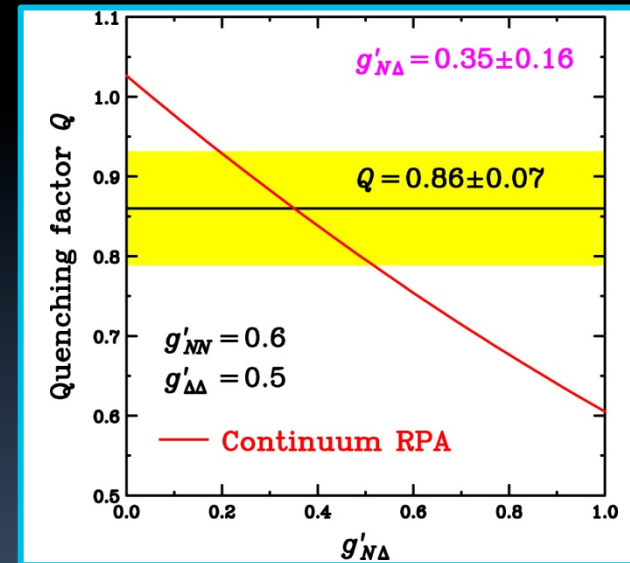
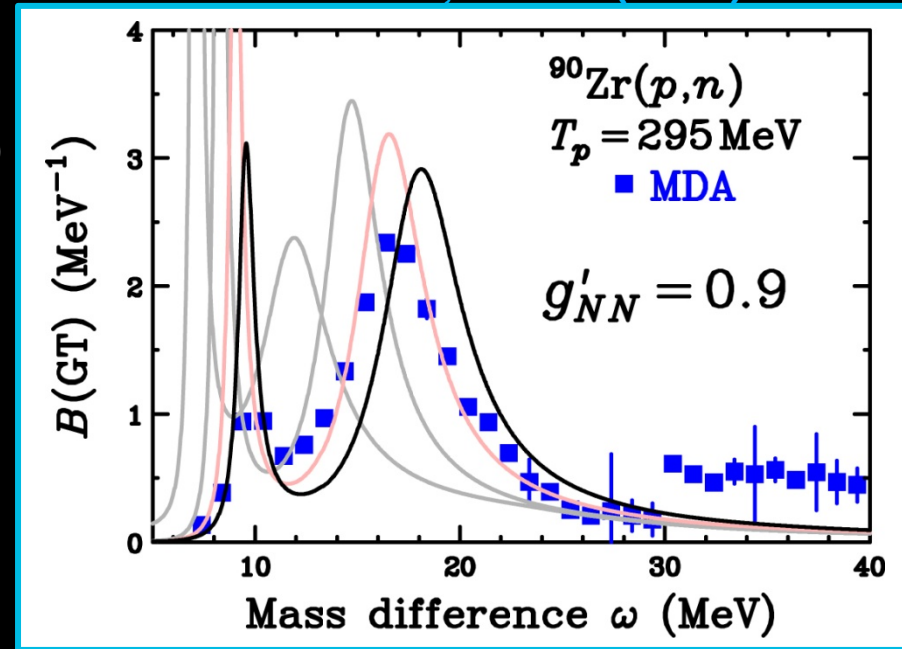
- g' dependence on GTGR
 - RPA(1p1h) by Ichimura group
 - GTGR peak position
 - **Strongly depends on g'_{NN}**

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

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

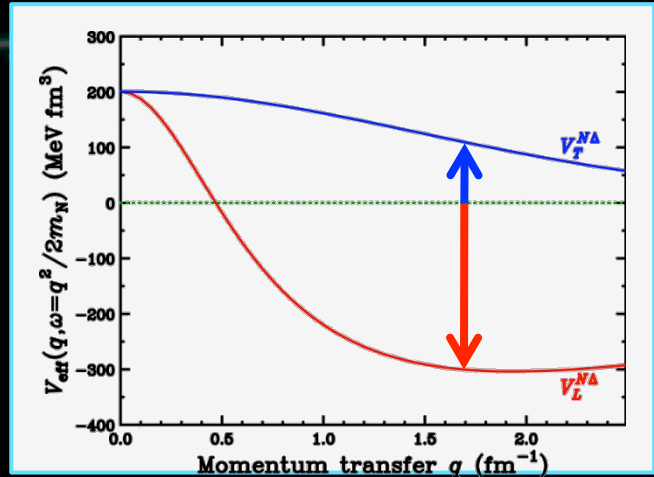
- $g'_{N\Delta}$ dependence on GT quenching Q
 - $Q = 0.86 \pm 0.07$ (*quadratic sum of errors*)
 - Q evaluated in RPA
 - **Strongly depends on $g'_{N\Delta}$**

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



Pionic Enhancement in QES

- 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.



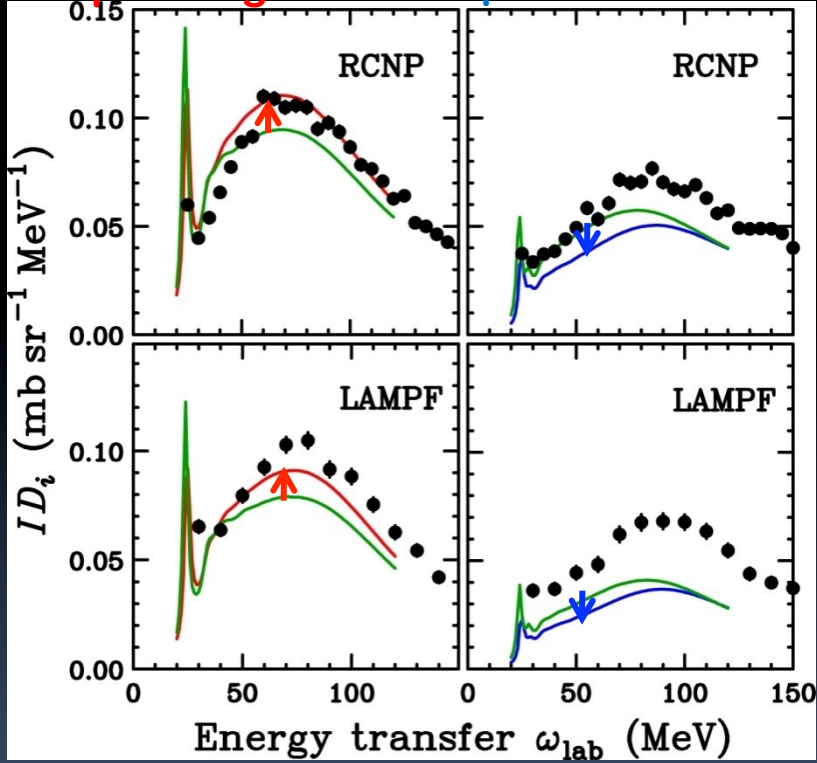
Spin-longitudinal Spin-transverse

- 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?



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

New Experiments for Pionic Correlations

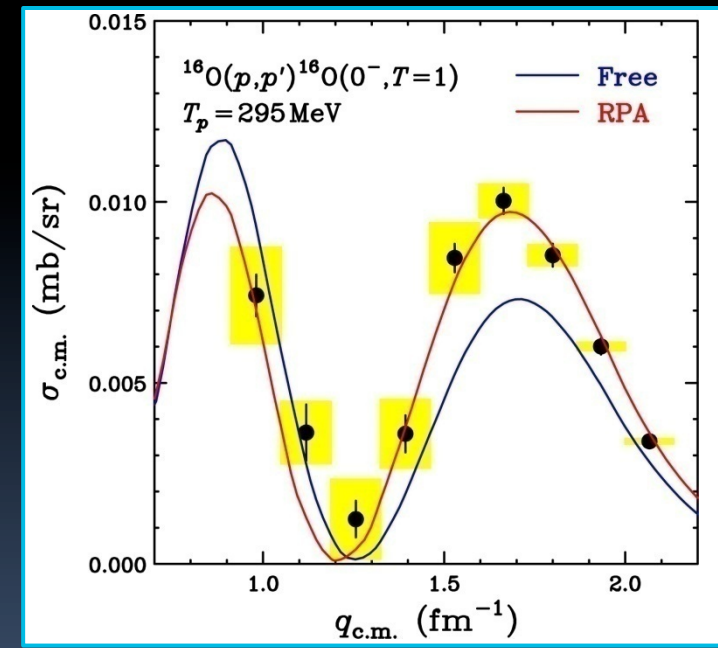
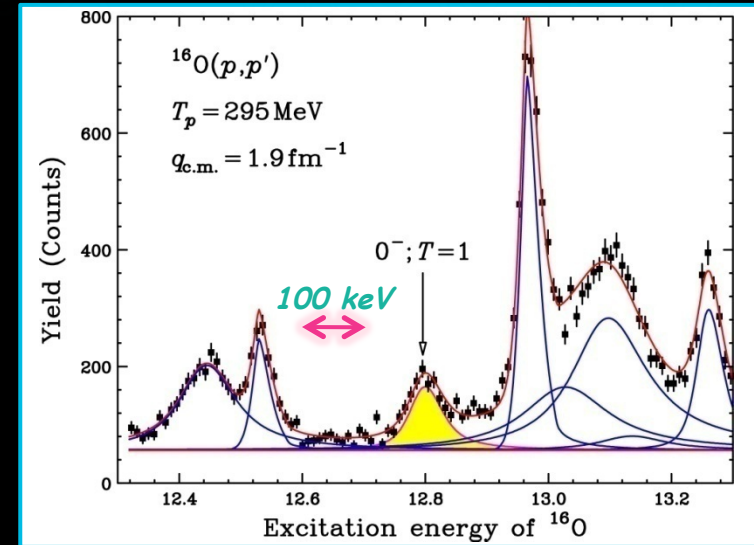
- **Results of quasi-elastic scattering**
 - Enhancement of spin-longitudinal OK
 - Quenching of spin-transverse NG
 - **Is Enhancement really due to attractive pionic correlations ?**
 - Spin-longitudinal/transverse modes were separated with D_{ij}
 - Simple reaction mechanism was assumed

