



Study of Spin Dipole Strengths in ^{12}N and ^{16}F via Complete Polarization Transfer Measurements

RCNP-E317 collaboration

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SD Sum Rules

Non-Energy-Weighted Sum Rule (NEWS)

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

- SD operator

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

- 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

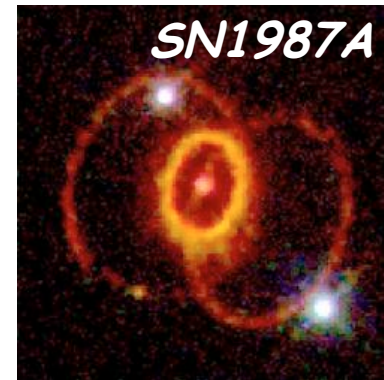
$$S_{-}^{\lambda} = \sum_{\mu} |\langle \lambda \mu | \hat{O}_{-}^{\lambda, \mu} | 0 \rangle|^2 = \begin{cases} \frac{3}{4\pi} 8b^2 = 5.98 \text{ fm}^2, & \lambda = 0^{-} \\ \frac{3}{4\pi} 24b^2 = 17.95 \text{ fm}^2, & \lambda = 1^{-} \\ \frac{3}{4\pi} 40b^2 = 29.92 \text{ fm}^2, & \lambda = 2^{-} \end{cases}$$

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

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

Scientific Motivation for SD Resonance

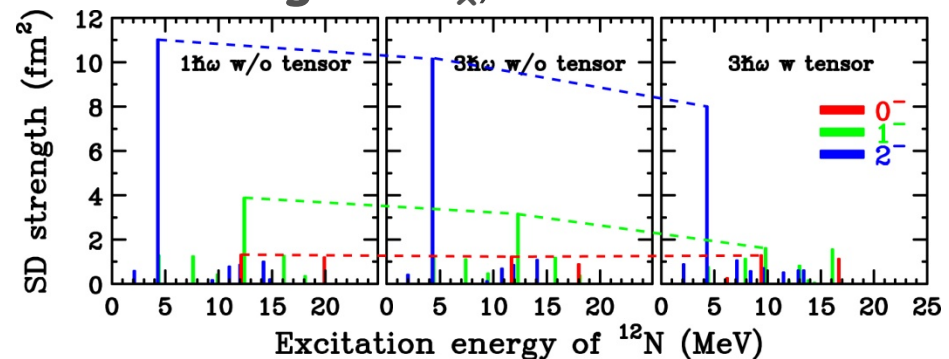
- **Search/Identify missing 0^- states**
 - Model (roughly) independent sum-rule
 - **Missing strength is crucial problem in nuclear physics.**
 - 0^- is the quantum number of pions
 - 0^- strength is sensitive to pions in nuclei
 - **Useful information on tensor correlations in nuclei**
(Toki and co-workers / RCNP theory group)
- **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 in ^{16}F is very important**



Tensor and Model Space Effects

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

- SD strengths 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 sensitive
- 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	Enhancement	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

Experimental 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

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

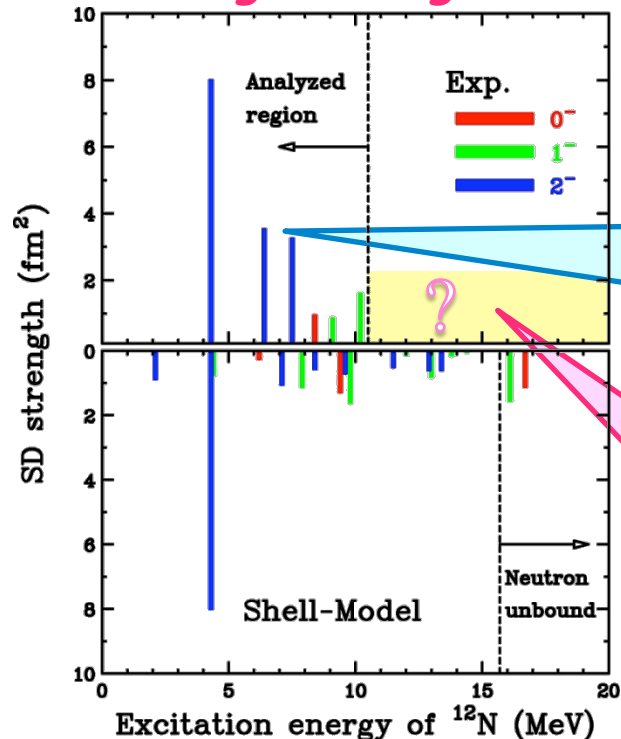
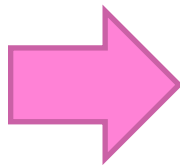
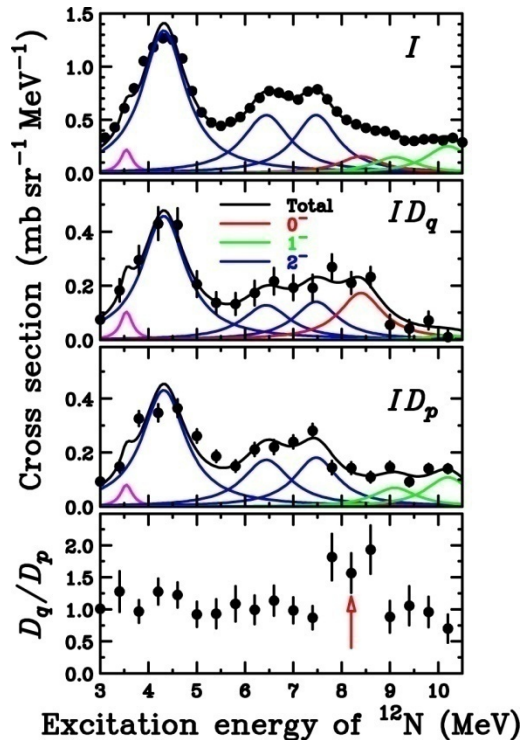
Separation to $ID_i \rightarrow$ Rigorous J^π assignment

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

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

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

- 2^- strength
 - $\sim 100\%$ NEWS
 - $E_x=6.4$ and 7.5 MeV have other J^π
 \Rightarrow (*Extended-*)MDA is important
- 0^- and 1^- strengths
 - Consistent with SM including tensor
 - *Large strengths in high E_x in SM*



