International Symposium “Perspective in isospin Physics”
~ Role of non-central interactions in structure and dynamics of unstable nuclei ~
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Study of spin-dipole excitations via (p,n) reaction with spin observables

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  - SD strengths provides information on tensor correlations
- Methods
  - Separate SD strengths into each J^{π} (0^-, 1^-, 2^-)
- Experiments
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- Results and Discussions
  - SD strength distribution in ^{208}Bi

    T. Wakasa, M. Okamoto, M. Dozono et al., PRC 85, 064606 (2012)
  - SD strength distribution in ^{12}N (Very preliminary results)
- Summary

Tensor correlations in nuclei

- Tensor force (manifestation of meson exchange)
  - NN Interaction is originally due to meson exchange
    ⇒ Plays significant roles in many nuclear properties

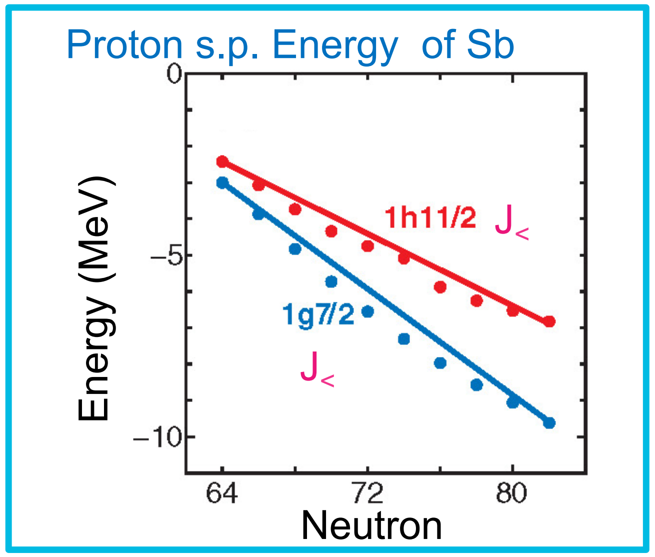
Structure of nuclei

Ground state properties

- total binding energy, radii, ...

e.g.) Evolution of single-particle energies of exotic nuclei

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



Dynamics of nuclei

Excited state properties

- excitation energy, strength, ...

Spin-Dipole (SD) mode is a good approach to tensor effects in nuclei

Spin-Dipole (SD) excitations

- (Isovector) SD operator

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

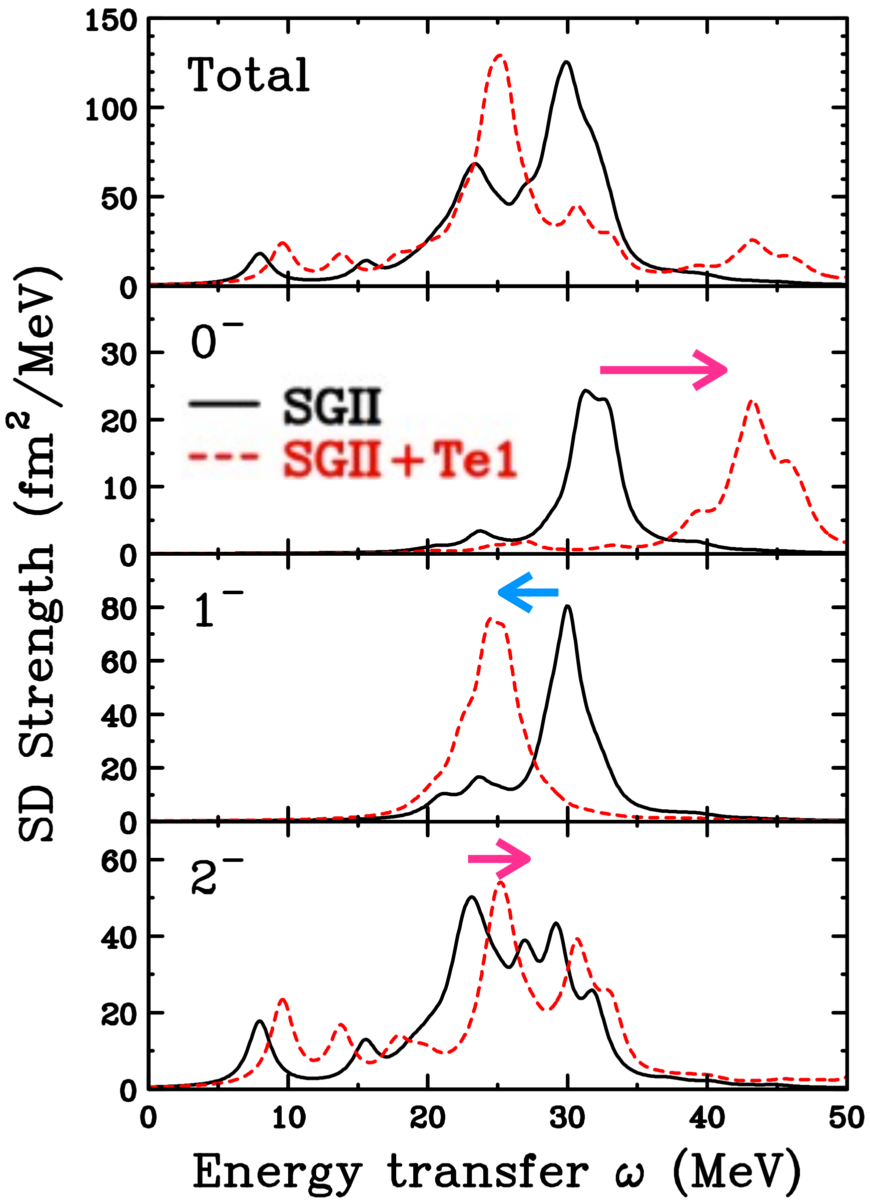
- $\Delta L=1$, $\Delta S=1$, $\Delta T=1$
- $\Delta J^{\pi} = 0^-, 1^-, 2^-$

Tensor effects on SD strengths

C. L. Bai, H. Sagawa et al., PRL 105, 072501 (2010); PRC 83, 054316 (2011)

- Results of self-consistent HF+RPA calc. including skyrme int.

$^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}$



ΔJ^{π}-dependent effect on SD strengths

J^{π}	Tensor effects
0^-	Hardening (repulsive)
	↕
1^-	Softening (attractive)
2^-	Hardening (repulsive)

J^{π} identification of SD states are important to pin down tensor force effects

Complete polarization transfer measurements for (p,n) reaction at RCNP

- Purpose
  - Investigate fine structure of SD excitations ($J^{\pi} = 0^-, 1^-, 2^-$)
    ⇒ Tensor correlations in nuclei
    However, experimental identification of J^{π} is very difficult
- Experiment
  - Complete polarization transfer D_{ij} measurements for the (p,n) reaction
    - Polarization transfer observables D_{ij} are sensitive to J^{π}
      ⇒ Separation/Identification of each SD J^{π} is possible
- Target
  - ^{208}Pb and ^{12}C
- Complete polarization transfer measurement is possible by using
  - High intensity polarized protons at RCNP
  - High efficiency neutron polarimeter NPOL3

