Decomposing Spin-Dipole Resonances by Complete Polarization Transfer Measurements

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Outline

Giant resonances and spin-dipole (SD) resonances

- Sum-rule (as an introduction)
  - Neutron skin thickness
- Strength distributions
  - Tensor force effects

New data and analysis of ^{208}Pb(p,n)

- Spin-parity decomposition ($J^{\pi}=0^{-}$, 1^{-}, 2^{-}) of SD strengths
- Tensor force effects on SD strengths
  - Softening for 1^{-} by triplet-even tensor force
  - Softening for 0^{-} by triplet-odd tensor force

Summary

Giant Resonances

Collective motion

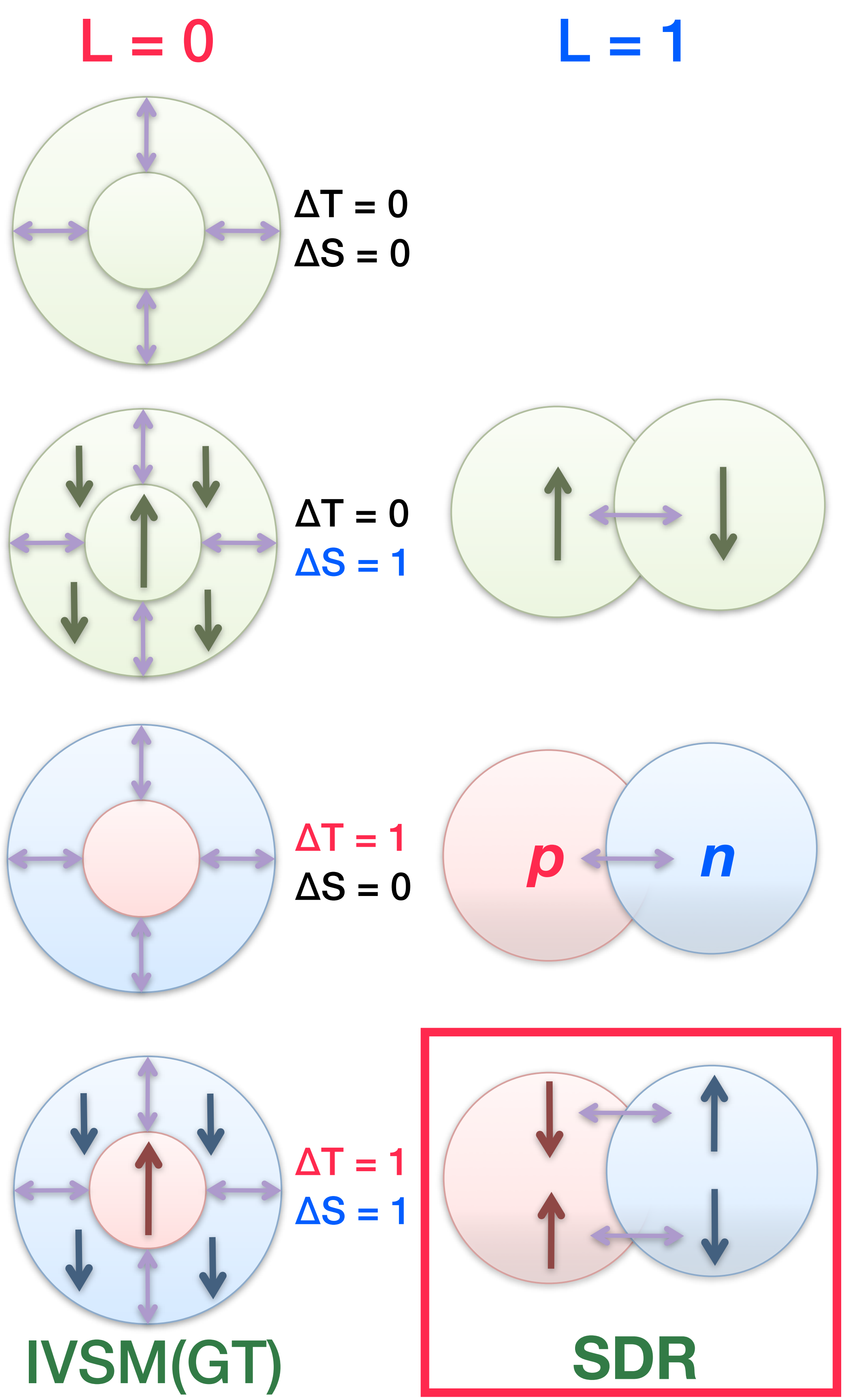
- Many nucleons participate coherently
- Classified by
  - Multipolarity : L
  - Spin : S
  - Isospin : T

IsoVector (IV) Spin-flip Dipole (SD)

- ΔS = 1 and ΔT=1
- Macroscopic picture
  - Dipole oscillation of p↑ (p↓) against n↓(n↑)

Information from GR

- Total strength → Neutron skin thickness
- Resonance peak → Residual interaction



Spin-Isospin Modes and Sum Rule

Spin-isospin transition operators [GR = Coherent 1p1h excitations]

- IV Spin-scalar $\hat{O}_\pm = \sum_k t_\pm(k) f(r_k)$
- IV Spin-vector $\hat{O}_\pm = \sum_\mu \sum_k t_\pm(k)\sigma_\mu(k) f(r_k)$