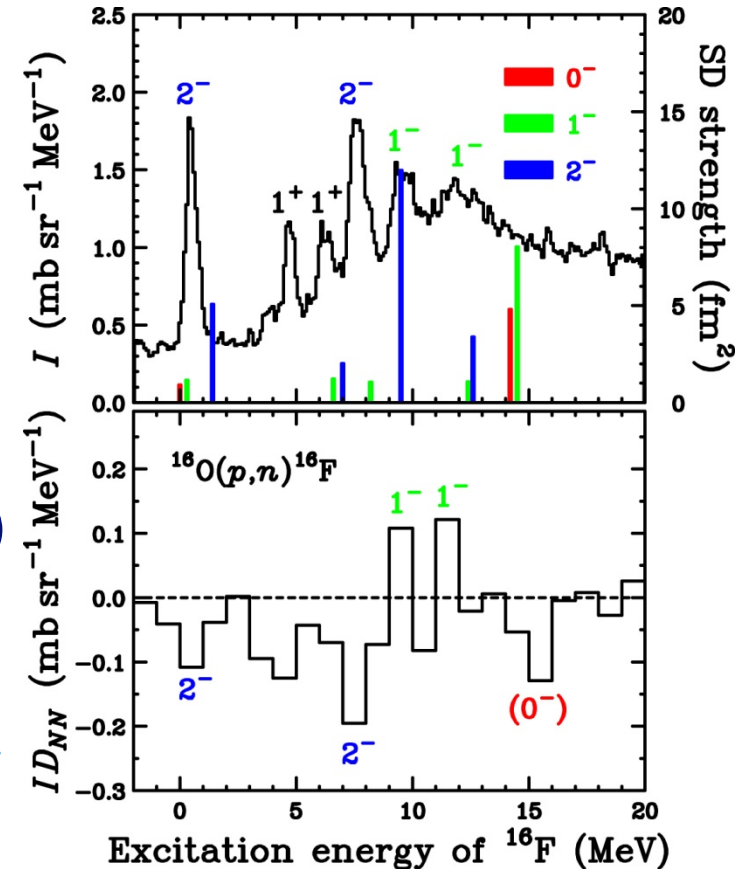
This Work
 Including other J^π
 \Rightarrow Separate in Extended-MDA

Including other L
 \Rightarrow Separate in MDA

Previous Results for SDR in ^{16}F

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

- $^{16}\text{O}(p,n)^{16}\text{F}$ at 135 MeV at IUCF
 - 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*

Importance of SDR in A=16

Detection of Supernova neutrinos in Super-Kamiokande

Supernova evolution

K. Langanke et al., PRL 76, 2629 (1996).

– Gravitational B.E. of nascent N.S. is released by $\nu\bar{\nu}$ production

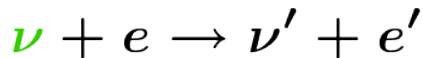
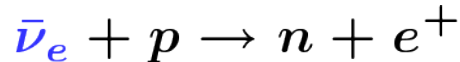
$$T_{\nu_x} = 8 \text{ MeV} > T_{\bar{\nu}_e} = 5 \text{ MeV} > T_{\nu_e} = 3.5 \text{ MeV}$$

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

SDR excitation

~~*SDR excitation*~~

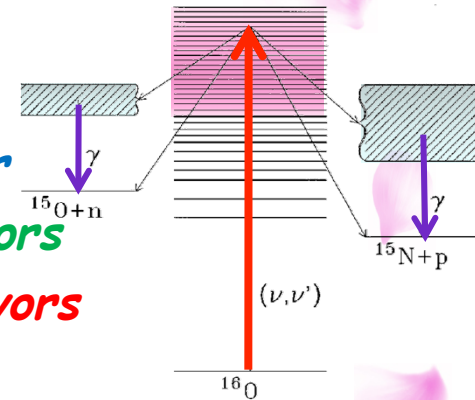
Neutrino detection in SK (γ -detection from A=15)



Sensitive to e-flavor

Sensitive to all-flavors

Sensitive to μ/τ -flavors



Theoretical prediction for $^{16}\text{O}(\nu, \nu'_x)^{16}\text{O}(\text{SDR})$

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 $^{12}\text{C}(d,^2\text{He})$
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 $J\pi$

- Extended MDA procedure (up to L=2)

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

$$ID_q = \underbrace{ID_q^{1+}}_{L=0} + \underbrace{ID_q^{0-}}_{L=1} + \underbrace{ID_q^{2-}}_{L=2} + \underbrace{ID_q^{3+}}_{L=2} \quad \text{Normal MDA}$$

- Separate ID_q^{0-} and ID_q^{2-} with IS_{NN} and IS_{LL}

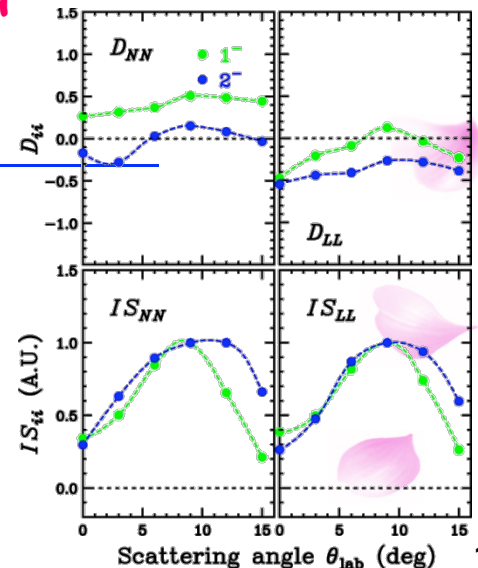
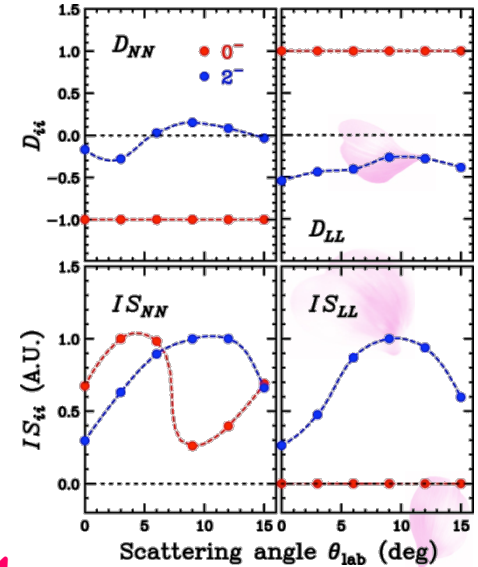
- No 0^- contribution in IS_{LL} **Extended MDA**