Polarization transfer observables D_{ij}

- Complete set of polarization transfer observables D_{ij}

Polarization transfer observables

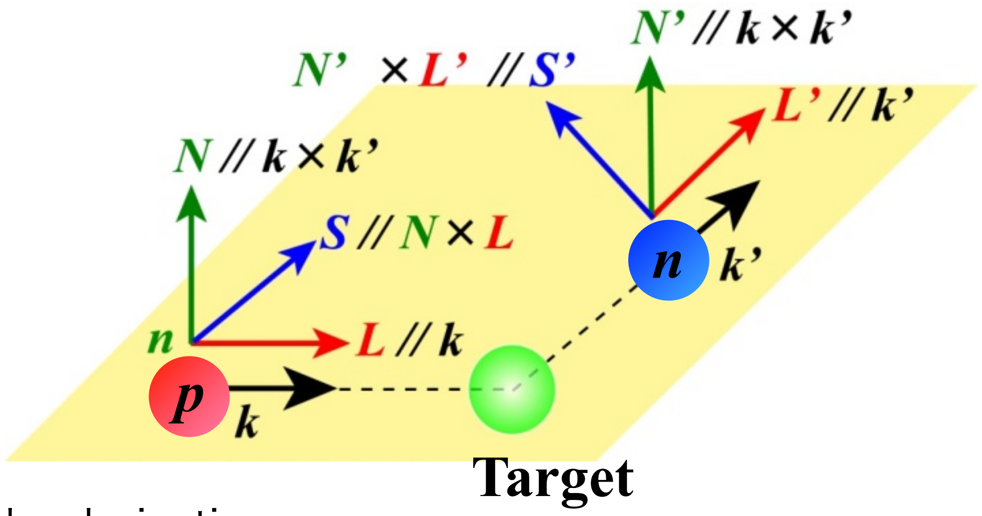
$$\begin{pmatrix} p'_{S'} \\ p'_{N} \\ p'_{L'} \end{pmatrix} = \left[\begin{pmatrix} D_{S'S} & 0 & D_{S'L} \\ 0 & D_{NN} & 0 \\ D_{L'S} & 0 & D_{L'L} \end{pmatrix} \begin{pmatrix} p_S \\ p_N \\ p_L \end{pmatrix} + \begin{pmatrix} 0 \\ P \\ 0 \end{pmatrix} \right] \times \frac{1}{1+p_N A_y}$$

Outgoing neutron polarization

Incident proton polarization

P : Induced polarization

A_y : Analyzing power



- Polarized cross sections ID_i

E. Bleszynski et al., PRC 26, 2063 (1982)

$$D_0 = \tfrac{1}{4}[1 + D_{NN} + (D_{S'S} + D_{L'L})\cos\alpha_1 + (D_{L'S} - D_{S'L})\sin\alpha_1],$$
$$D_n = \tfrac{1}{4}[1 + D_{NN} - (D_{S'S} + D_{L'L})\cos\alpha_1 - (D_{L'S} - D_{S'L})\sin\alpha_1],$$
$$D_q = \tfrac{1}{4}[1 - D_{NN} + (D_{S'S} - D_{L'L})\cos\alpha_2 - (D_{L'S} + D_{S'L})\sin\alpha_2],$$
$$D_p = \tfrac{1}{4}[1 - D_{NN} - (D_{S'S} - D_{L'L})\cos\alpha_2 + (D_{L'S} + D_{S'L})\sin\alpha_2],$$

$$\Rightarrow \begin{cases} D_L = D_q \\ D_T = D_n + D_p \end{cases}$$

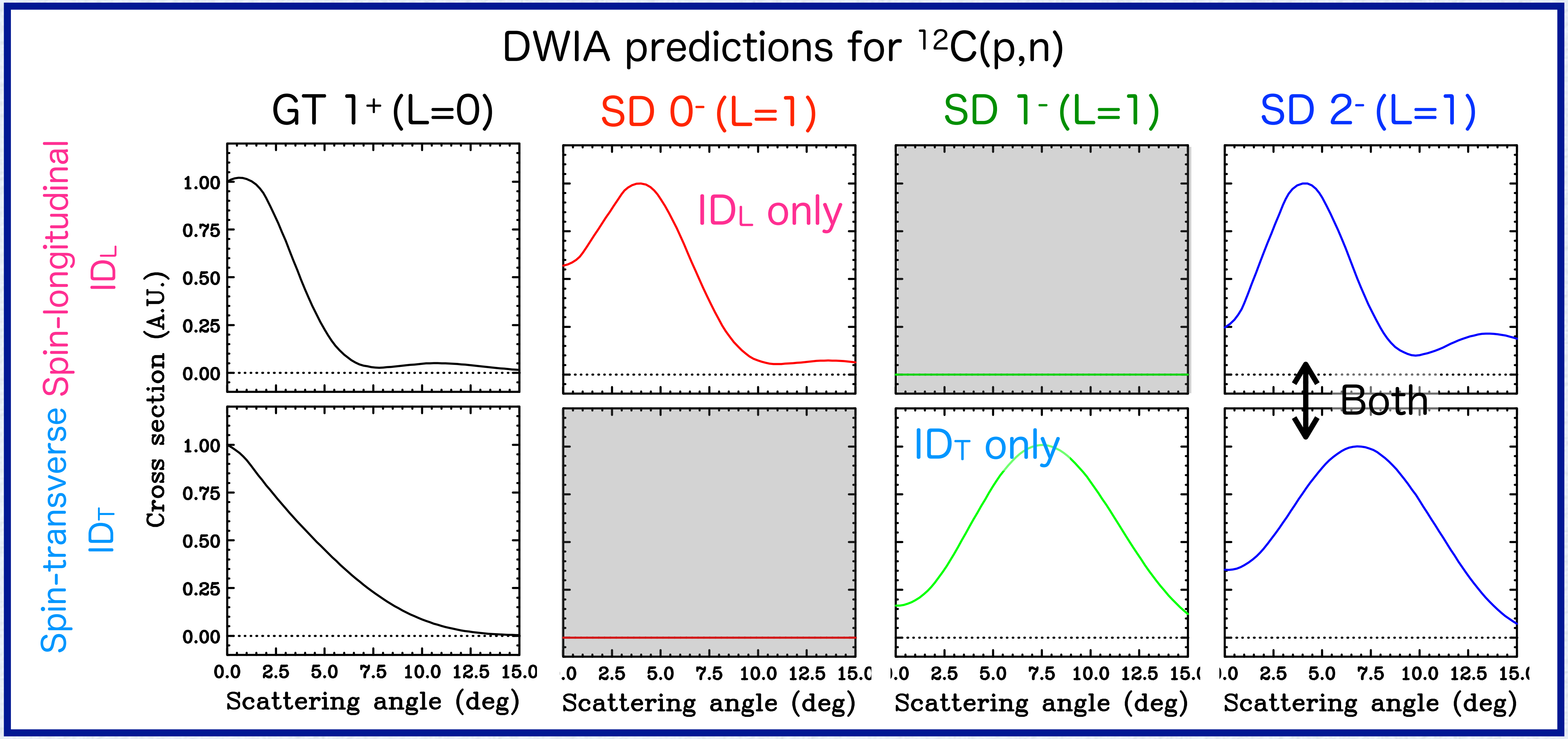
α_1 & α_2 are rotation angles in lab. frame → c.m. frame

- Separate c.s. I into ID_i using complete set of D_{ij}
  - $I = ID_0 + ID_L + ID_T$
  - ID_0 : Spin-scalar $\Delta S=0$
  - ID_L, ID_T : Spin-vector $\Delta S=1$
    - ID_L : Spin-longitudinal (π-mode, $\sigma \cdot q$)
    - ID_T : Spin-transverse (ρ-mode, $\sigma \times q$)

Separation of SDR into Each J^{π}

~ Multipole decomposition using ID_i (D_{ij}) ~

- "Normal" MDA : Can't separate into each J^{π} with same L
  ⇒ "Extended" MDA using polarized cross sections ID_i