→ **More systematic data desired**
- **New experiments at RCNP**
 - Measure σ of $^{16}\text{O}(p,p')^{16}\text{O}(0^-, T=1) \cdots$ RCNP-E155
 - **Pure spin-longitudinal mode → Separation with D_{ij} is not required**
 - Measure D_{ij} of $^{12}\text{C}(p,n)^{12}\text{N}(1^+, T=1) \cdots$ RCNP-E256
 - $q=0 \sim 2.0 \text{ fm}^{-1}$
 - **Separation to spin-longitudinal/transverse modes can be checked by q-dependence**

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

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

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



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

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

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

Extract
Spin-longitudinal (π)
with PTO

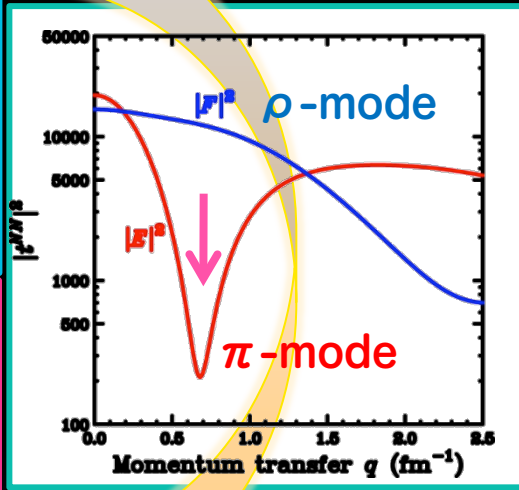
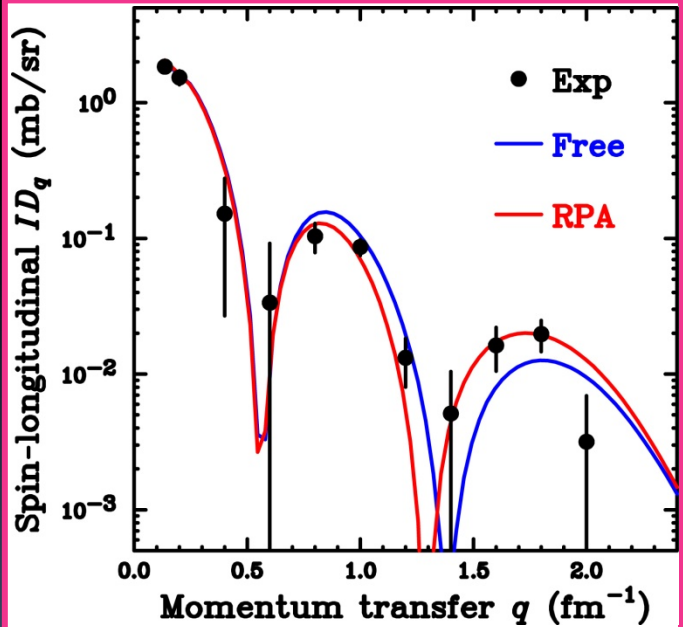
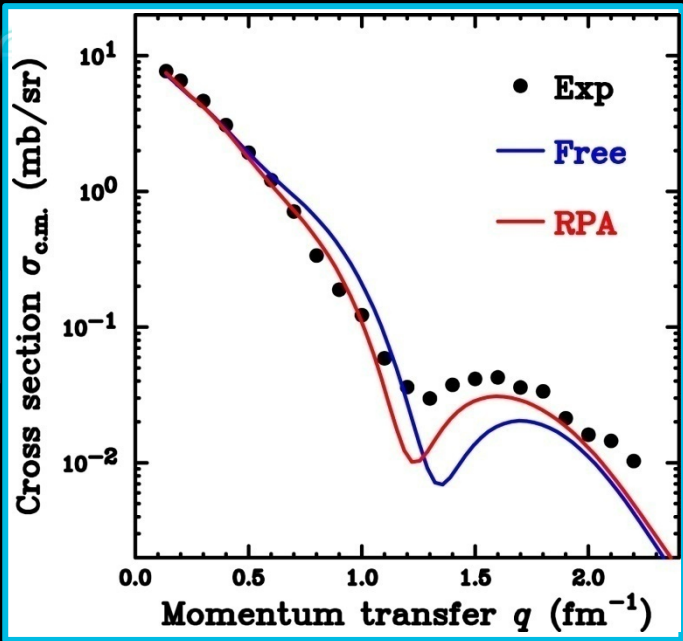
- Polarized cross section
 - $ID_q = KN |E|^2 R_q$
 - $ID_p = KN |F|^2 R_p$

Separation of π/ρ -mode
with PTO is reliable

- Comparison with Free
 - Significant enhancement

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

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



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

- Theoretical prediction
 - Blue : w/o correlations
 - Red : w/ correlations
 - B(GT) is normalized at $q=0$
 → **g' effects have been excluded for the GT case**

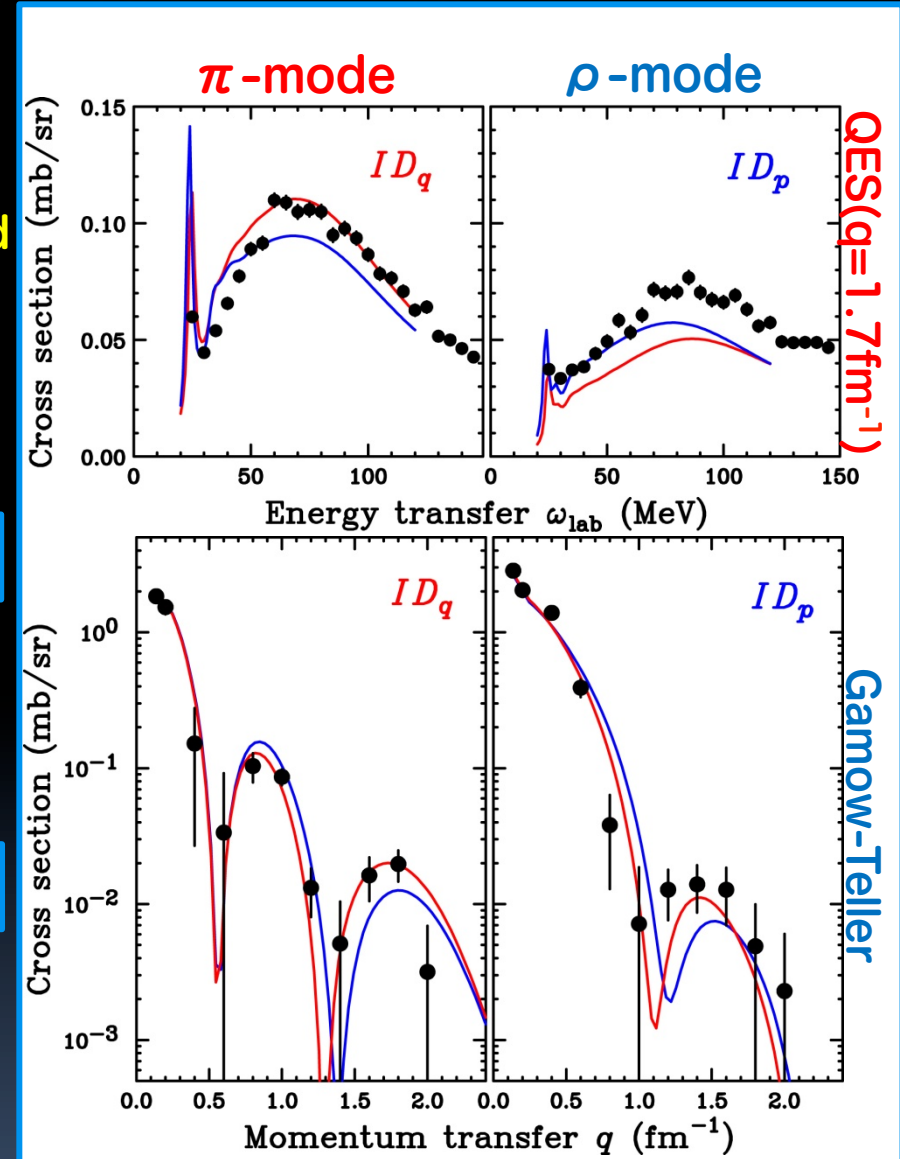
- π -mode
 - At large q
 - Exp. = **RPA** > **Free(w/o corr.)**