- Separate ID_p to each L using normal MDA

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

- Separate ID_p^{1-} and ID_p^{2-} with D_{NN} and D_{LL}

- Significant difference in D_{ij} **Extended MDA**

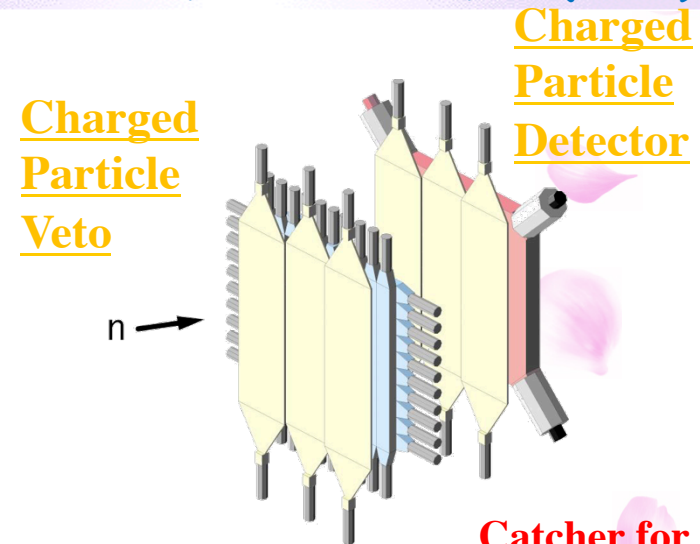


Separation to each $J\pi$

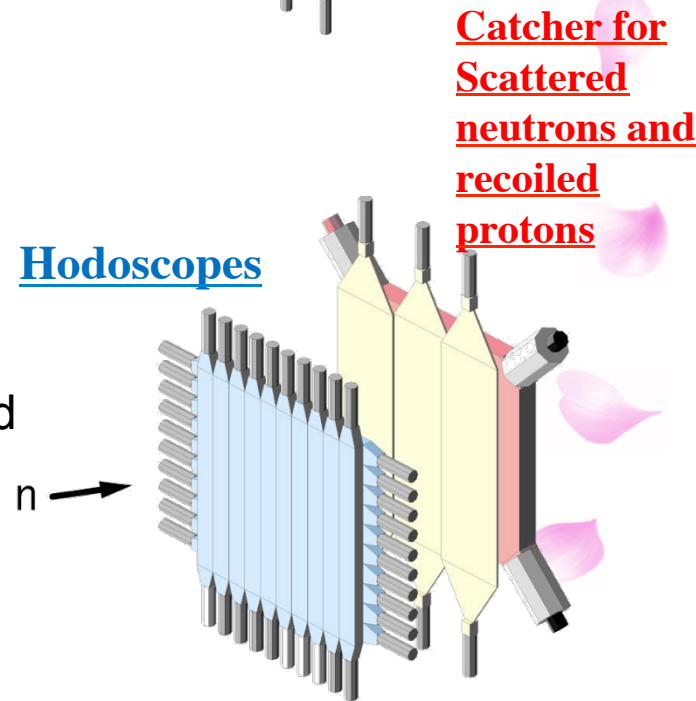
Neutron Detector/Polarimeter NPOL3

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 : $e \sim 0.01$
 - 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}



Beam Time Requirements

- Required data
 - ID_i with $\delta ID_i = 10\%$ at $0^\circ - 15^\circ$ (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 \times 3 settings 72 hours
- Calibration of NPOL3 1.5 days
 - Measure ε by using ${}^7\text{Li}(p,n){}^7\text{Be}(g.s.+0.43\text{MeV})$ 12 hours
 - Measure $A_{y,\text{eff}}$ using ${}^2\text{H}(p,n)$ 24 hours
- Cross sections and analyzing powers ($0^\circ \sim 15^\circ$) 1.5 days
 - ${}^{12}\text{C}(p,n)$ 1 hours \times 16 angles 16 hours
 - ${}^{16}\text{O}(p,n)$ 1 hours \times 16 angles 16 hours
- Polarization transfer observables ($0^\circ \sim 15^\circ$) 12.0 days
 - ${}^{12}\text{C}(p,n)$ 6 hours \times 4 settings \times 6 angles 144 hours
 - ${}^{16}\text{O}(p,n)$ 6 hours \times 4 settings \times 6 angles 144 hours
- Total 16.5 days

Beam 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	
• <i>Ice target system</i>	700,000	<i>Different from E313</i>
• <i>Plastic Scinti. BC408 × 2</i>	1,500,000	Repair neutron counters
• <i>PMT(H6410 × 2, H2431 × 2)</i>	900,000	
• <i>Support system for NPOL3</i>	1,000,000	Used with NPOL2 In TOF tunnel
• <i>Base for the support</i>	500,000	
– 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, Tohoku Univ.

- Y. Sakemi P
- T. Nagano M



RCNP, Osaka Univ.

- 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.

Young students will gain experience in nuclear physics experiments at RCNP

Kyushu-RCNP-CYRIC Collaboration

Contribution to SPIN2008

I have a great honor to give a plenary talk for nuclear spin physics in SPIN 2008.

RCNP data and information on
Observation of missing O^- strength
Tensor correlations in nuclei
should be impressive!!

(The experiment on ^{12}C can be performed before summer)

October 6 - 11, 2008

University of Virginia, Charlottesville, VA

SPIN 2008

The 18th International Spin Physics Symposium

Figures in E317 Proposal



Figure 1

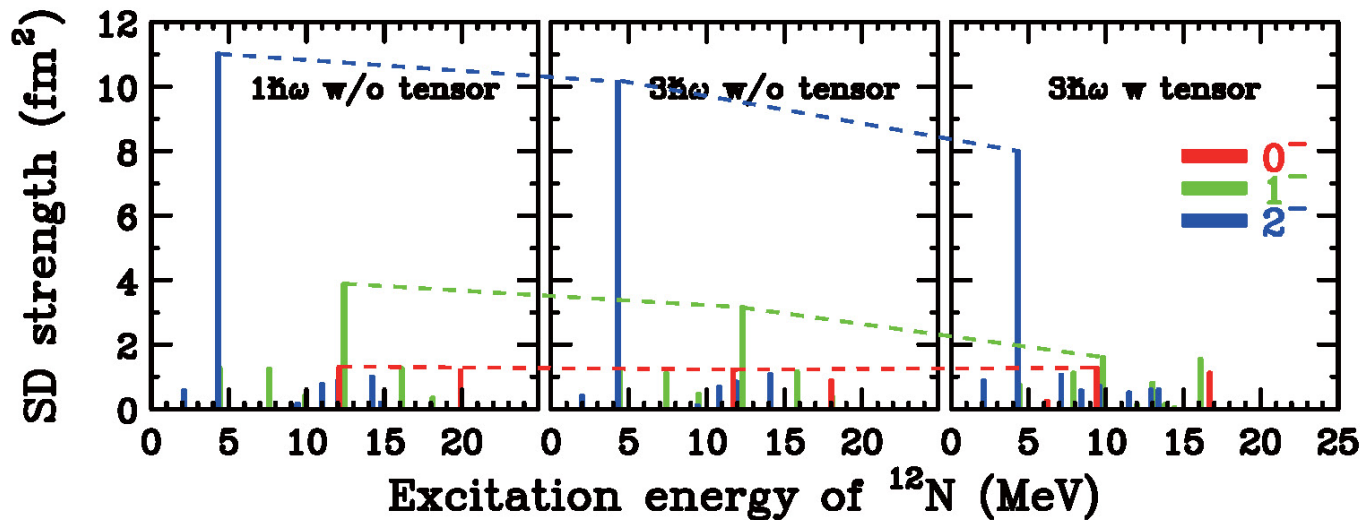


Figure 1: SD strengths of shell model calculations in ¹²N with Michigan 3-range Yukawa (M3Y) interaction; (left) the 1ħω configuration space without tensor interaction. (middle) the 3ħω configuration space without tensor interaction. (right) the 3ħω configuration space with tensor interaction.