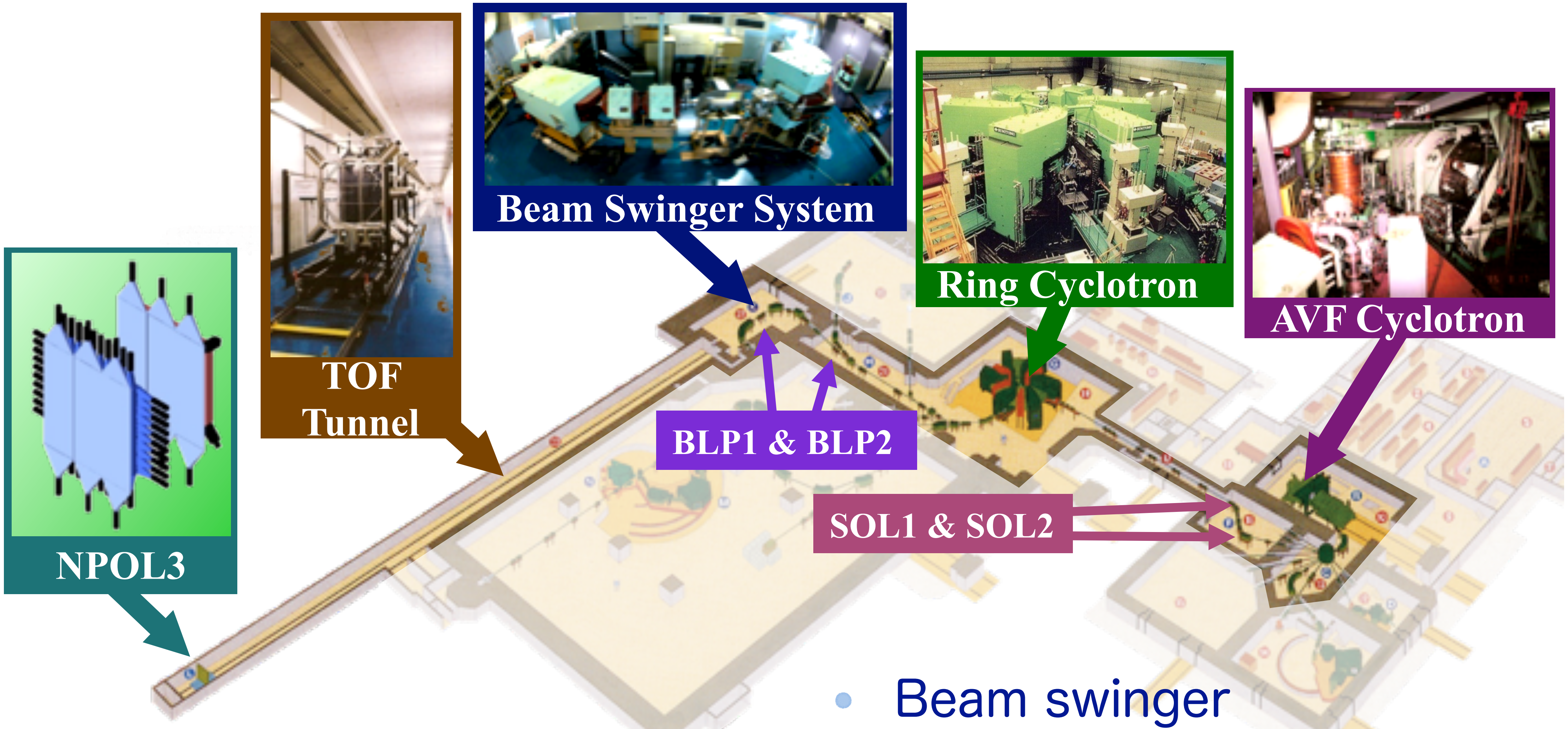


Multipole decomposition for spin-longitudinal(π) and transverse(ρ) c.s.

⇒ Can separate/specify each SD J^{π}

Experiment

Research Center for Nuclear Physics Osaka University

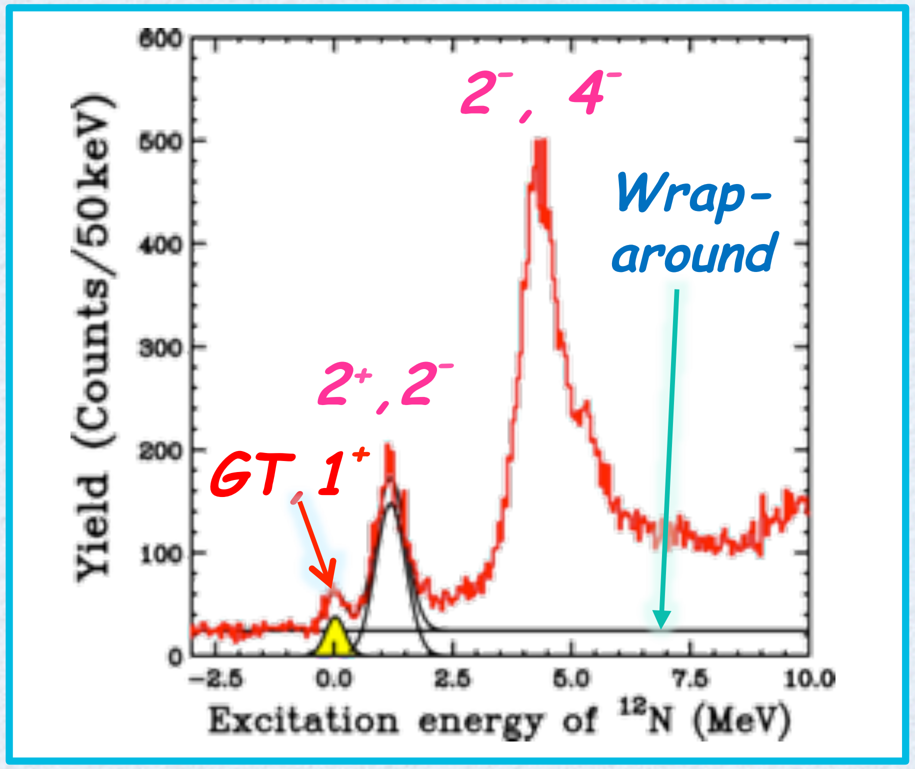


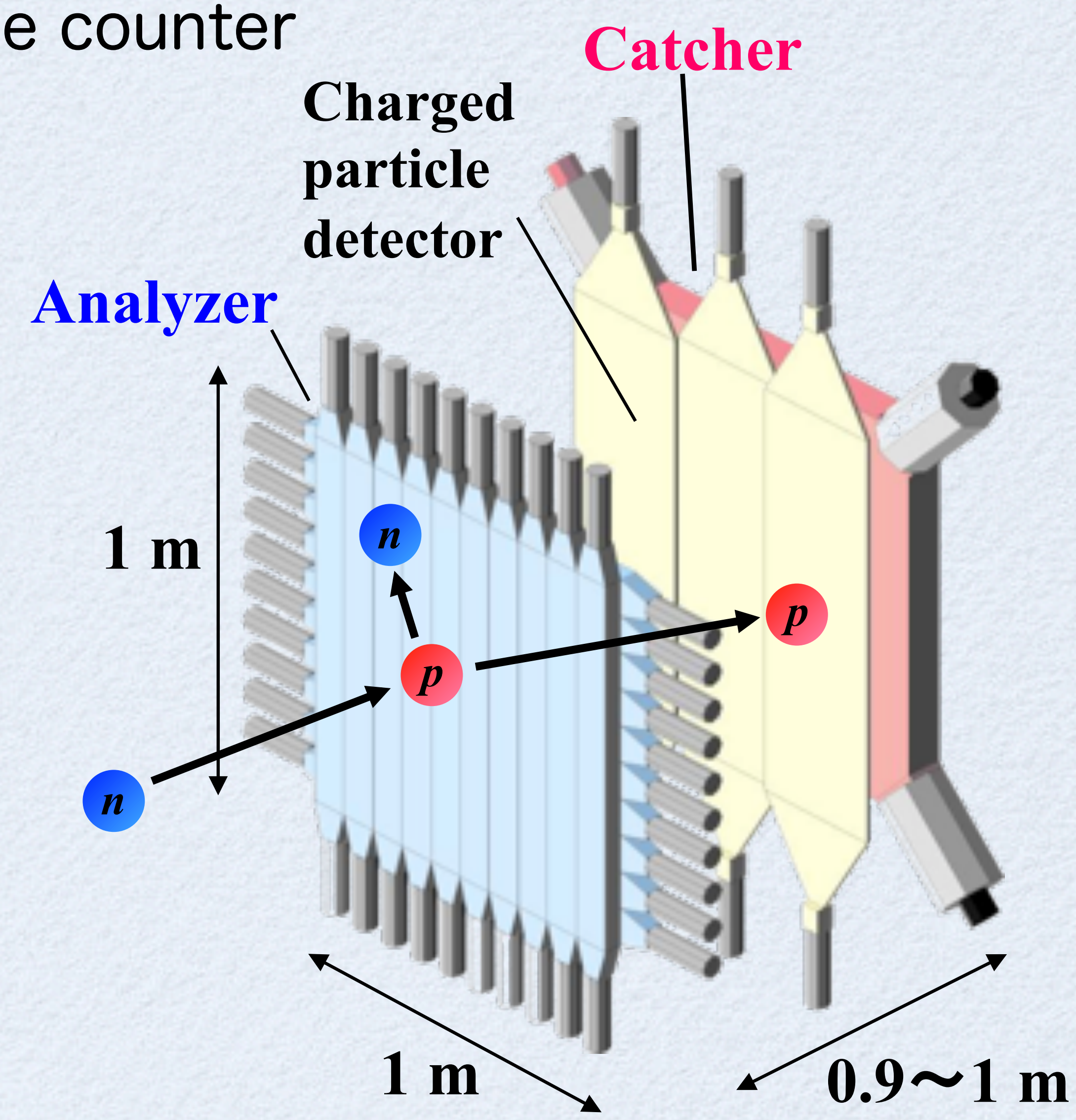
- 296 MeV Polarized protons
  - Predominantly excite GT and SDR
- Beam polarization
  - Control with 2-sets of solenoids
  - Measure with 2-sets of BLP by p-p
- Beam swinger
  - Cover $q=0.1\text{-}2.0\ \text{fm}^{-1}$
- Neutron measurement
  - NPOL3 with 100m TOF
  - Complete measurement of neutron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