Attractive π -corr. at large q

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

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

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



Short-Range Tensor Correlations

- Spin-transverse (e,e') response

- Enhancement from RPA
 - Higher-order (2p2h) effects
 - MEC

- Different g' for pi and rho-modes

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

Longitudinal (pi)
Transverse (rho)

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

$$= \underbrace{g'}_{\text{Central}} \sigma_1 \cdot \sigma_2 + \underbrace{h'}_{\text{Short-range tensor}} S_{12}(q)$$

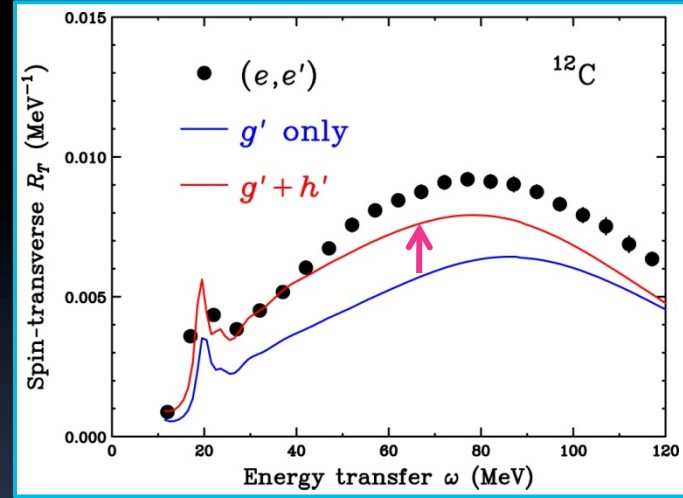
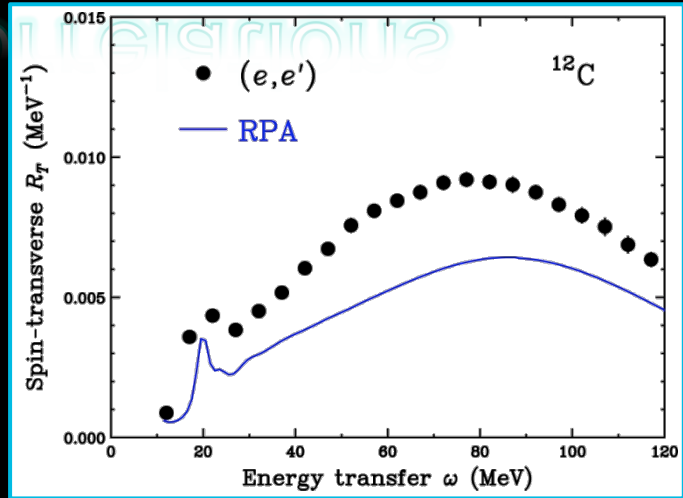
- Short-range tensor h'

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

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

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

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



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

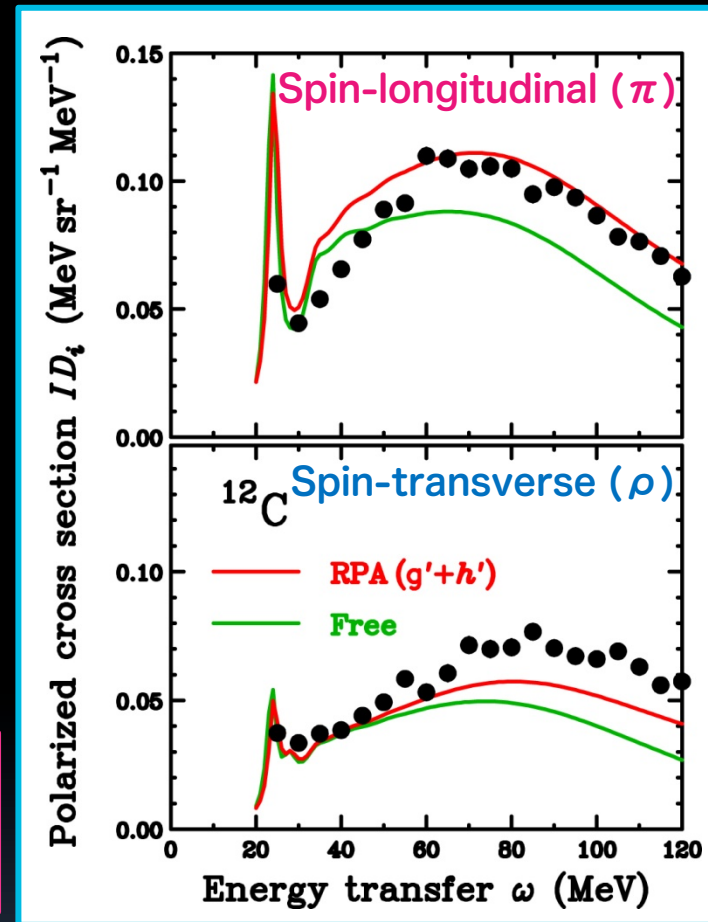
DWIA with Short-Range Tensor Correlations

- Short-range tensor h'
 - **Determined by (e,e') response**
 - Include Higher-order (2p2h)
 - Parameter-free calc.
- Spin-longitudinal (π) mode
 - g' values are adjusted **within errors**
 - $g'_{NN}=0.6 \rightarrow 0.5$
 - $g'_{N\Delta}=0.35 \rightarrow 0.2$

$\pi + g'$ (less repulsive) + h' (repulsive)
 \rightarrow **Net attractive effects for π -mode**
 \rightarrow Enhancement of π -mode

- Spin-transverse (ρ) mode

$\rho + g'$ (less repulsive) + h' (attractive)
 \rightarrow **Repulsive effects by g' are cancelled by h'**
 \rightarrow Weak enhancement of ρ -mode



Short-range tensor correlations can provide better description for QES at large q

- ✓ **Discrepancy at large ω (Higher-order effects not included by h' ?)**
- ✓ **h' treatment for higher-order effects is reasonable ?**

Gamow-Teller and Spin-Dipole Strengths

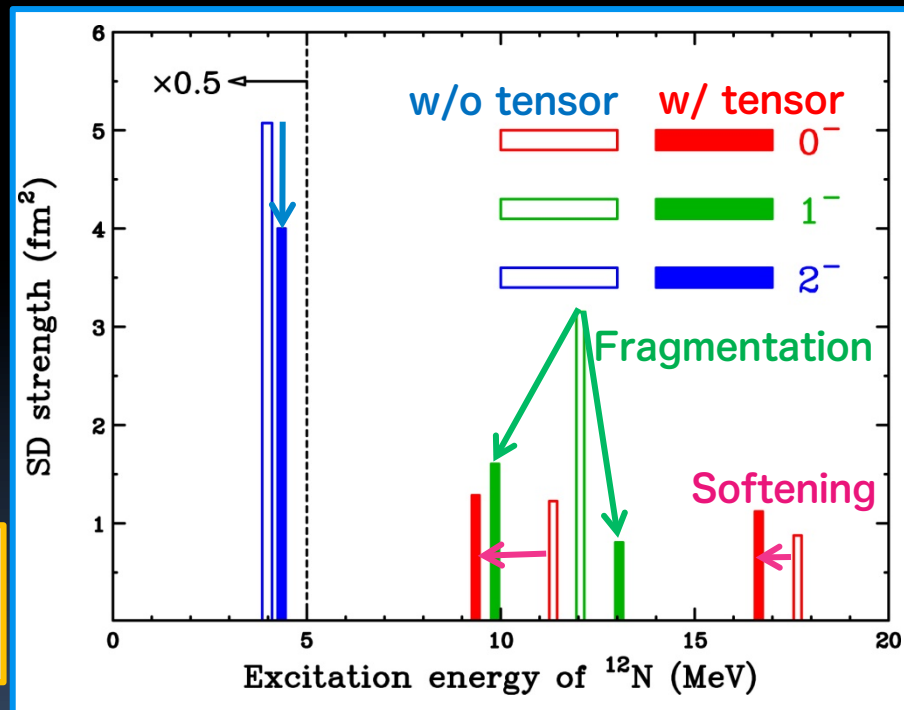
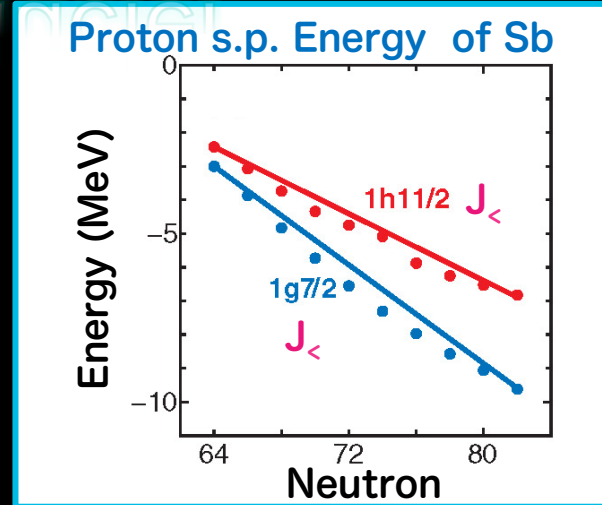
Tensor Force Effects in Nuclei