Figure 2

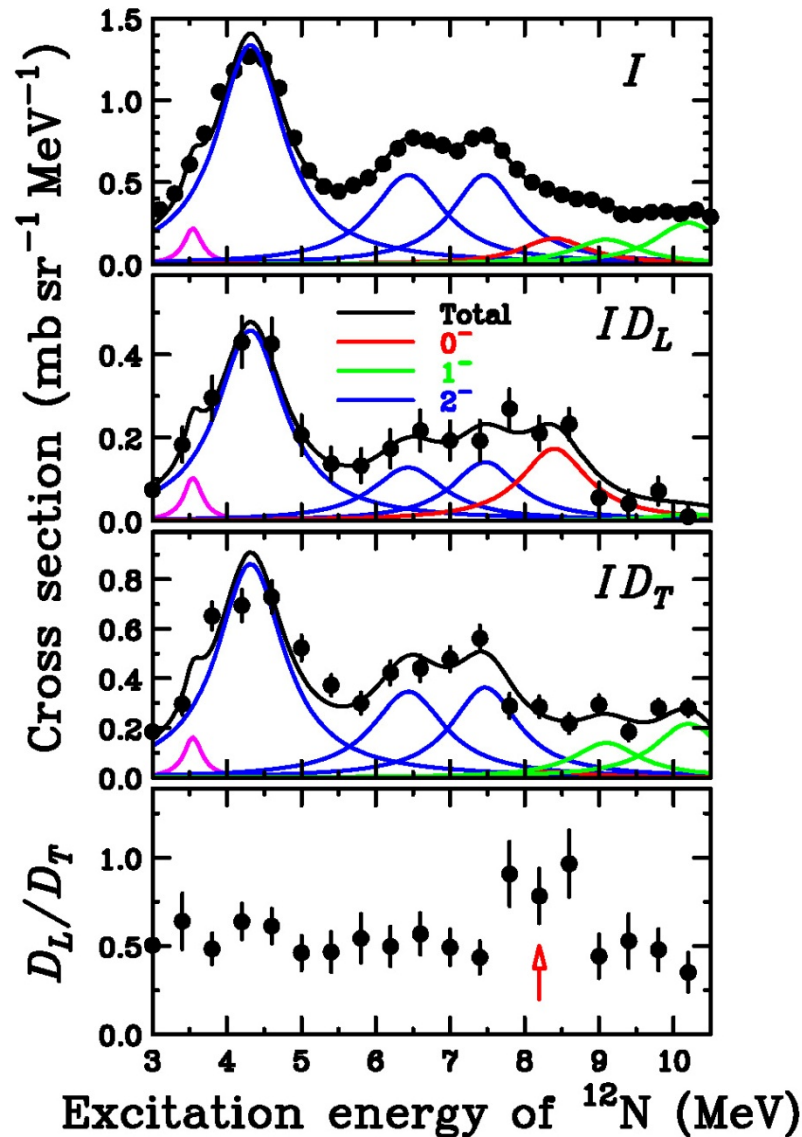


Figure 2: Measurements of $^{12}\text{C}(\vec{p}, \vec{n})$ at $T_p=296$ MeV and $\theta_{\text{lab}} = 0^\circ$; (top panel) the unpolarized cross section I . (2nd panel) the spin-longitudinal polarized cross section ID_L . (3rd panel) the spin-transverse polarized cross section ID_T . (bottom panel)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

Figure 3

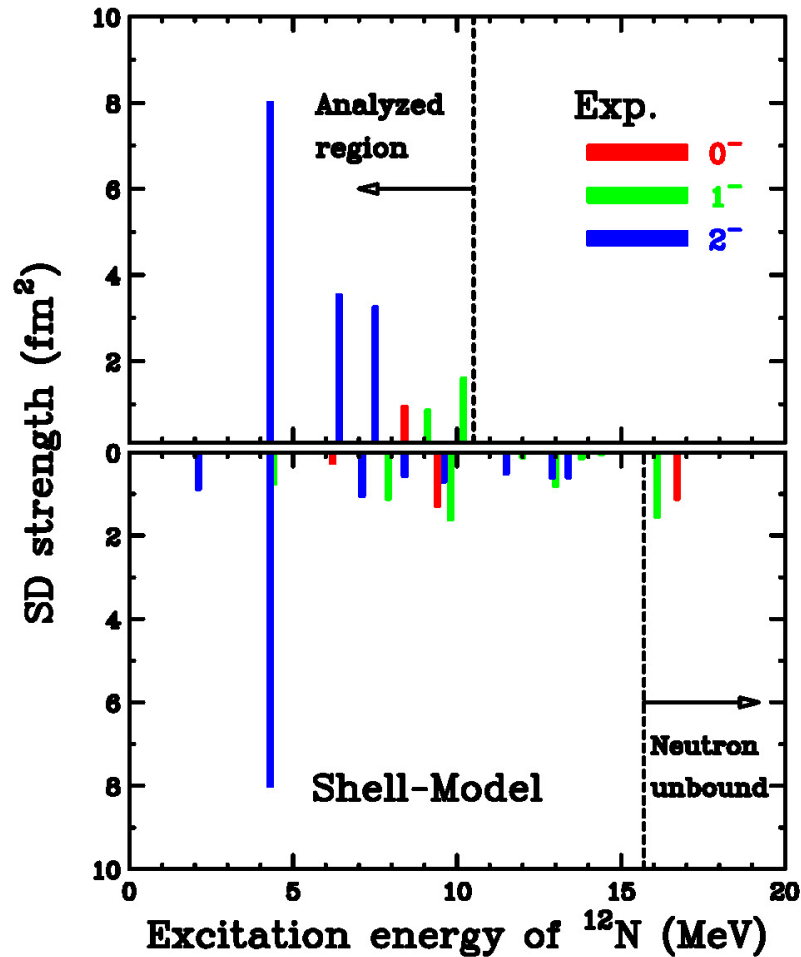


Figure 3: SD strengths in ¹²N obtained from the ¹²C(\vec{p}, \vec{n}) reaction (top panel) compared with shell-model calculations with Michigan 3-range Yukawa (M3Y) interaction in the $3\hbar\omega$ configuration space.