Neutron Detector/Polarimeter NPOL3

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

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





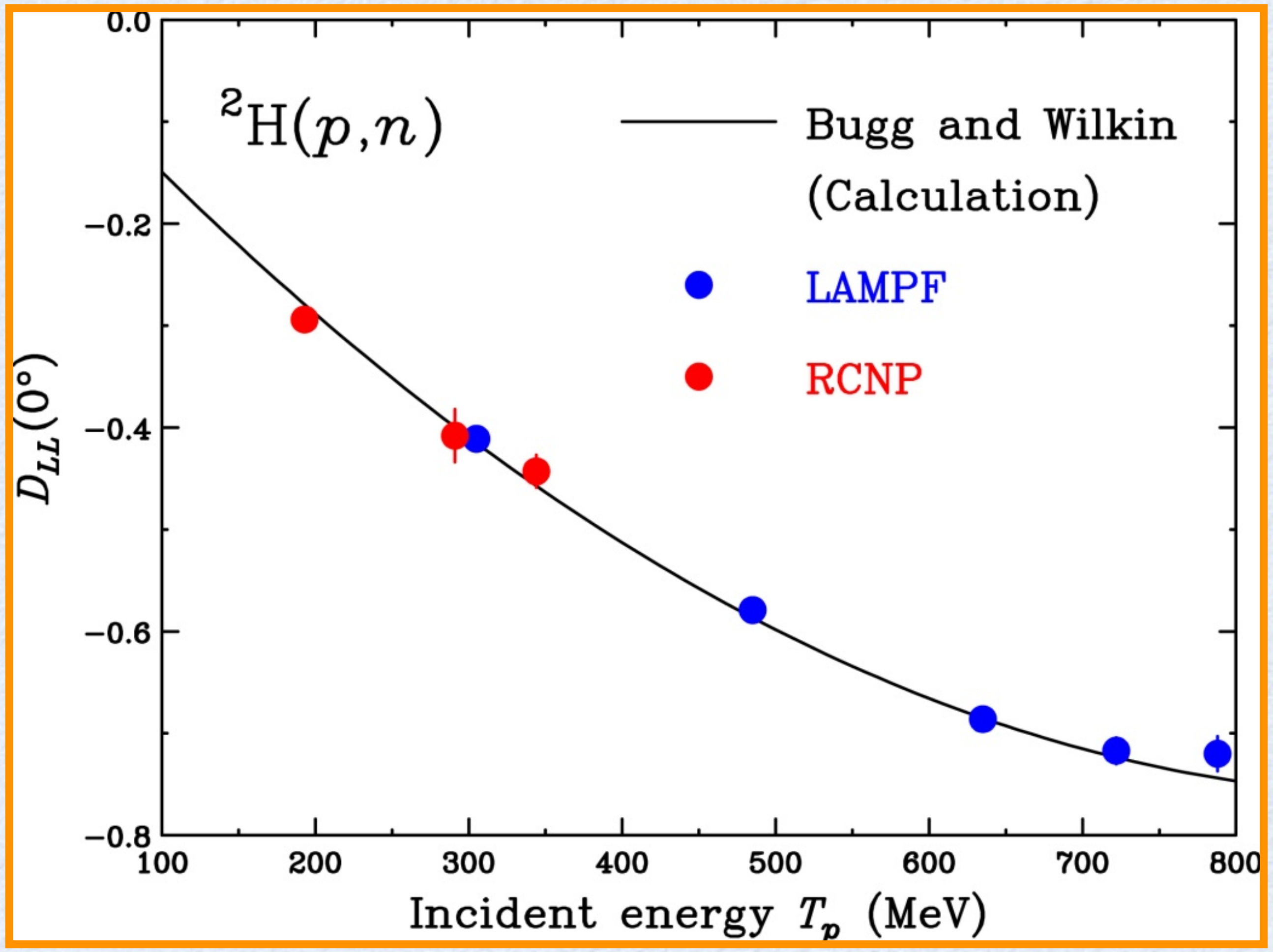
- Neutron polarimeter mode
  - Neutron polarization is determined from asymmetry of n+p events
  - High performance FOM=$1.0\text{x}10^{-4}$

Accuracy of Polarization Measurement

T. Wakasa et al., PRC 77, 054611 (2008).

- Polarization transfer D_{LL} for ^{2}H(p,n)^{2}He at 0deg
  - Benchmark reaction ⇒ accuracy of polarization data
    - Reliable theoretical calculations
    - Reliable experimental data
  - Theoretical calculations (—)
    - Including deuteron D-state
    - Including p-p FSI (^{2}He)
  - LAMPF data (●)
    - Consistent with calculations
    - Calculations are reliable
  - RCNP data (●)
    - Consistent with LAMPF data and calculations

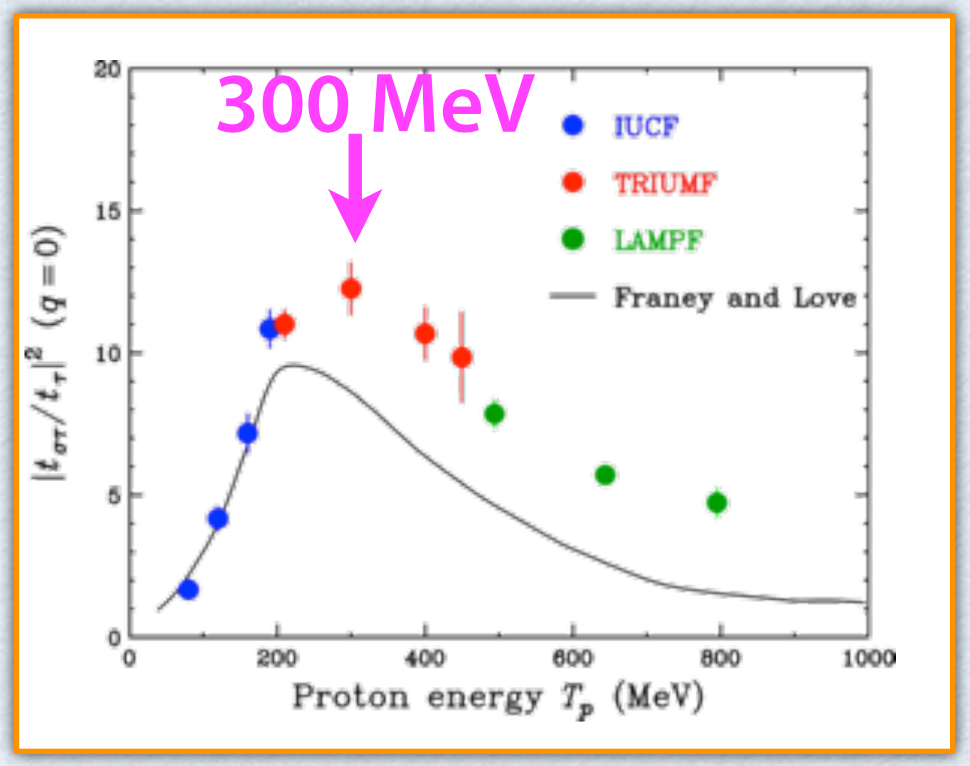
D.V. Bugg and C. Wilkin, NPA 467, 575 (1987).
M.W. McNaughton et al., PRC 45, 2564 (1992).