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

- Tensor force
 - NN int. is originally due to meson exchange
 - **Tensor force is a manifestation of meson exchange**

- Shell-structure due to tensor force
 - Due to tensor correlations, excess neutrons (j_{\downarrow})
 - Pull-up proton-orbit with j_{\downarrow}
 - **Pull-down proton-orbit with j_{\downarrow}**
 - **Experimental data for Sb are well reproduced**

- Tensor force effects on SD
 - **Attractive** effects for $J^{\pi}=0^{-}, 2^{-}$
 - **Repulsive** effects for $J^{\pi}=1^{-}$



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

Experimental Study of SDR in ^{12}B

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

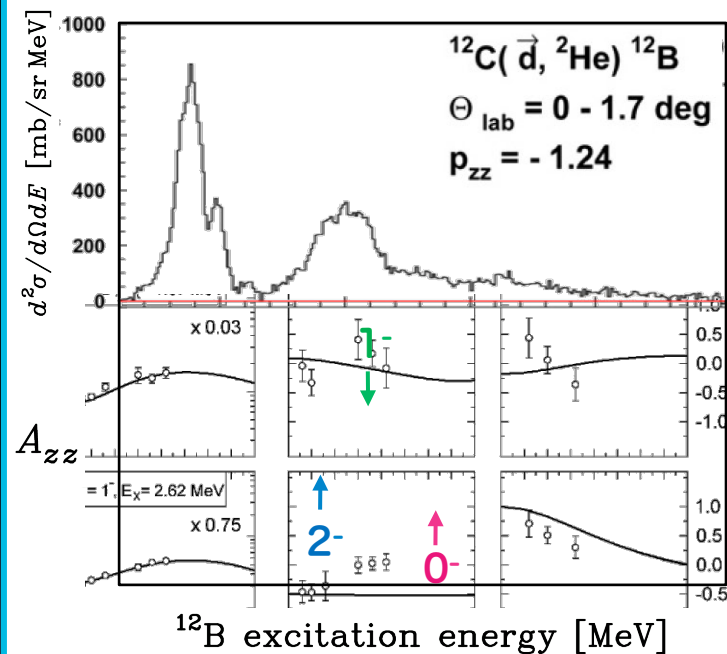
$$A_{zz}(0^\circ) = \begin{cases} -2 & \text{for } 0^- \\ +1 & \text{for natural parity} \end{cases}$$

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

Consistent with calc. employing tensor forces

- ✓ 0^- was identified at 9.3 MeV
- ✓ 1^- seems to be weak (fragmented)
- Systematic data and calc. desired

KVI data
 $\Delta E = 130 \text{ KeV}$



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

$0\nu 2\beta$ Decay and Nuclear Matrix Element

F.Simkovic et al., PRC 77,045503(2008).

- If $0\nu 2\beta$ decay is observed
 - Neutrino: Majorana particle ($\bar{\nu}=\nu$)
 - Neutrino has finite mass
 - **ABSOLUTE** value of mass

▪ Relation between $T_{1/2}$ and m_ν

Phase space, etc Effective mass

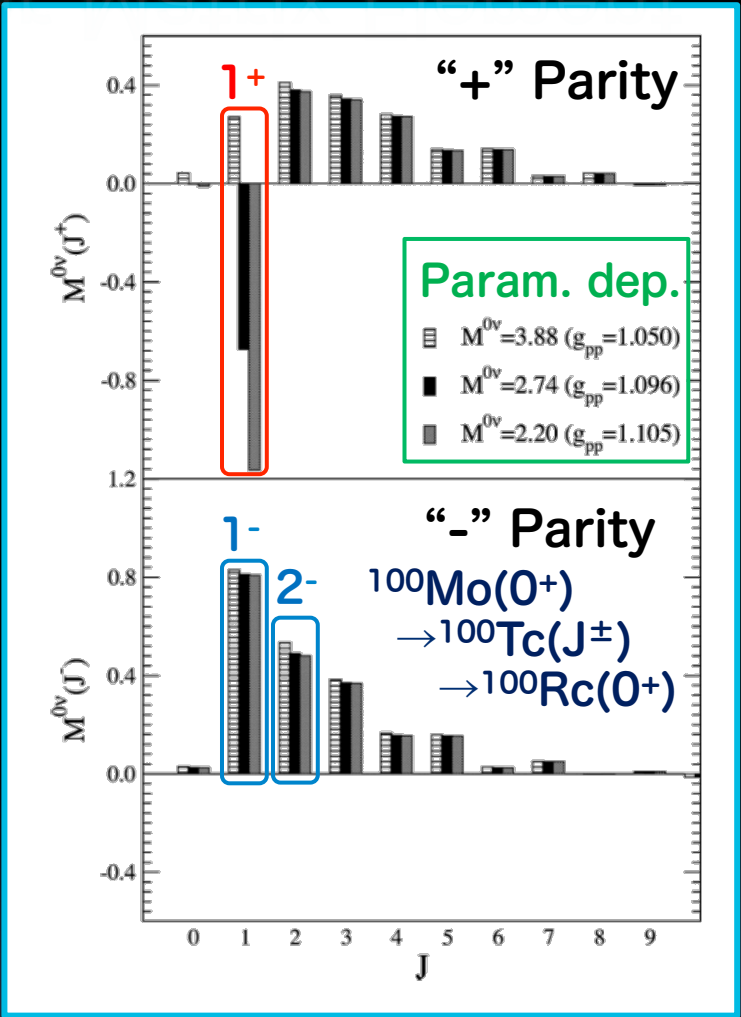
$$\frac{1}{T_{1/2}} = G^{0\nu} |M^{0\nu}|^2 |\langle m_\nu \rangle|^2$$

$0\nu 2\beta$ exp. Nuclear matrix (theory)

- $M^{0\nu}$ information from nuclear physics is very important

Accuracy of $M^{0\nu}$

- $0^+ \rightarrow 1^+ \text{ (GT)} \rightarrow 0^+$
 - Sensitive to parameter in theory
- $0^+ \rightarrow 1^-, 2^- \text{ (SDR)} \rightarrow 0^+$
 - Dominant component



“Experimental” GT and SDR strengths in 2β -decay nuclei
 → Constraint to “theory” would improve accuracy of $M^{0\nu}$

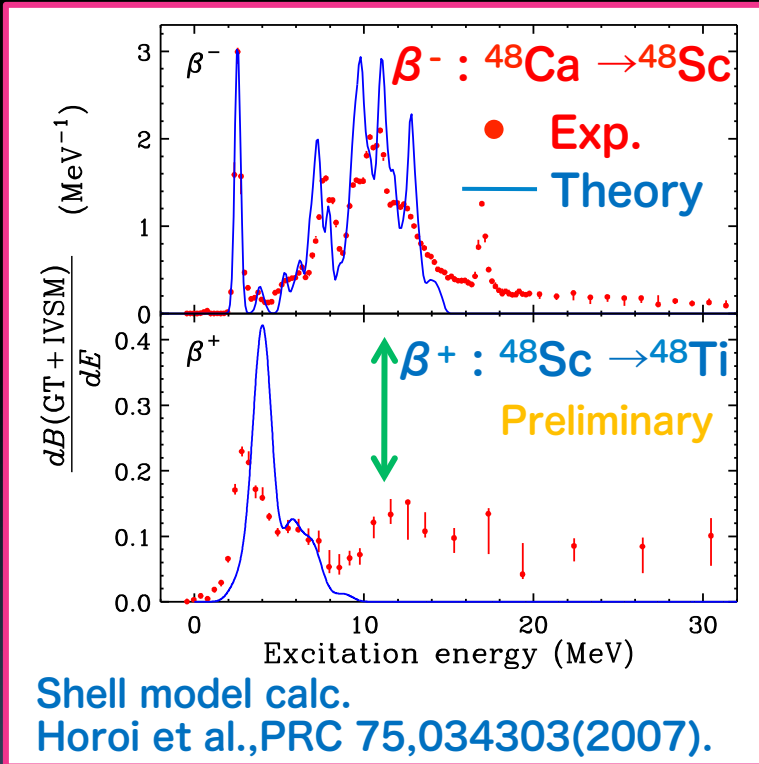
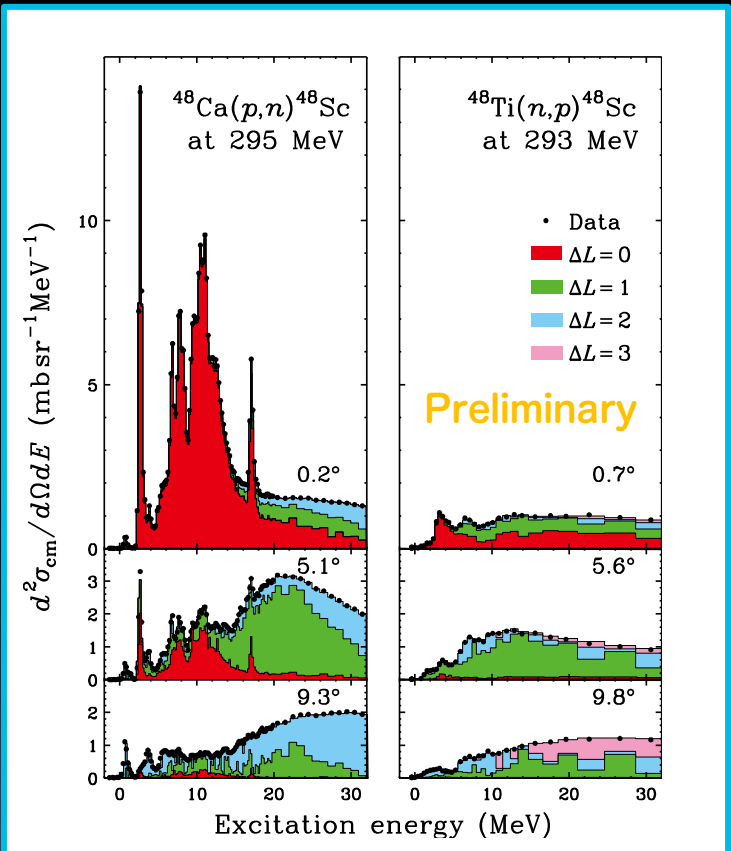
Intermediate GT Strength in ^{48}Sc