Figure 4

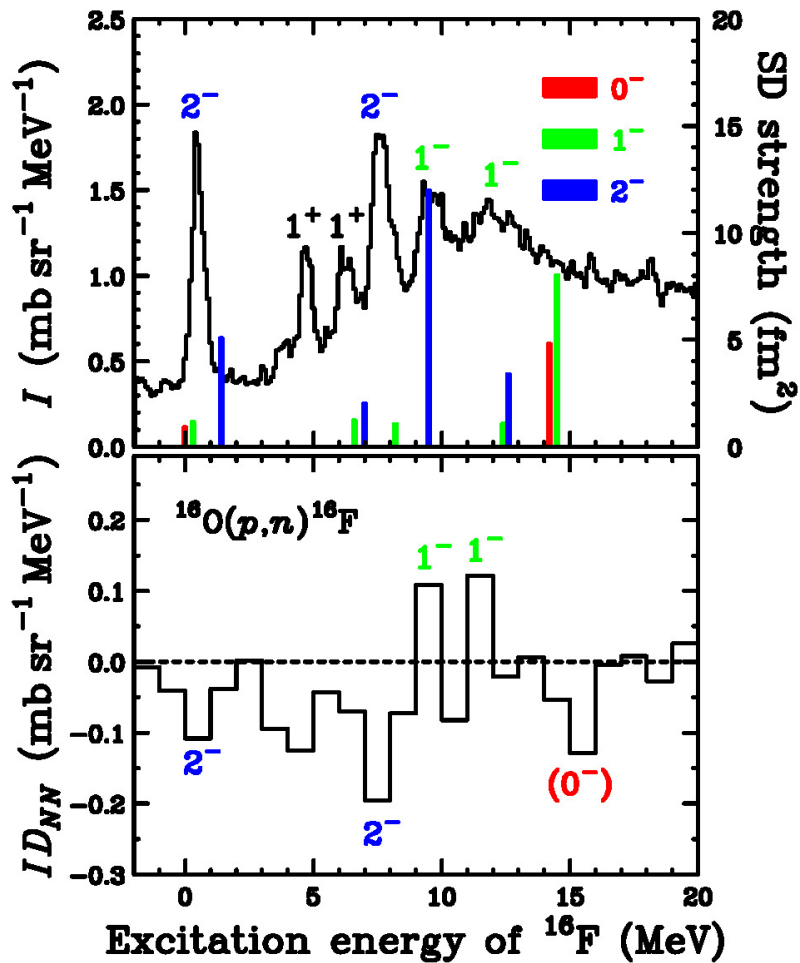


Figure 4: Measurements of $^{16}\text{O}(\vec{p}, \vec{n})$ at $T_p=135$ MeV and $\theta_{\text{lab}} = 0^\circ$; (top panel) the unpolarized cross section I . (bottom panel) $ID_{NN}(0^\circ)$. The red, green, and blue curves are the results of the SM calculations for 0^- , 1^- , and 2^- , respectively.

Figure 5

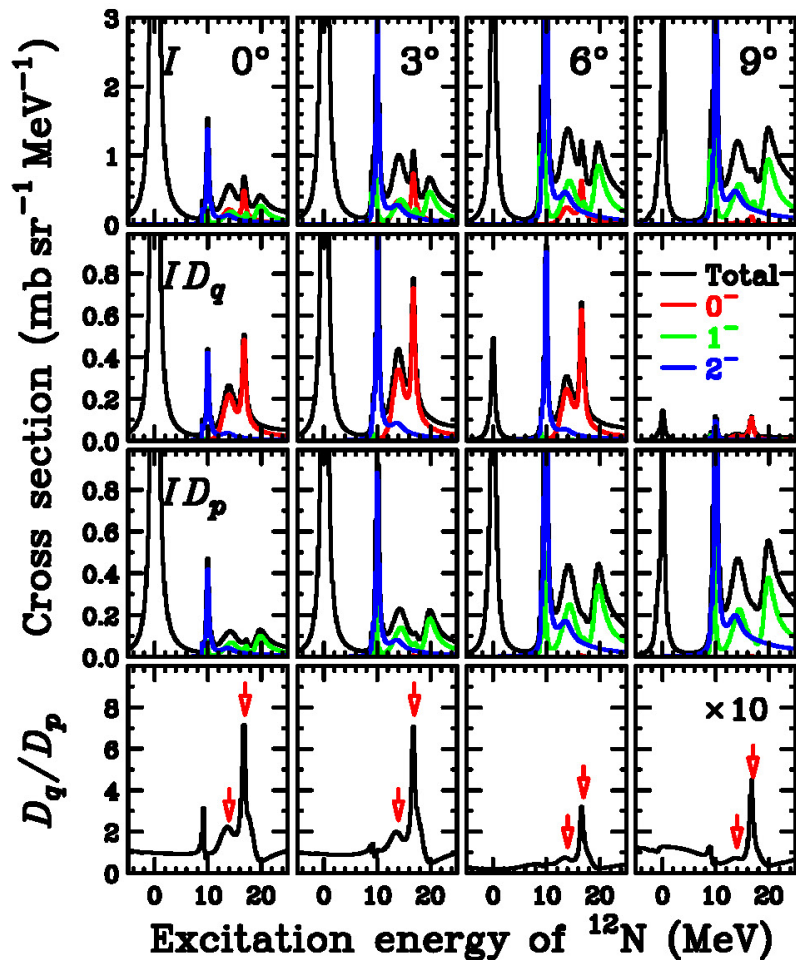


Figure 5: DWIA+RPA predictions for $^{12}\text{C}(p, n)$ at $T_p=295$ MeV and $\theta_{\text{lab}}=0^\circ-9^\circ$. The red, green, and blue curves represent contributions from 0^- , 1^- , and 2^- SD excitations, respectively. The 0^- SD states are clearly observed in D_q/D_p as indicated by the red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

Figure 6

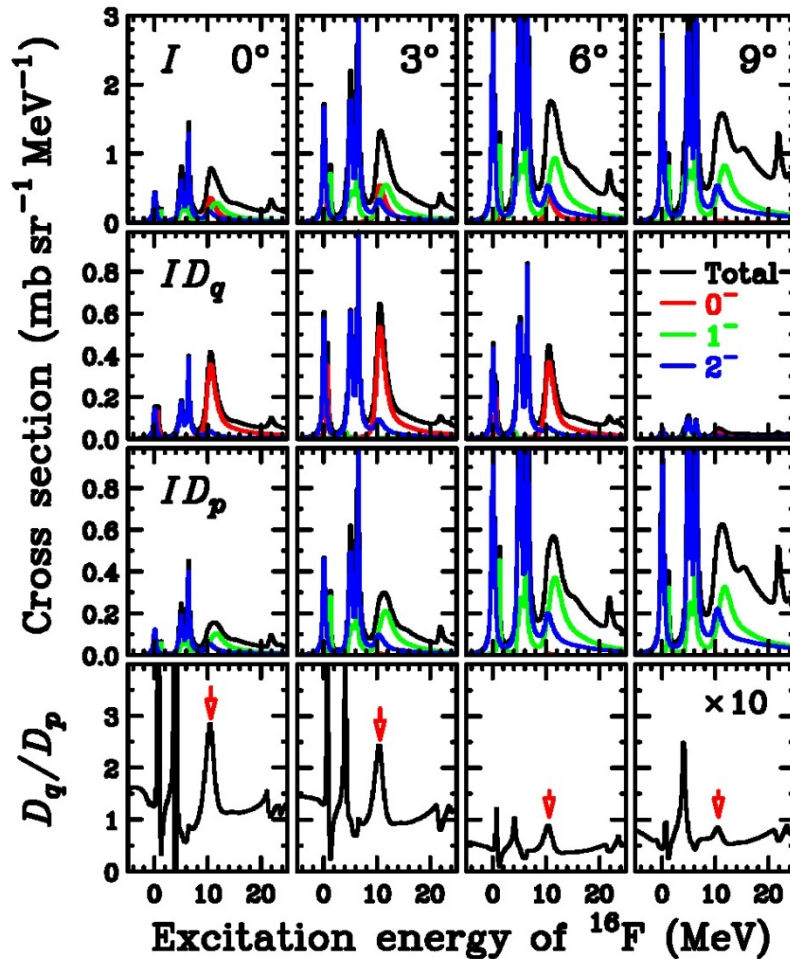


Figure 6: DWIA+RPA predictions for $^{16}\text{O}(p,n)$ at $T_p=295$ MeV and $\theta_{\text{lab}}=0^\circ-9^\circ$. The red, green, and blue curves represent contributions from 0^- , 1^- , and 2^- SD excitations, respectively. The 0^- SD states are clearly observed in D_q/D_p as indicated by the red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