Our polarization data are reliable and accurate with 3%

Summary of Experimental Conditions

- Beam
  - 296MeV polarized proton
    - Spin-isospin excitations are dominant at small-q
      ⇒ GDR etc. is negligibly small
    - Distortion effects are smallest
      ⇒ Analysis based on DWIA is reliable
    - Current : 500nA, Polarization : 0.59-0.70



- Targets
  - ^{208}Pb: Enriched (>>99% ^{208}Pb) 634 mg/cm^2
  - ^{12}C: natural (98.9% ^{12}C) 140 mg/cm^2
- Obtained spectra
  - ^{208}Pb(p,n)^{208}Bi
    - Polarized c.s. (ID$_i$) at θ=0, 2, 4, 5.5, 7.0 deg
  - ^{12}C(p,n)^{12}N
    - Polarized c.s. (IDi) at θ=0, 2, 4, 6, 9, 12, 15 deg
  - ⇒ MDA has been performed to separate SD J^{π}

Results of ^{208}Pb(p,n)^{208}Bi

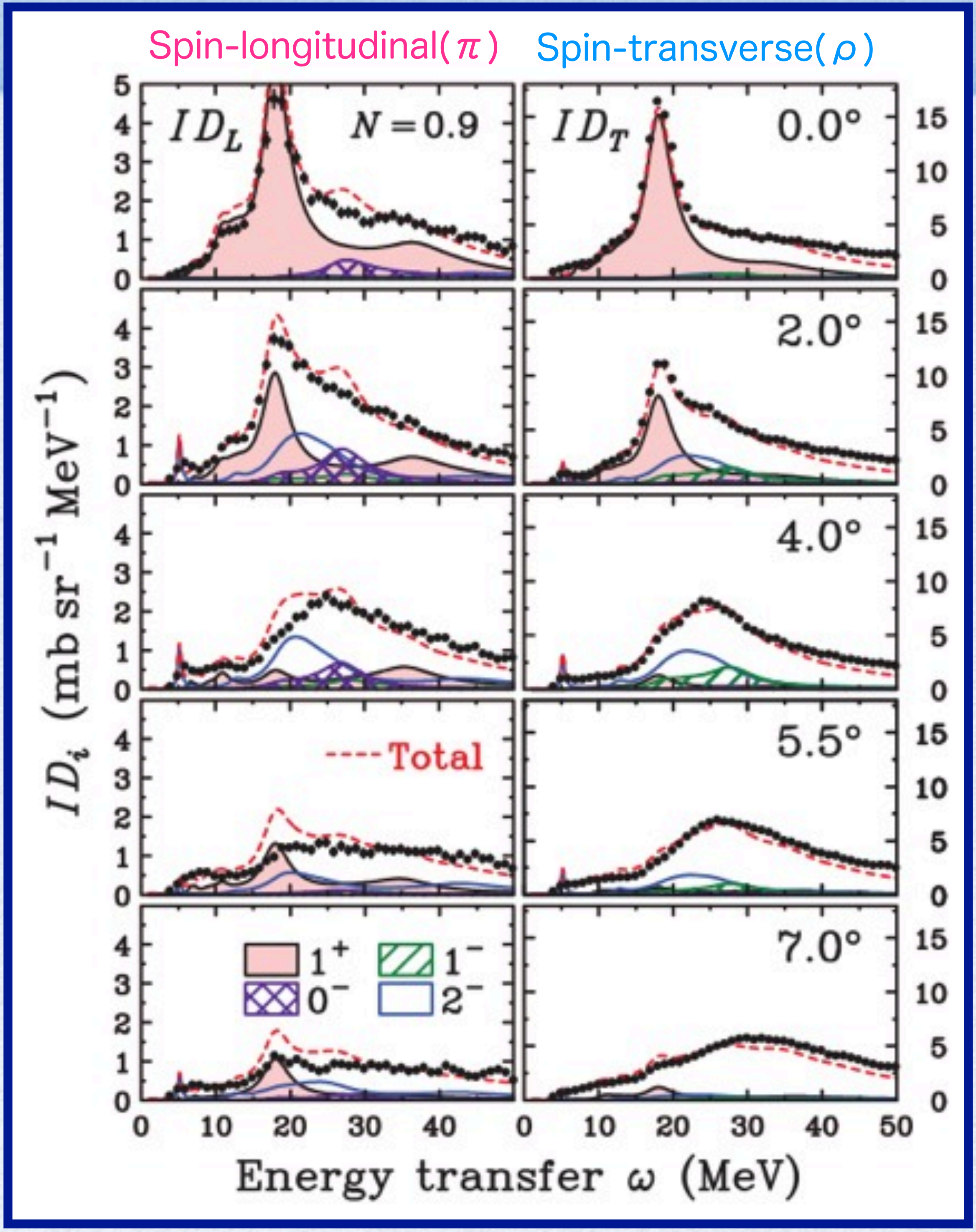
Spin-Dipole Resonances in ^{208}Bi

T. Wakasa, M. Okamoto, M. Dozono et al., PRC 85, 064606 (2012)

Polarized cross sections for ^{208}Pb(p,n)^{208}Bi

Comparison with DWIA+RPA

- DWIA+RPA calc. (up to $J^{\pi}=9^{+}$)
  - Code: crdw by Ichimura group
  - RPA parameters (LM param. g')
    - Determined by GT strength of ^{90}Zr
- GT resonance is dominant at 0^{o}
  - Reasonably reproduced by calc.
- SD resonance is dominant at ~4^{o}
  - Also reasonably reproduced by calc.
  - Some discrepancies can be found
    - Predict 0^{-} bump in ID_{L} at ω~27MeV
      ⇔ Exp. data do not show clear bump
    - ω-dependence is slightly different at 4^{o}