courtesy of K.Yako

- Measure $^{48}\text{Ca}(p,n)$ and $^{48}\text{Ti}(n,p)$
 - Multipole decomposition analysis
 - **Extract GT-1+(L=0)**
 - **L=0 strength up to 30 MeV**
- Exp. vs. Theor. GT strength
 - Reasonable description for β^-
 - Missing for β^+ at $E_x > 10$ MeV (In part, IVSM)

Important information for refining 2β -decay matrix element



Shell model calc.
 Horoi et al., PRC 75,034303(2007).

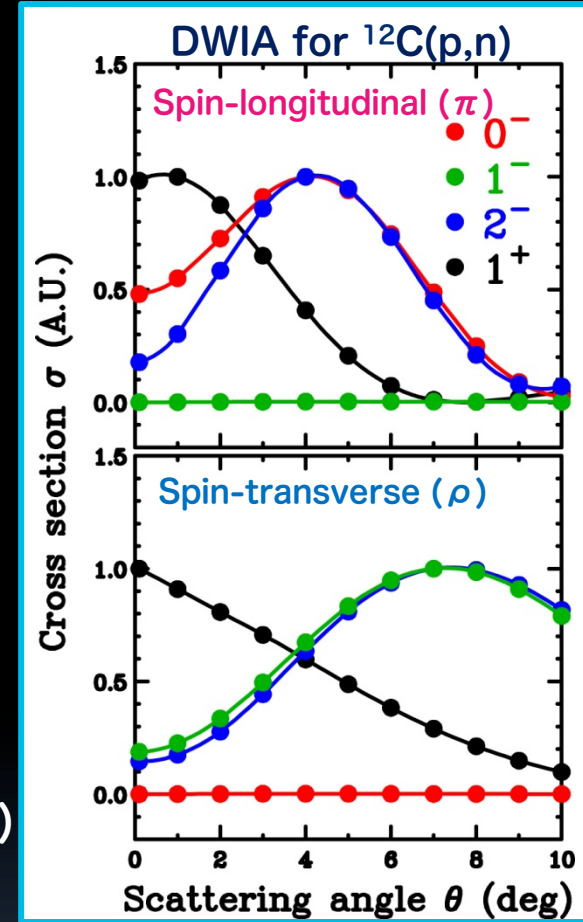
Separation of SDR into Each J^π

- Separation of SDR(L=1) into $0^-, 1^-, 2^-$ is important
 - The SDR contribution to $M^{0\nu}$ is largest
 - Contributions depend on J^π
 - Tensor effects depend on J^π

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

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

Easy to separate

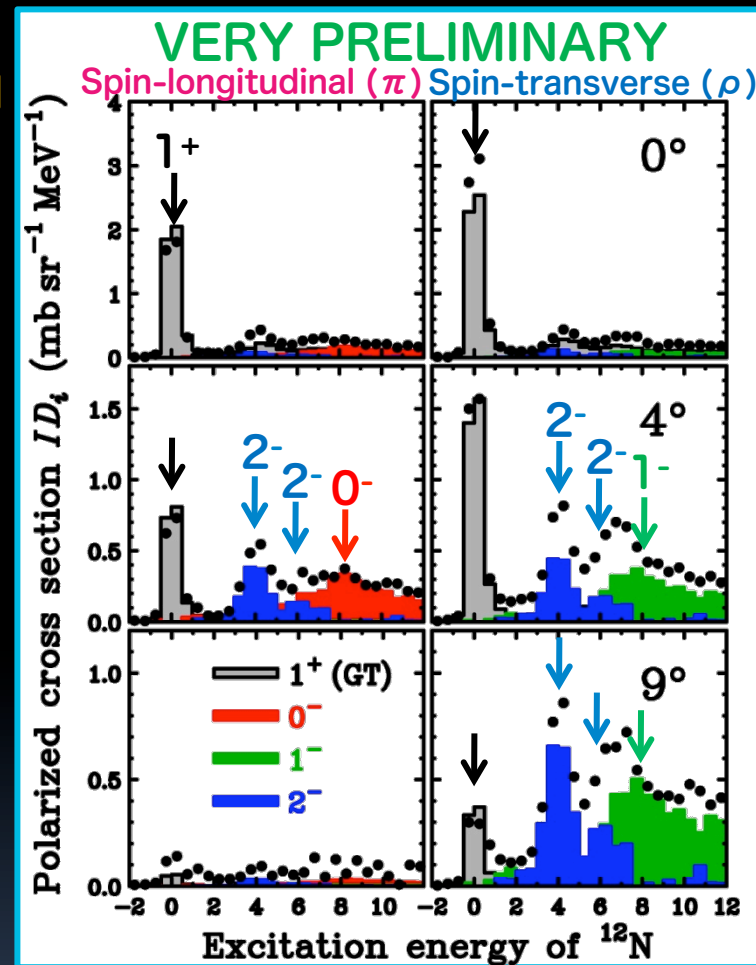


Multipole decomposition for spin-longitudinal (π) and transverse (ρ) c.s.
 → Can separate/specify not only L, BUT ALSO J^π

Challenge to Separate SDR into Each J^π

- Apply the new method to $^{12}\text{C}(p,n)$
 - High resolution $^{12}\text{C}(d,^2\text{He})$ data are available
 - Can check the reliability
 - J^π for SDR at 7 MeV is still controversial
 - Information on tensor correlations
- Preliminary results (with partial data)
 - Proper assignments for known states
 - GT at 0.0 MeV $\rightarrow 1^+$
 - SDR at 4 MeV $\rightarrow 2^-$
 - Identification of 0^-
 - Strength at 8 MeV $\rightarrow 0^-$
 - Decomposition of SDR at 7 MeV
 - Lower-energy side : 2^-
 - Higher-energy side : 1^-
- Consistent with high res. $^{12}\text{C}(d,^2\text{He})$
 - J^π decomposition seems to be reliable