Figure 7

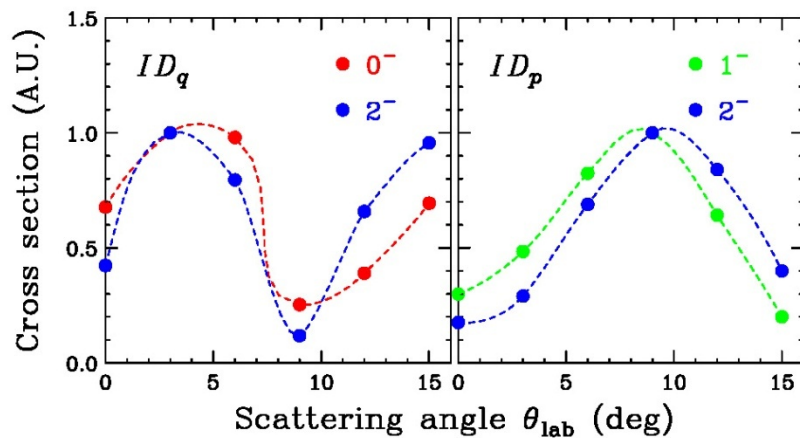


Figure 7: DWIA+RPA predictions for ID_q (left panel) and ID_p (right panel) of the $^{12}\text{C}(p,n)$ reaction at $T_p=295$ MeV. The red, green, and blue filled-circles are the results for 0^- , 1^- , and 2^- SD excitations, respectively.

Figure 8

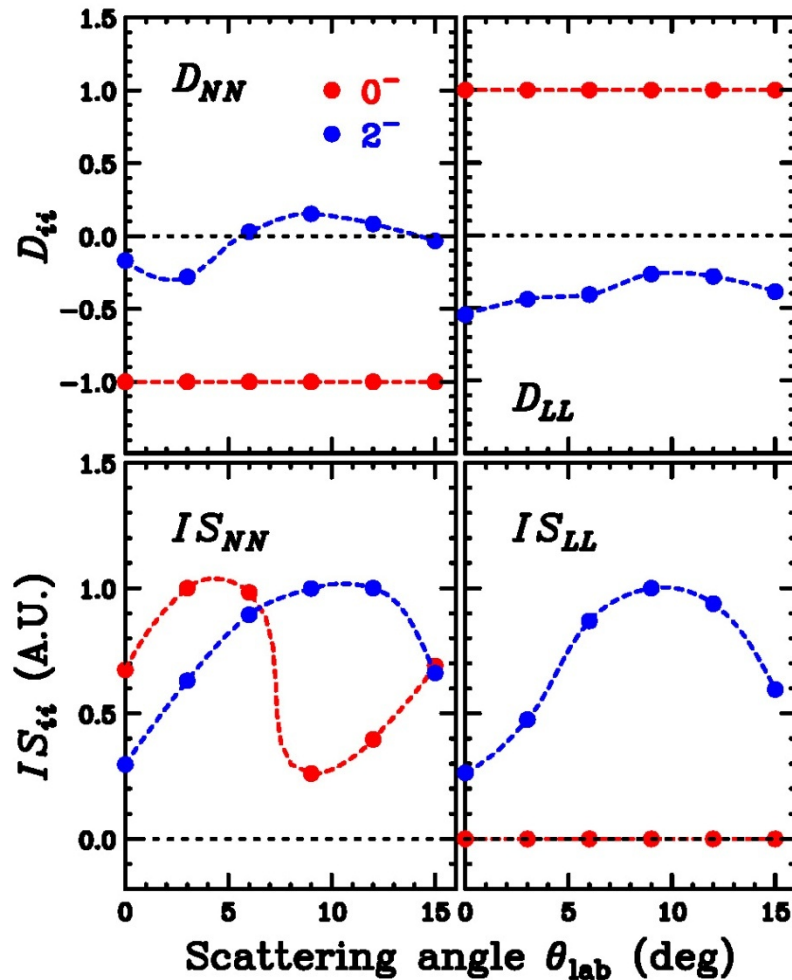


Figure 8: DWIA+RPA predictions for S_{ii} (top panels) and IS_{ii} (bottom panels) of the $^{12}\text{C}(p,n)$ reaction at $T_p=295$ MeV. The red and blue filled-circles are the results for 0^- and 2^- SD excitations, respectively.

Figure 9

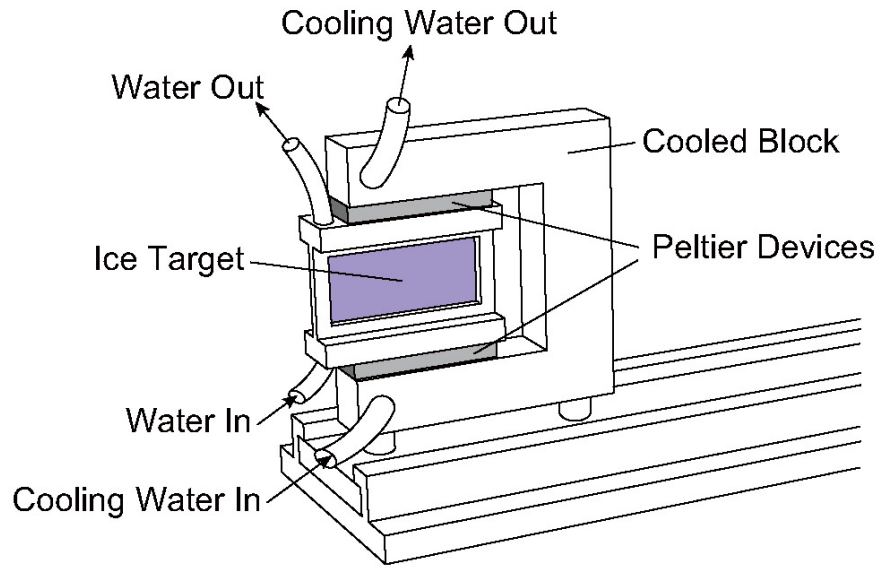


Figure 9: Illustration of the ice target system for this experiment.