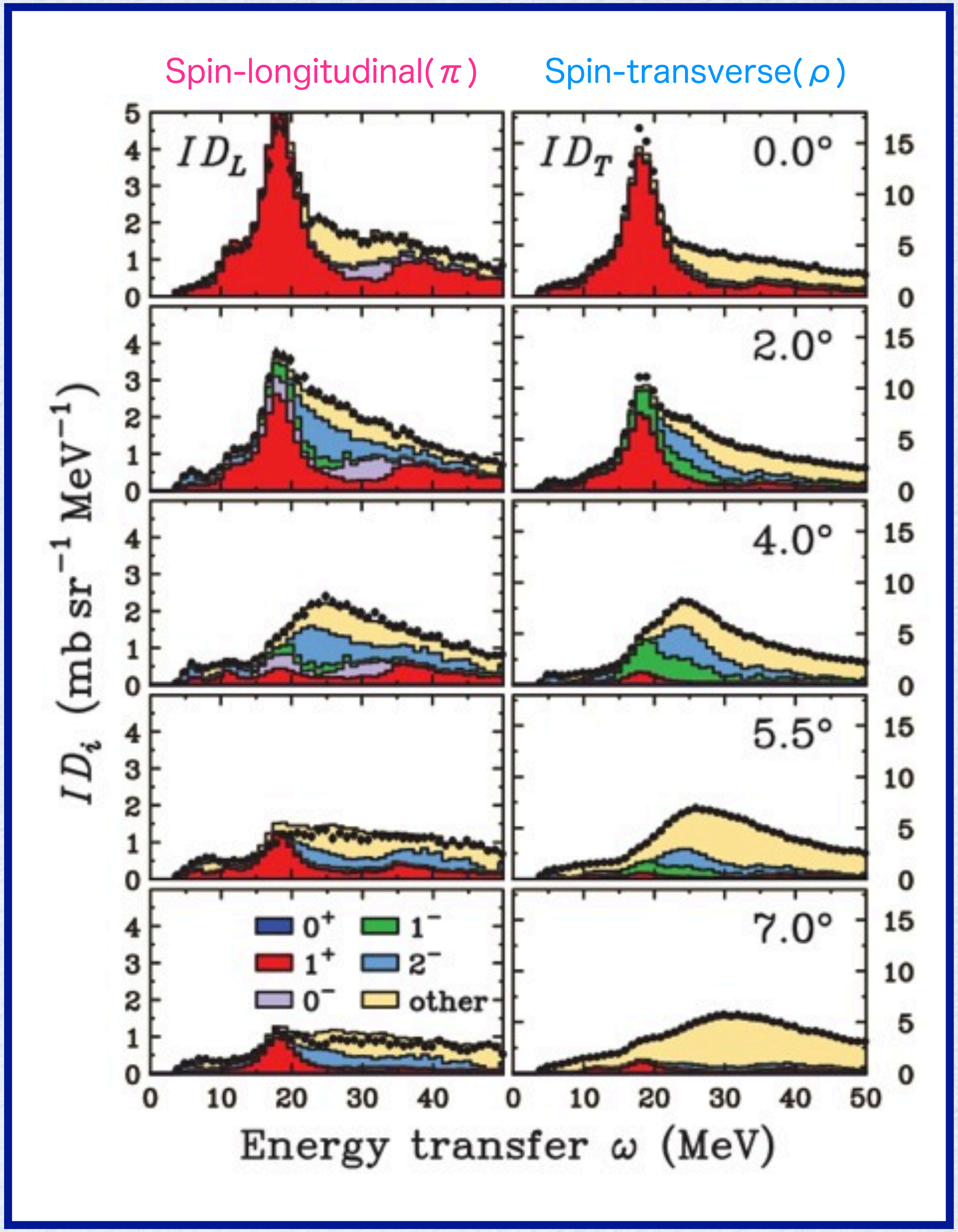


J^{π} structure of SDR is different from that predicted by the present calc.
⇒ Deduce each J^{π} distribution "experimentally" by MDA in ID_{L} and ID_{T}

Results of MDA

- MDA in ID_L and ID_T
  - Reasonably reproduce both ID_i data
  - Proper assignment for GTR

- SD 0^-
  - Significant strength at ω~32 MeV in ID_L
- SD 1^-
  - Two bumps at ω~19 and 25 MeV in ID_T at 4^o
- SD 2^-
  - Broad bump at ω~24 MeV in ID_L and ID_T at 4^o

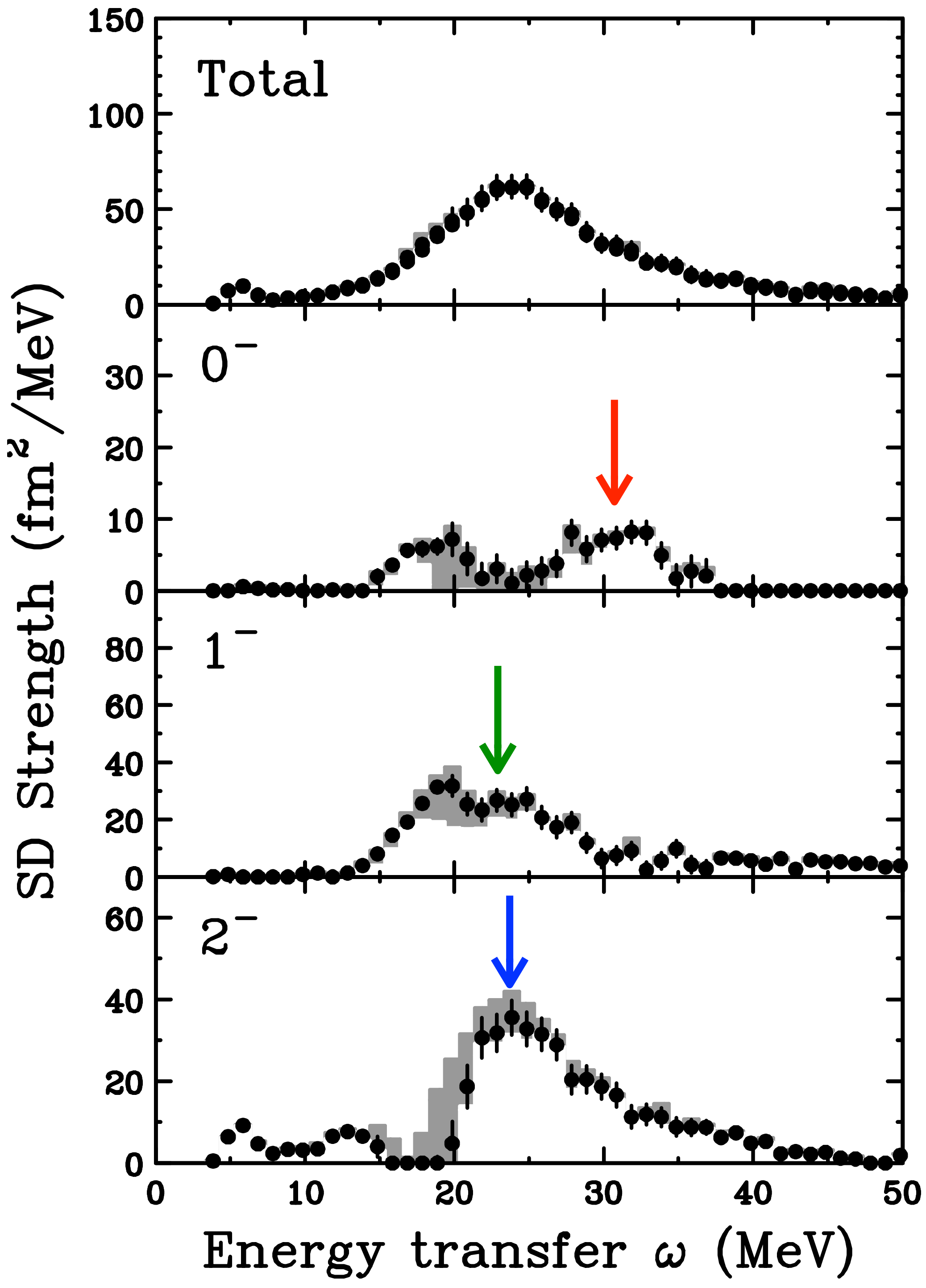


SD Strength Distributions

- Deduce B(SD) from $\sigma(4^{o})$
  - Proportionality relation
    - $\sigma(4^\circ) \simeq \hat{\sigma}_{\mathrm{SD}} B(\mathrm{SD})$
  - $\hat{\sigma}_{\mathrm{SD}}$ is evaluated in DWIA
    - Uncertainty ~ 15%
- Experimental B(SD) from MDA
  - Uncertainties
    - —— : Statistical uncertainty
    - ▨ : MDA uncertainty
    - ~15% systematic uncertainty from σ_{SD}
- J^{π} dependence is clearly observed
  - Exp. data : $E_x(2^-) \sim E_x(1^-) < E_x(0^-)$

    ↕ Inconsistent
  - Simple prediction : $E_x(2^-) < E_x(1^-) < E_x(0^-)$

    (Unperturbed 1p-1h excitation energy)



We compare with the self-consistent HF+RPA calculations including tensor

SD Strength Distributions

C. L. Bai, H. Sagawa et al., PRC 83, 054316 (2011)

- HF+RPA calc. (w/ and w/o tensor)
  - Skyrme-type tensor int.
    - Triplet-Even T :
      Constrained by GT and SD 1^-
    - Triplet-Odd U : Not well constrained