M.Dozono et al.,
RCNP-E317

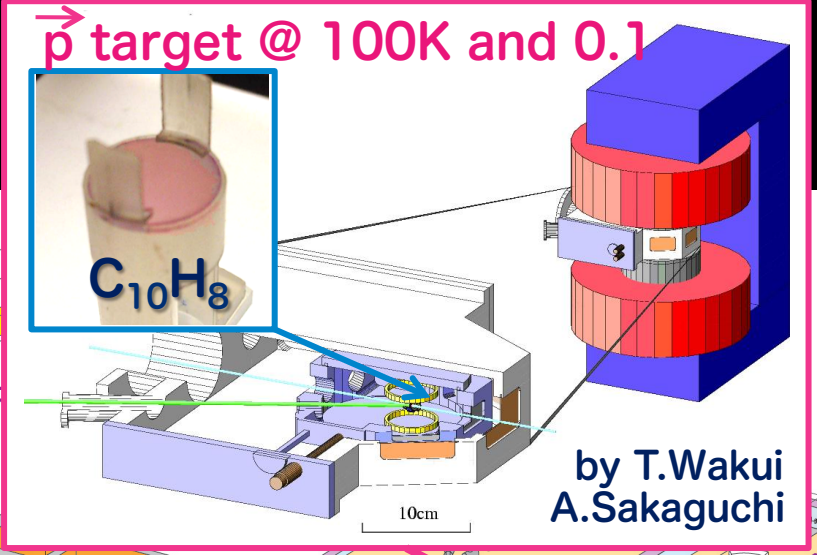
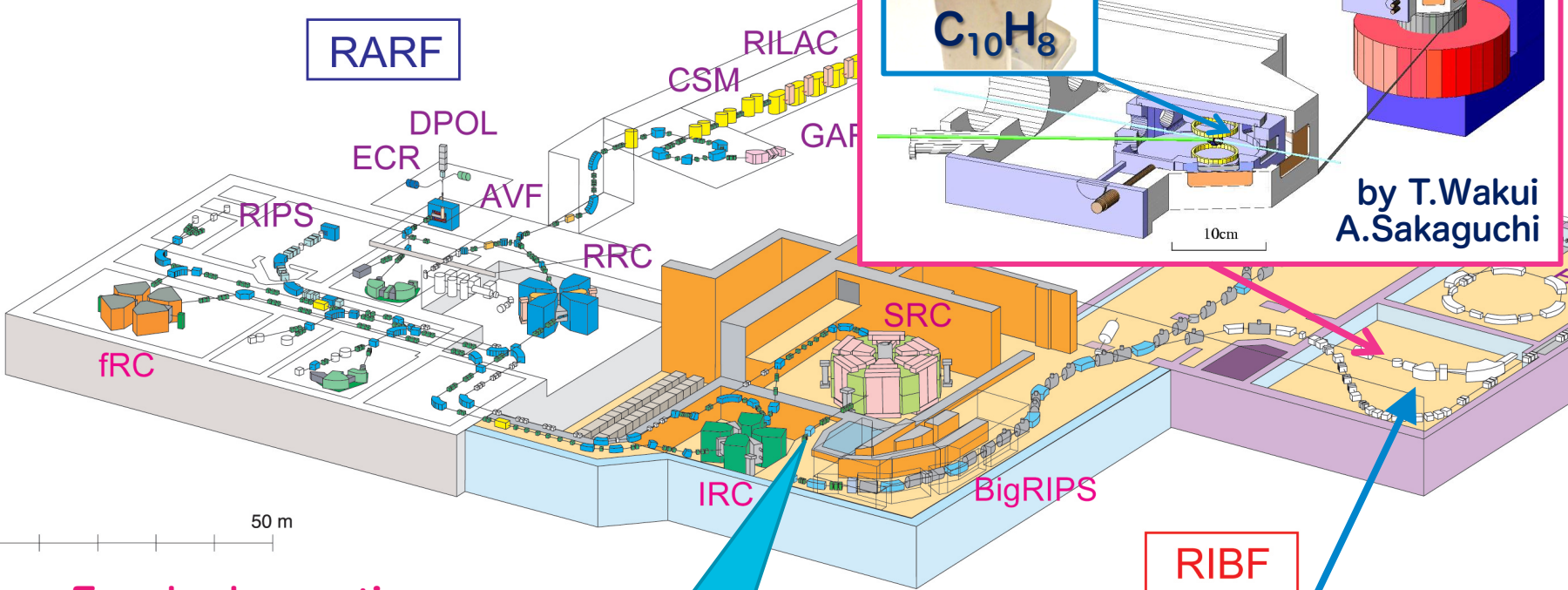


Much more detailed analysis required,
 But seems to be applicable to 2β -decay nuclei

Summary and Outlook

- Three nucleon force effects in few nucleon systems
 - Data is accumulating
 - 3NF effects are clear
 - Defects in spin-dependent part of 3NF → Short-range 3NF
 - Theoretical development
 - Coulomb and Relativistic effects → Important but limited
 - New formalism, e.g. χ EFT → Systematic understanding
- Pionic correlations in spin and isospin responses
 - Signature of pionic enhancements as a precursor of π - cond.
 - Quasi-elastic Scatt., $^{16}\text{O}(p,p')^{16}\text{O}(0^-, T=1)$, $^{12}\text{C}(p,n)^{12}\text{N}(1^+, T=1)$
 - Unified understanding in $\pi + \rho + g'$ employing short-range tensor
- Gamow-Teller and Spin-Dipole Strengths
 - Strengths can be experimentally extracted via MDA
 - Spin-parity can ALSO be separated
 - Tensor forces → Important and should be considered
 - 2β -decay matrix element

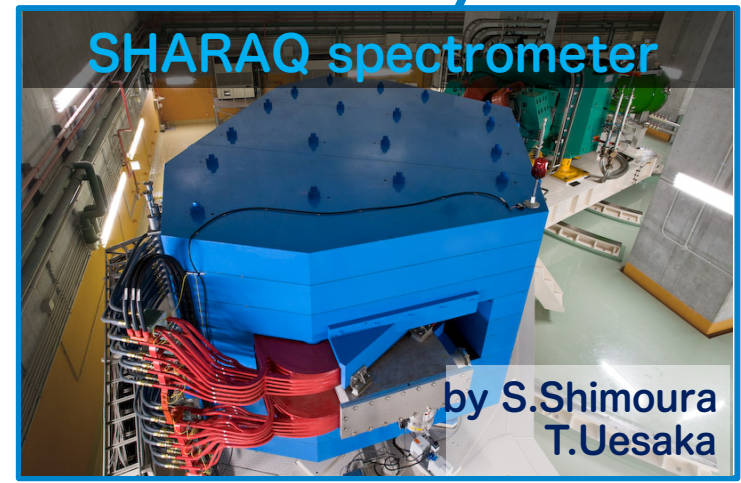
RI Beam Factory at RIKEN



Few-body reaction
with polarized d beam
@ 200-440 MeV/A

Polarimeter
by K.Sekiguchi

$\delta p/p = 15000$ with dispersion match
exothermic ($Q > 0$) reaction $\Rightarrow q = 0$
with RI-beam @ 300 MeV/A



Acknowledgement

- Thanks to all collaborators involved with relevant experiments, in particular to
 - K. Yako (University of Tokyo)
 - K. Sekiguchi (RIKEN Nishina Center)
 - Y. Maeda (Miyazaki University)
 - M. Dozono (Kyushu University)
 - E. Ihara (Kyushu University)

for valuable comments and figure preparation.

Thank you for your attention

Backup

Progress in Theoretical Treatment —Coulomb Interaction—

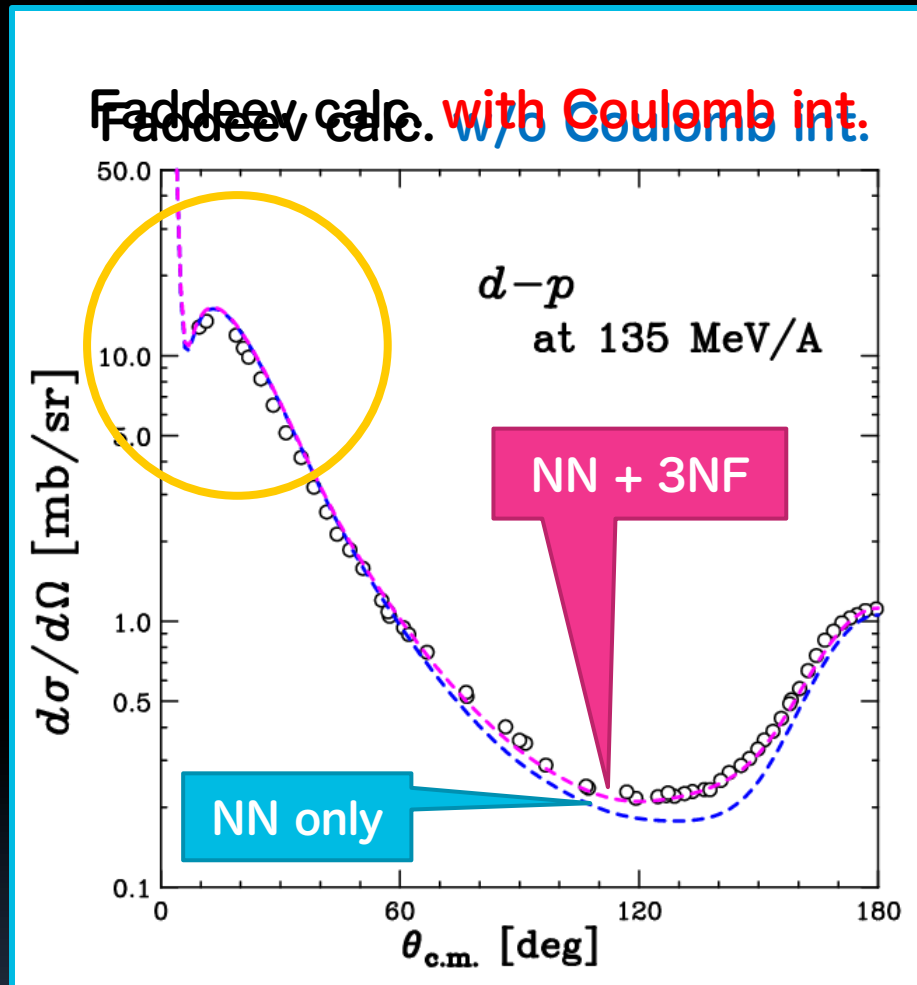
- Failure at small θ
 - Coulomb int. effects
 - Inherently lacking in Faddeev calc.