Figure 10

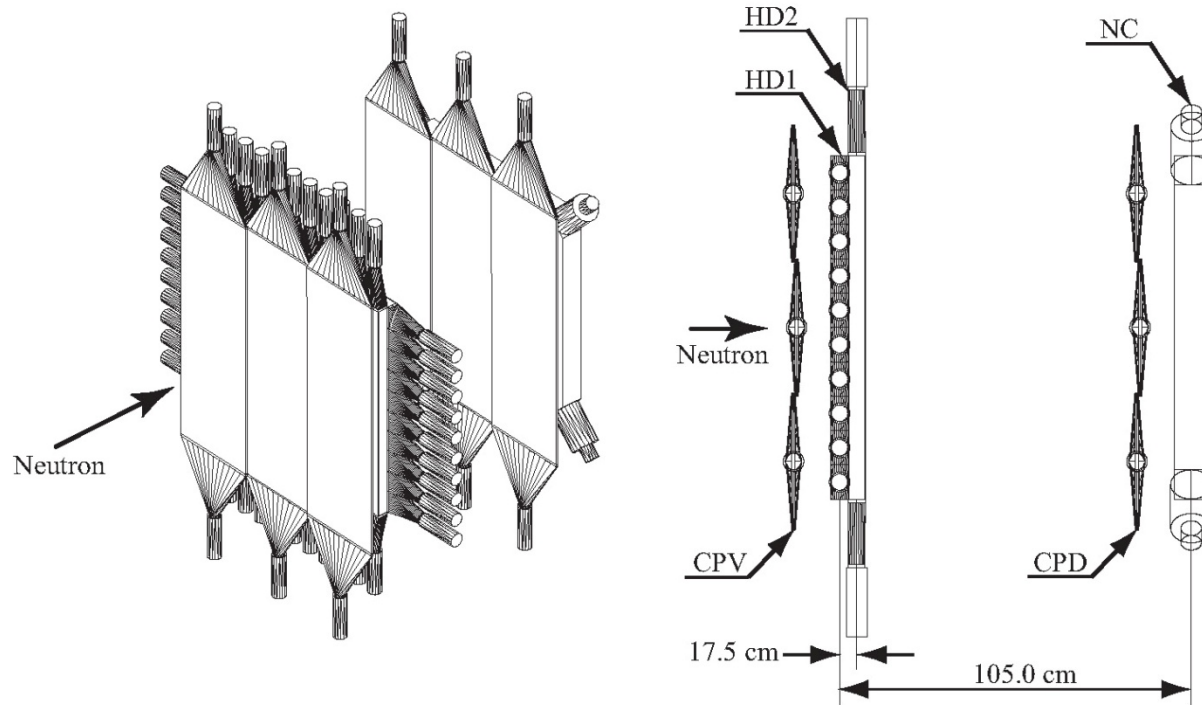


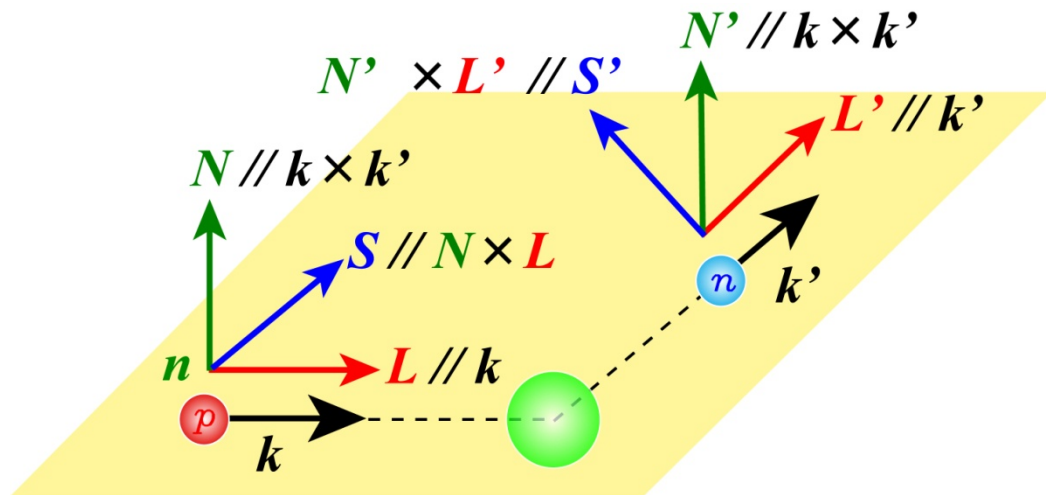
Figure 10: Schematic (left) and top (right) views of the NPOL3 system. In the polarimetry mode of NPOL3, HD1 and HD2 are the analyzer planes while NC is the catcher plane. Thin plastic scintillator planes are used to veto (CPV) or identify (CPD) charged particles.

Misc

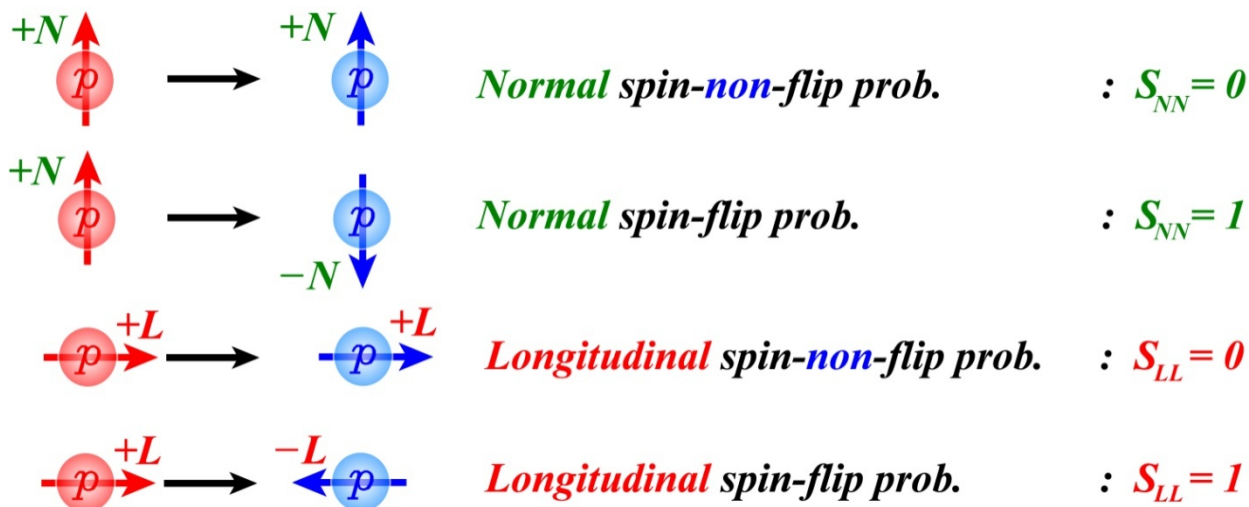


Coordinate System and Polarization Observables

- 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_{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

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

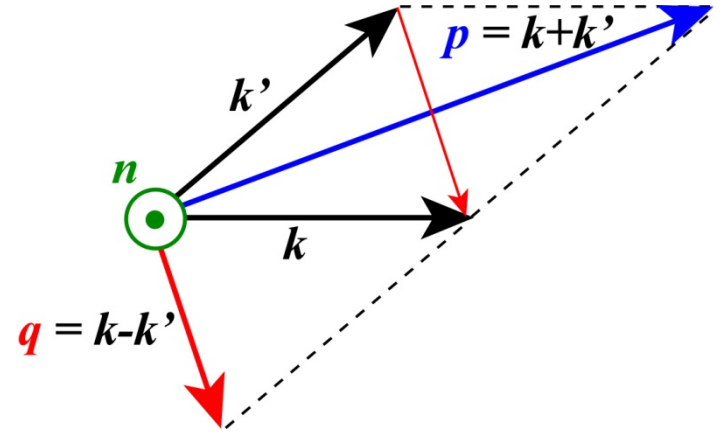
- Kerman-McManus-Thaler notation

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

- Cross section and polarization observables

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

$$D_{nn}(E, q) = D_{NN}(E, q) = \frac{\text{Tr}(t^+ \vec{\sigma}_1 \cdot \hat{n} t \vec{\sigma}_1 \cdot \hat{n})}{\text{Tr}(t^+ t)} = \frac{A^2 + B^2 + 2C^2 - E^2 - F^2}{A^2 + B^2 + 2C^2 + E^2 + F^2}$$