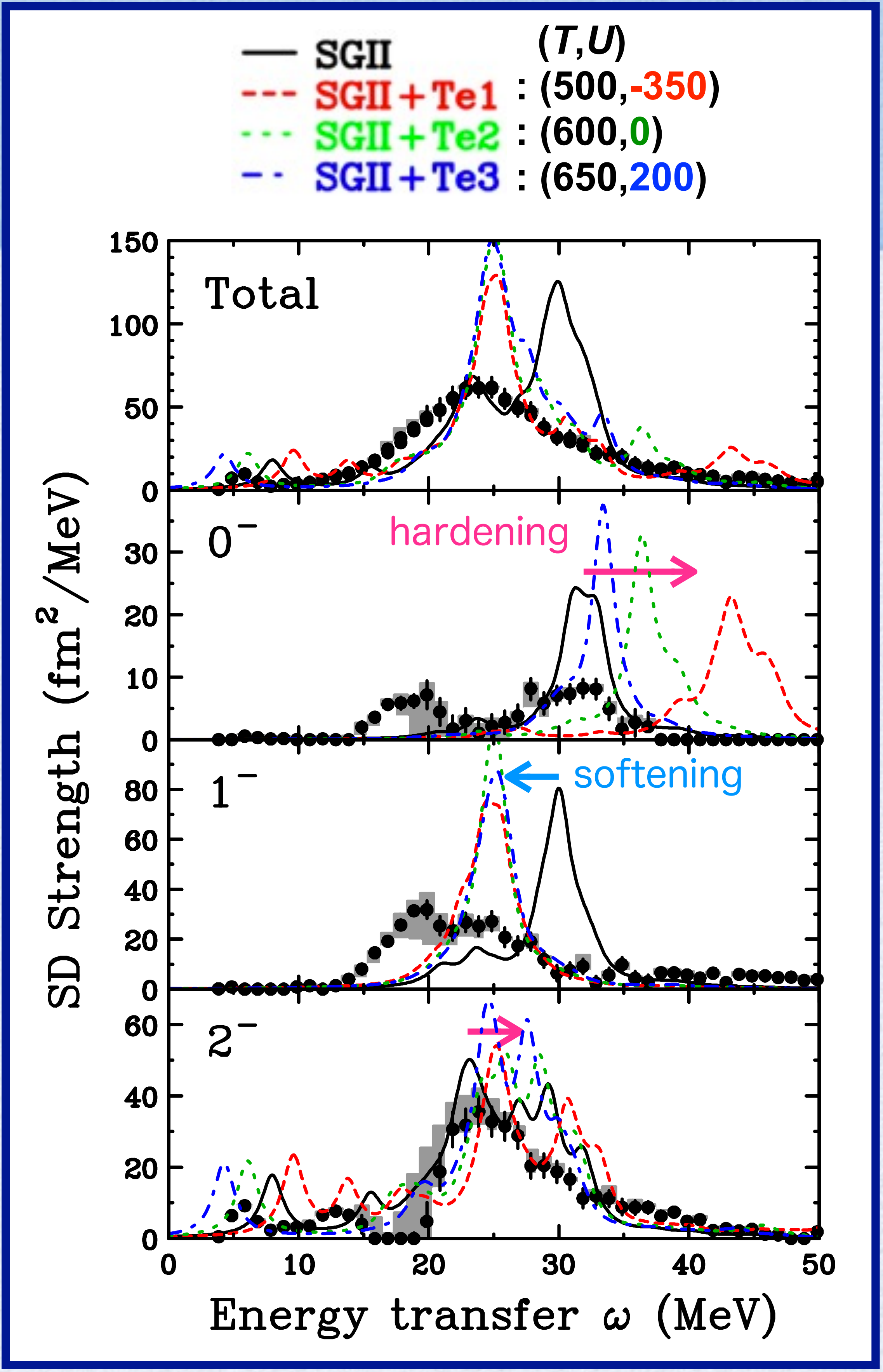
$$V^T = \frac{T}{2}\left\{\left[(\sigma_1\cdot\mathbf{k}')(\sigma_2\cdot\mathbf{k}') - \frac{1}{3}(\sigma_1\cdot\sigma_2)\mathbf{k}'^2\right]\delta(r) + \delta(\mathbf{r})\left[(\sigma_1\cdot\mathbf{k})(\sigma_2\cdot\mathbf{k}) - \frac{1}{3}(\sigma_1\cdot\sigma_2)\mathbf{k}^2\right]\right\}$$

Triplet-Even

$$+\frac{U}{2}\left\{(\sigma_1\cdot\mathbf{k}')\delta(\mathbf{r})(\sigma_2\cdot\mathbf{k}) + (\sigma_2\cdot\mathbf{k}')\delta(\mathbf{r})(\sigma_1\cdot k) - \frac{2}{3}[(\sigma_1\cdot\sigma_2)\mathbf{k}'\cdot\delta(\mathbf{r})\mathbf{k}]\right\}.$$

Triplet-Odd

- Sequence of SDR peak
  - w/o tensor : $E_x(2^-) < E_x(1^-) < E_x(0^-)$
  - w/ tensor : $E_x(2^-) \sim E_x(1^-) < E_x(0^-)$
  - ⇒ Reasonably reproduce exp. data
- SD 0^-
  - Sensitive to Triplet-Odd U
  - Prefers to SGII+Te3 (U is positive)