- Coulomb int. can be included
 - Screening+Renormalization
$$w_R(r) = \frac{\alpha}{r} \exp \left[- \left(\frac{r}{R} \right)^n \right]$$

$n = 4 \quad R \rightarrow \text{large}$

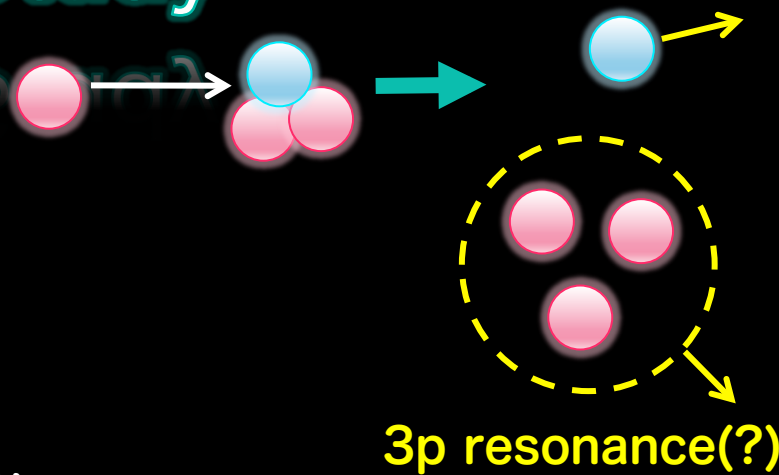
- Coulomb interaction
 - Significant at small θ
 - Reproduce the data well

At Intermediate energies,
Coulomb interaction effects
are limited at very forward angles

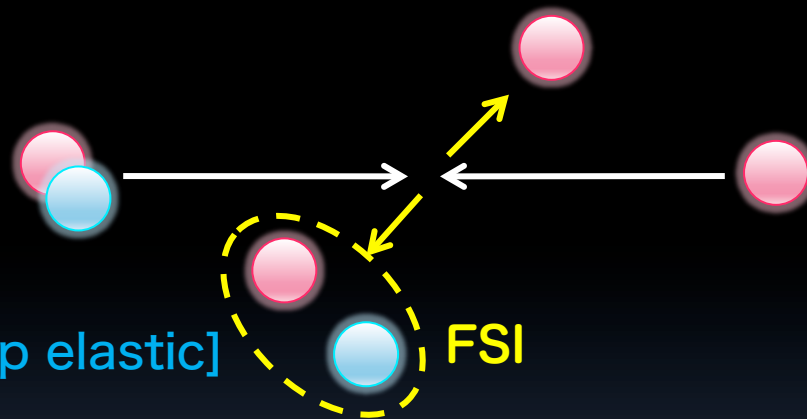


Extensions of 3NF Study

- ${}^3\text{He}(p,n){}^3\text{p}$
 - Form $3p(T=3/2)$ system
 - $d+p \rightarrow T=1/2$ only
 - Existence of $3p$ resonance
 - Signature of $T=3/2$ 3NF
 - NO 3N resonance in Faddeev calc. with NN only



- $d+p \rightarrow p+p+n$ [$d+p$ breakup]
 - Many kinematic config.
 - Check 3NF models
- $d+p \rightarrow d+p$ at higher energies [$d+p$ elastic]
 - Relativistic effects
- $d+p \rightarrow {}^3\text{He} + \gamma$ [$d+p$ radiative capture]
 - Expected to be sensitive for short-range 3NF



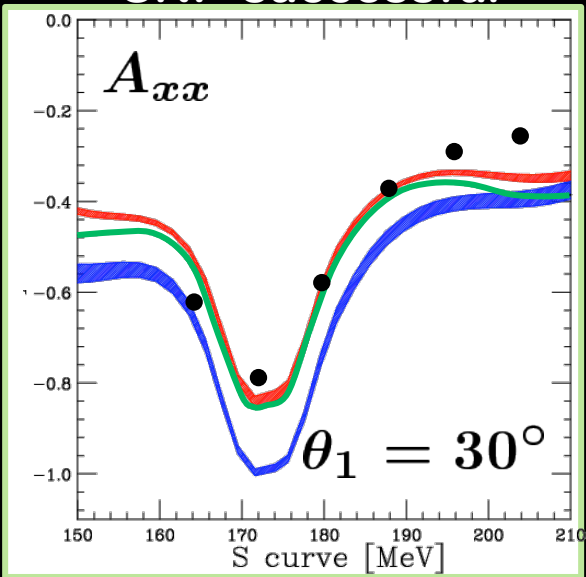
d-p breakup

$$\vec{d} + p = \vec{p}_1 + (p_2 n)_{\text{FSI}}$$

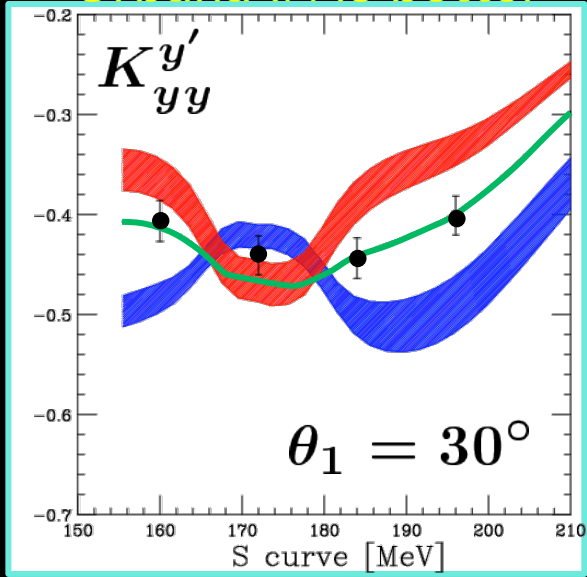
at $E_d = 135 \text{ MeV}/A$ and $\phi_{12} = 180^\circ$

courtesy of K.Sekiguchi

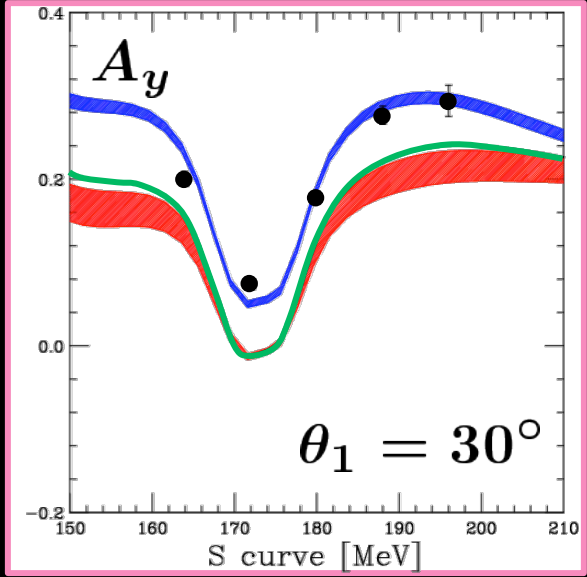
3NF successful



Urbana IX is better



No 3NF



— 2NF only
 — 2NF + TM99-3NF
 — 2NF + Urbana IX-3NF

3NF effects in d-p breakup

- ✓ A_{xx} : **BETTER** description of the data
 - ✓ $K_{yy'y'}$: **BETTER** description by Urbana IX (NOT conclusive)
 - ✓ A_y : **WORSE** description of the data
- Challenging data for refining 3NF (short-range 3NF etc.)

Gamow-Teller and Spin-Dipole Strengths

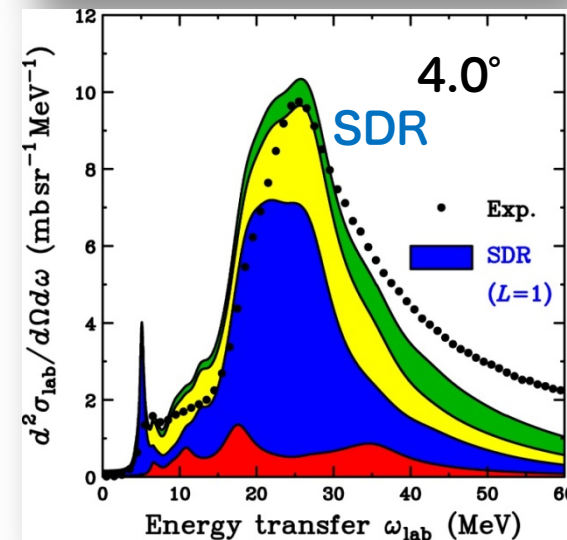
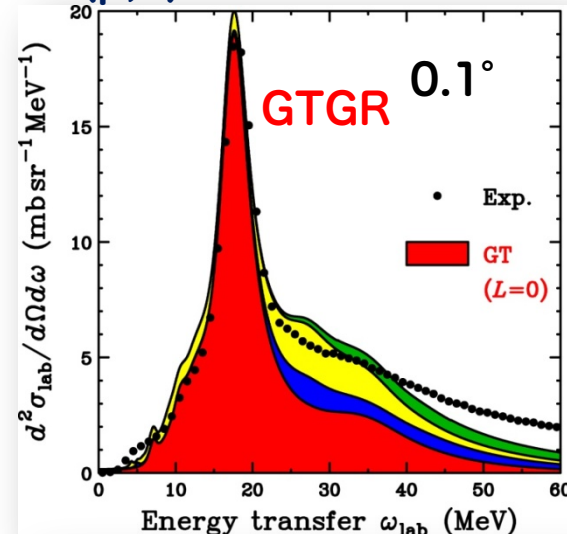
- Gross Features of GT and SD strength
 - Reasonably reproduced
 - DWIA+RPA with $\pi + \rho + g'$
 - HF+RPA with Skyrme Int.
 - Quasi-particle RPA
 - ...