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

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

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

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

Power of Polarization Observables

Filter to Spin-Parity

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

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

- 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

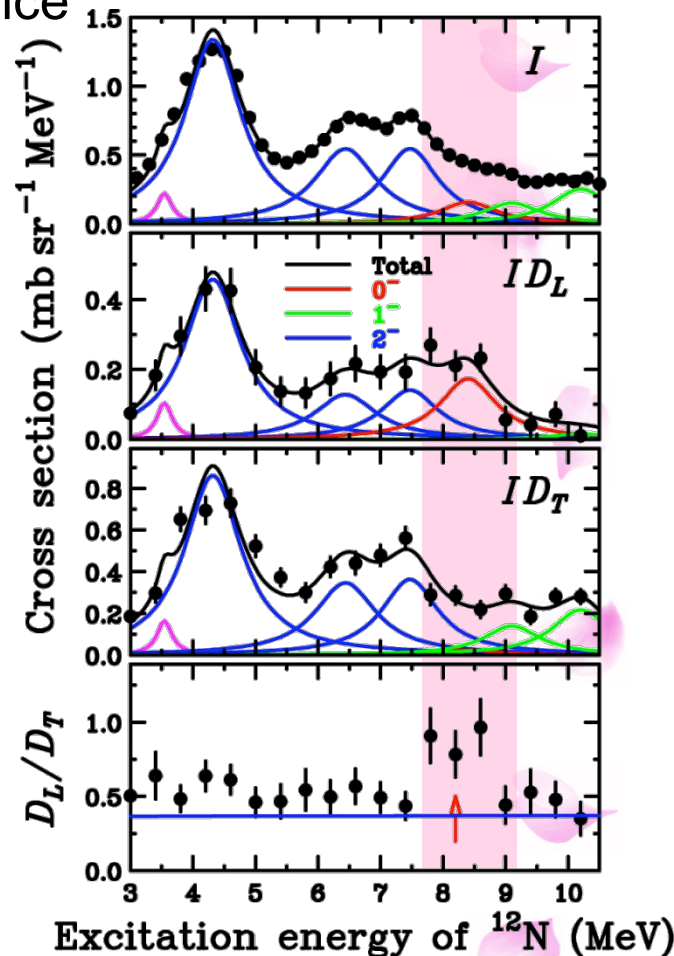
- PWIA with central only

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

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

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

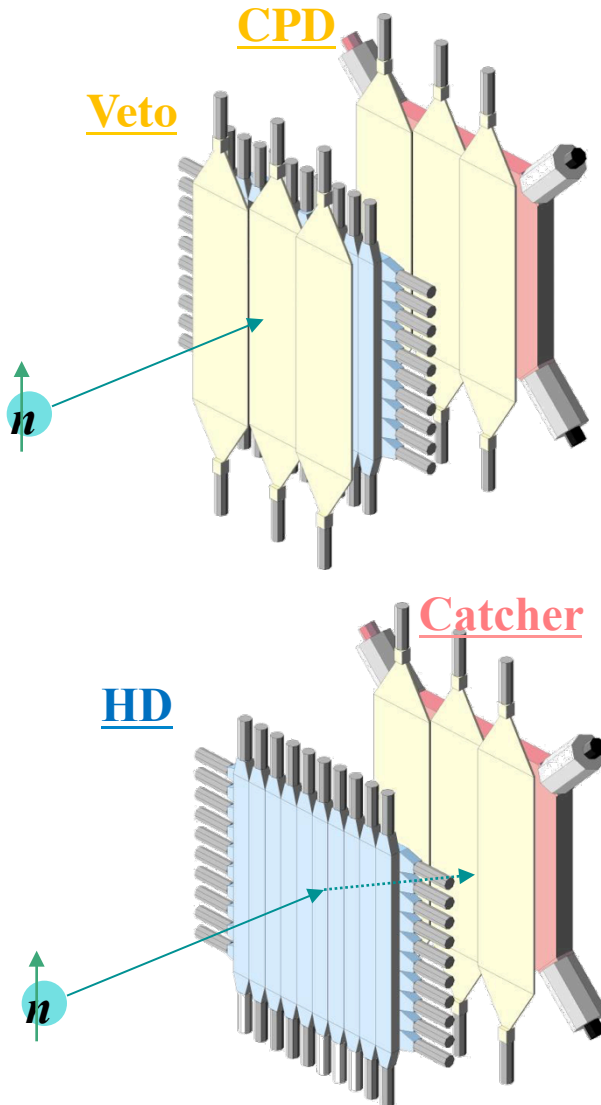
Significantly different



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

Neutron Detector/Polarimeter NPOL3

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



Veto/CPD

.... Veto/Identify protons

HD

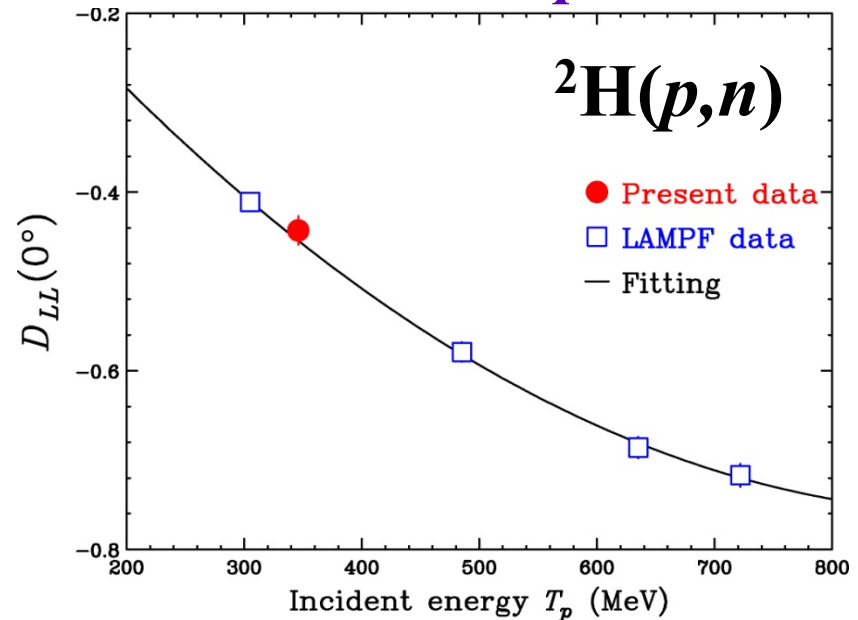
.... Neutron scatterer (analyzer)

Catcher

.... Detect recoil protons

Left/Right asymmetry

→ Neutron polarization



Consistent with previous data \Rightarrow High reliability