Present data provides valuable information to determine tensor

Very Preliminary Results of $^{12}C(p,n)^{12}N$

Spin-Dipole Resonances in ^{12}N

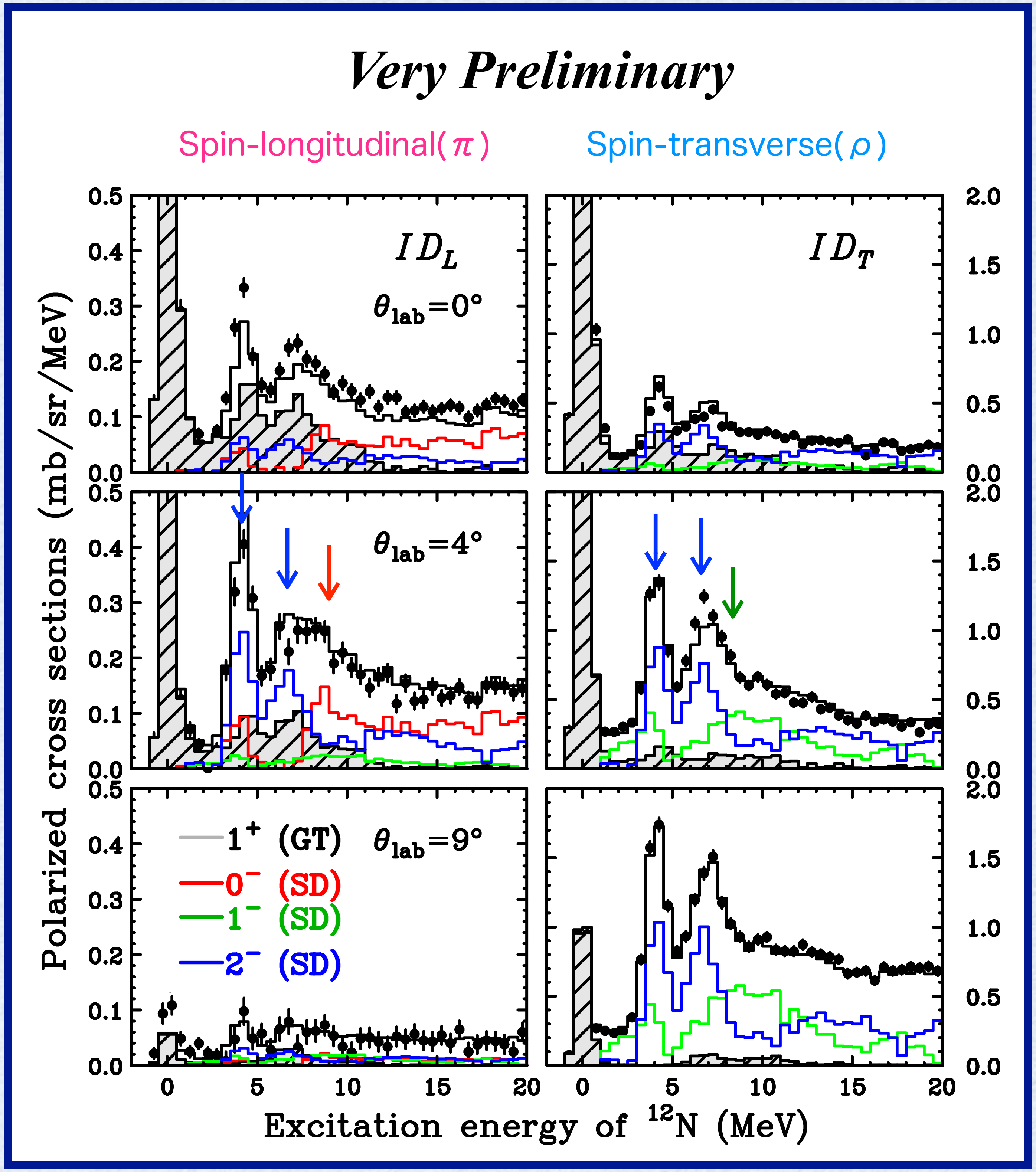
Results of MDA

- MDA in ID$_L$ and ID$_T$
  - Reasonably reproduce both ID$_i$

- SDR at 4 MeV
  - Mainly 2^-
  - Consistent with previous charge-exchange studies

- SDR at 7 MeV
  - Lower-energy side : 2^-
  - Higher-energy side : 0^- and 1^-

- Continuum beyond 10 MeV
  - 0^- and 2^- are dominant in ID$_L$
  - 1^- and 2^- are dominant in ID$_T$



SD Strength Distributions

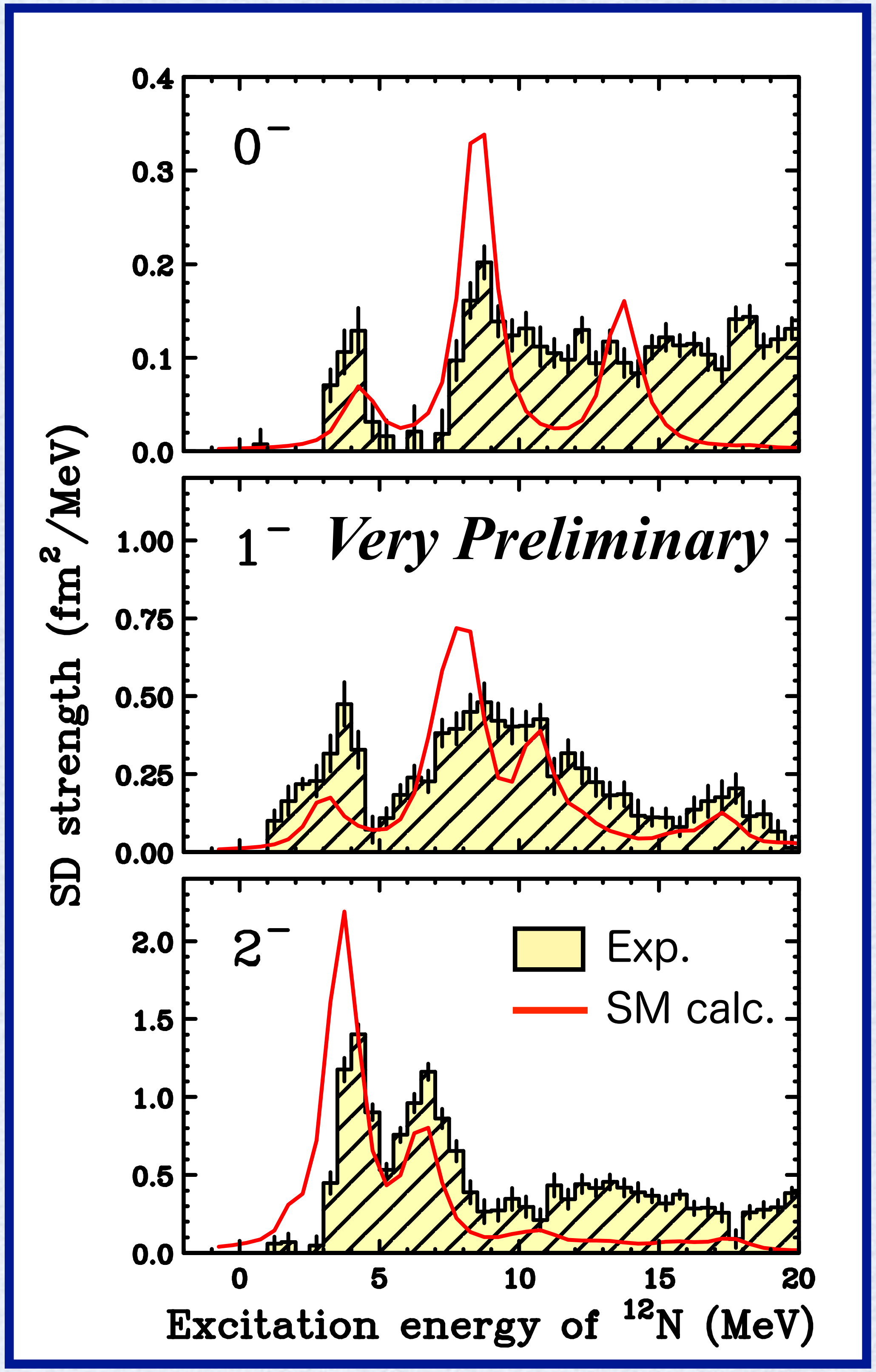
- Deduce B(SD) from $\sigma(4^{\circ})$
  - Proportionality relation
    - $\sigma(4^\circ) \simeq \hat{\sigma}_{\mathrm{SD}} B(\mathrm{SD})$
  - $\hat{\sigma}_{\mathrm{SD}}$ is evaluated in DWIA
    - Uncertainty ~ 15%

- Shell-model calc. (—)

  T. Suzuki et al., PRC 74, 034307 (2006).

  - SFO interaction
    - Modified tensor components
  - Reasonably reproduce all J^{π} distributions

For quantitative understanding, more detailed analyses are needed (in progress)



Summary

- Dynamics originating from tensor force in nuclei
  - Spin-Dipole Resonance is a good approach
- The first data for SDR with NPOL3
  - High statistics data for MDA including polarization observables
- SDR have been separated into each J^{π}
  - ^{208}Bi
    - J^{π}-dependence is clearly evident in the SD strength distributions
      - $E_x(2^-) \sim E_x(1^-) < E_x(0^-)$

      ⇒ Reasonably reproduced by HF+RPA calculations including tensor
  - ^{12}N (Preliminary results)
    - SDR at 4 MeV : mainly 2^-
    - SDR at 7 MeV
      - Lower-energy side (~6MeV) : 2^-
      - Higher-energy side (~9MeV): 0^- and 1^-

Present data and further investigations of SD excitations will provide valuable insight into tensor correlation effects in nuclei

Collaborators

- RCNP-E317 and -E351 collaborators
  - Kyushu University
    - T. Wakasa, M. Okamoto, T. Noro, K. Sagara, Y. Yamada, S. Kuroita, T. Imamura, H. Shimoda, Y. Sueta, T. Yabe
  - RCNP, Osaka University
    - K. Hatanaka, H. Okamura, A. Tamii
  - RIKEN Nishina center
    - H. Matsubara
  - CNS, University of Tokyo
    - K. Yako
  - CYRIC, Tohoku University
    - Y. Sakemi
  - Miyazaki University
    - Y. Maeda, T. Saito, H. Miyasako
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