- Detailed information is ALSO important
 - 2β -decay nuclear matrix elements
 - Tensor interaction effects



Recent experimental studies and efforts
To extract GT and SD strengths

$^{208}\text{Pb}(p,n)$ at 295 MeV



T.W. et al., NPA 599,217c(1996).
RCNP-E57.

Neutron Skin Thickness and SD Sum Rule

H.Sagawa et al., PRC 76,024301(2007).

- Neutron-skin thickness δ_{np}

$$\delta_{np} \equiv \sqrt{\langle r^2 \rangle_p} - \sqrt{\langle r^2 \rangle_n}$$

Proton r.m.s Neutron r.m.s

- Relate to physics on nuclear matter
- δ_{np} has linear correlation with
 - Symmetry energy
 - EOS of neutron matter

- Proton and neutron distributions

- Fundamental properties

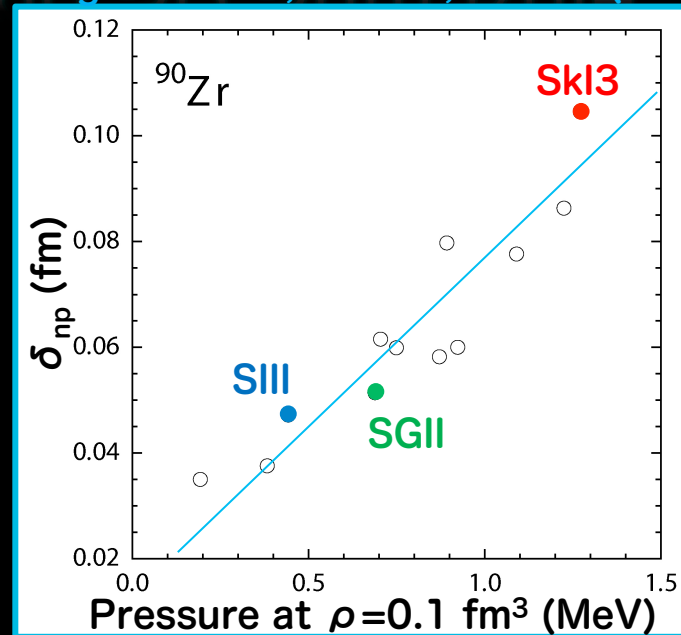
- Proton r.m.s. → Well known $\delta \left(\sqrt{\langle r^2 \rangle_p} \right) < 0.01 \text{ fm}$
- Neutron r.m.s. → Poorly known $\delta \left(\sqrt{\langle r^2 \rangle_n} \right) \simeq 0.1 \text{ fm}$

- SD sum rule and δ_{np} (Model Independent)

$$S_{(p,n)} - S_{(n,p)} = \frac{9}{4\pi} \left(N \langle r^2 \rangle_n - Z \langle r^2 \rangle_p \right) \longrightarrow \delta_{np}$$

\uparrow
 \uparrow
 \downarrow
 \uparrow

(p,n)
(n,p)
deduced
e-scattering



Multipole Decomposition and SD Sum Rule

K.Yako et al., PRC 74,051303(R)(2006).

- MD analysis for $^{90}\text{Zr}(p,n)$ and (n,p)

- Deduce $\Delta L=1$ cross section
 - (p,n) at 4.6°
 - SDR at 20 MeV
 - (n,p) at $4^\circ - 5^\circ$
 - $\Delta L=1$ at $E_x < 10$ MeV

- SD strength

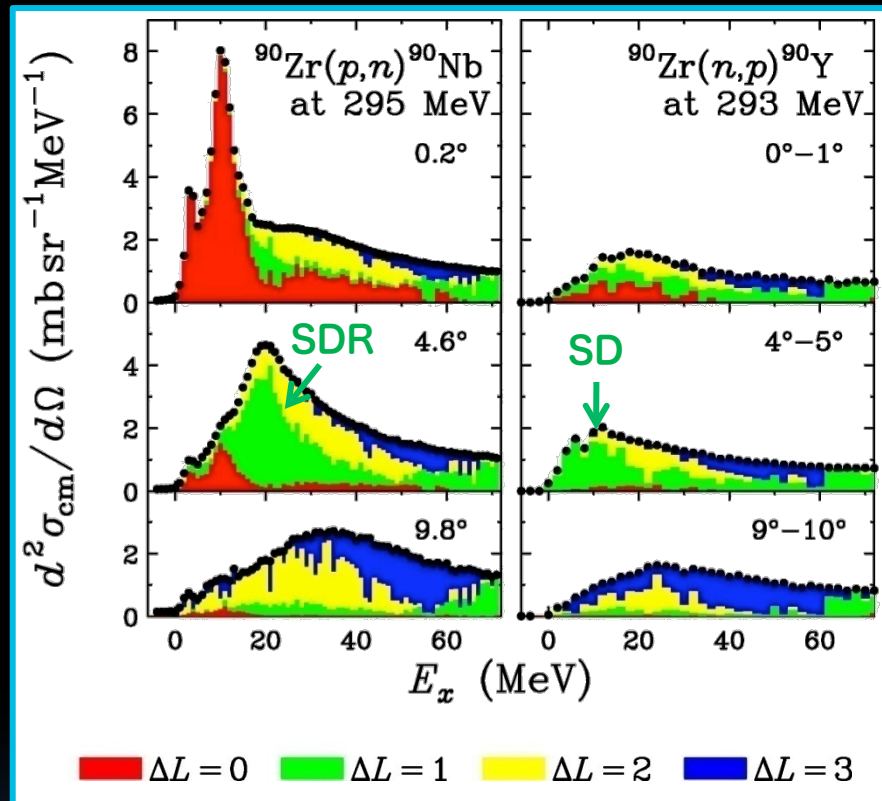
- Use proportionality relation
 - $L=1$ c.s. \propto SD strength
 - Proportionality coefficient is determined by DWIA

- Integrated SD strengths

- $S_- = 247 \pm 4(\text{stat.}) \pm 12$ (MD)
 - $S_+ = 98 \pm 4(\text{stat.}) \pm 5$ (MD)

$$S_- - S_+ = 148 \pm 13 \text{ fm}^2$$

$$\sqrt{\langle r^2 \rangle}_p = 4.19 \text{ fm}$$



Only 1% rel. error

$$\sqrt{\langle r^2 \rangle}_n = 4.26 \pm 0.04 \text{ fm}$$

$$\therefore \delta_{np} = 0.07 \pm 0.04 \text{ fm}$$

Neutron Skin Thickness and EOS

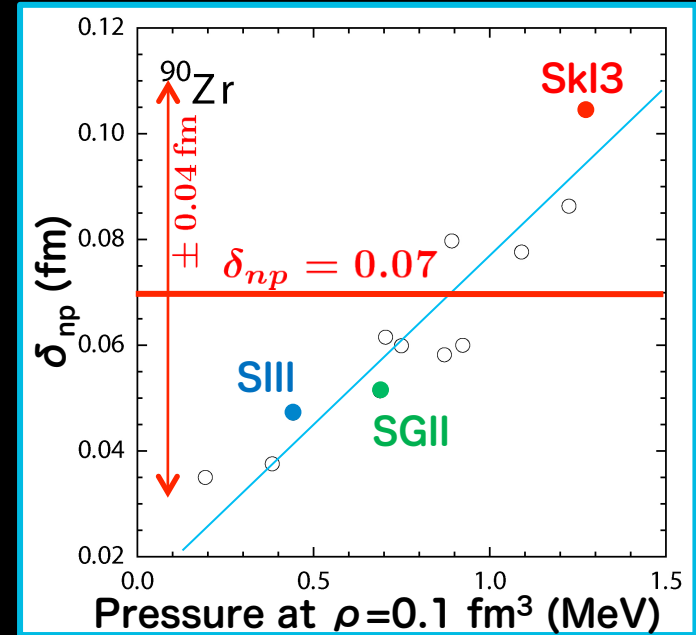
K.Yako et al., PRC 74,051303(R)(2006).

H.Sagawa et al., PRC 76,024301(2007).

- δ_{np} from SD sum rule

$$\delta_{np} = 0.07 \pm 0.04 \text{ fm}$$

- Model independent
 - Consistent with predictions
- Neutron-matter EOS
 - **Constrain to EOS → Difficult !!**
- Comparison with other model-dependent studies



Method	δ_{np} (fm)	Reference
SD sum rule	0.07 ± 0.04	This work, PRC 74,051303R(2006).
Proton elastic scatt.	0.09 ± 0.07	Ray, PRC 18,1756(1978).
Antiprotonic X-ray	0.09 ± 0.02	Trzcinska, PRC 67, 054605 (2003).

δ_{np} from SD sum rule is consistent with other results (model-dependent)
 δ_{np} for ^{208}Pb could constrain to EOS → Experimental challenge