Model-independent sum-rule

(p,n) (n,p)

$$\underbrace{\sum_m \left|\langle m|\hat{O}_-|0\rangle\right|^2}_{\equiv S^-} - \underbrace{\sum_n \left|\langle n|\hat{O}_+|0\rangle\right|^2}_{\equiv S^+} = \left[N\langle (f(r))^2\rangle_n - Z\langle (f(r))^2\rangle_p\right] \times \begin{cases} 1 & \text{: scalar} \\ 3 & \text{: vector} \end{cases}$$

neutron proton

SD sum-rule (ΔL = ΔS = ΔT = 1)

- $S_- - S_+ = \frac{9}{4\pi}(N\langle r^2\rangle_n - Z\langle r^2\rangle_p)$

from charge radius

Sum-rule value gives

- rms radius of neutron distribution: $\sqrt{\langle r^2\rangle_n}$
- neutron skin thickness: $\delta_{np} = \sqrt{\langle r^2\rangle_n} - \sqrt{\langle r^2\rangle_p}$

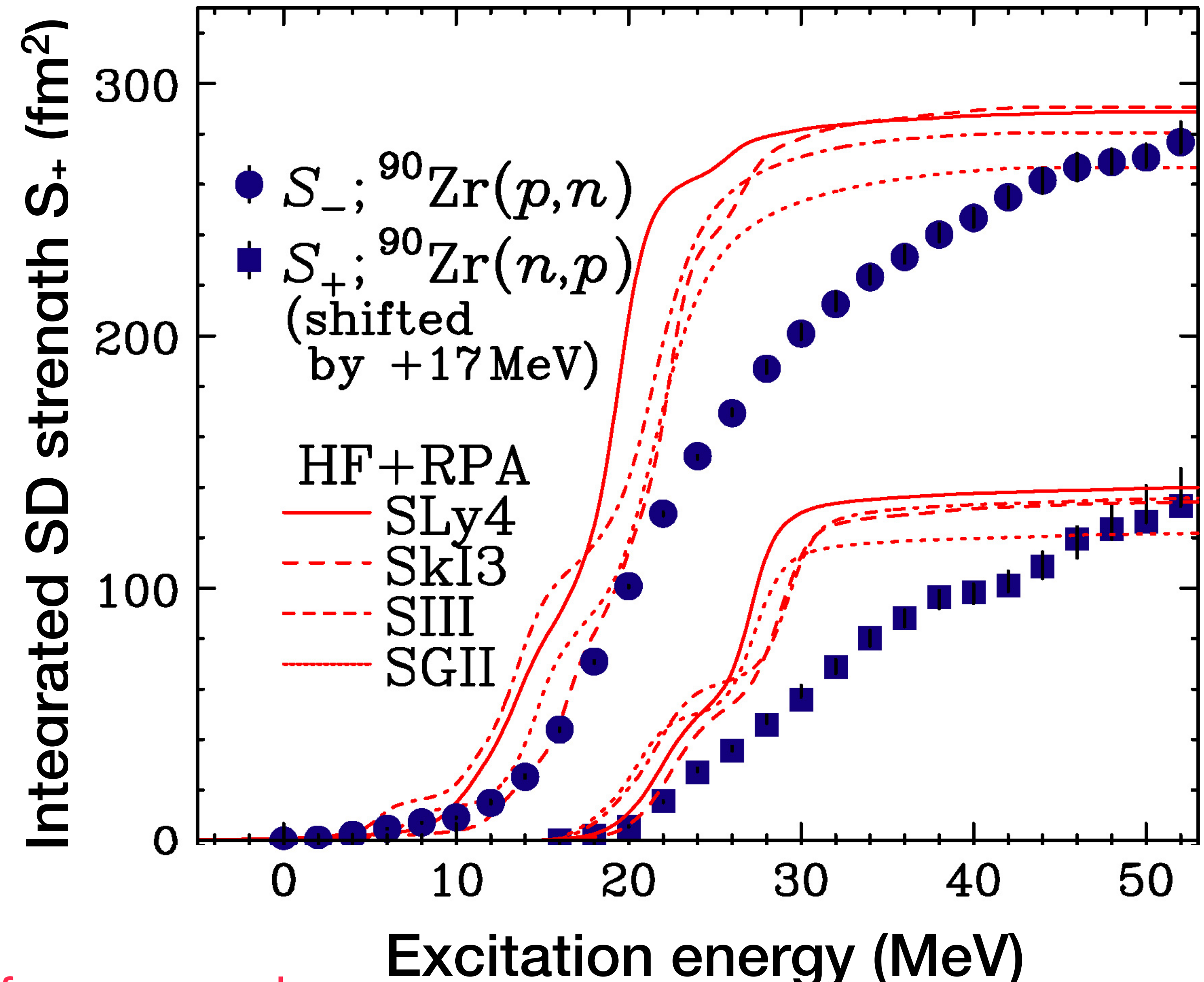
SD sum-rule and neutron skin thickness

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

Running sum of SD strength

$$S_{\pm} = \int_0^{E_x} \frac{dB(\mathrm{SD}_{\pm})}{dE} dE$$

- Exp. values approach HF+RPA values at 50 MeV



Sum-rule value

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

Rms radius

- $\sqrt{\langle r^2 \rangle_p} = 4.19\ \mathrm{fm}$
- $\sqrt{\langle r^2 \rangle_n} = 4.26 \pm 0.04\ \mathrm{fm}$ from sum-rule

- Neutron skin thickness : $\delta_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p} = 0.07 \pm 0.04\ \mathrm{fm}$
  - cf. goal of parity violation electron scattering: ±0.04 (1%)
- How about SD strength distributions?

SD strength distributions

Exp. strength

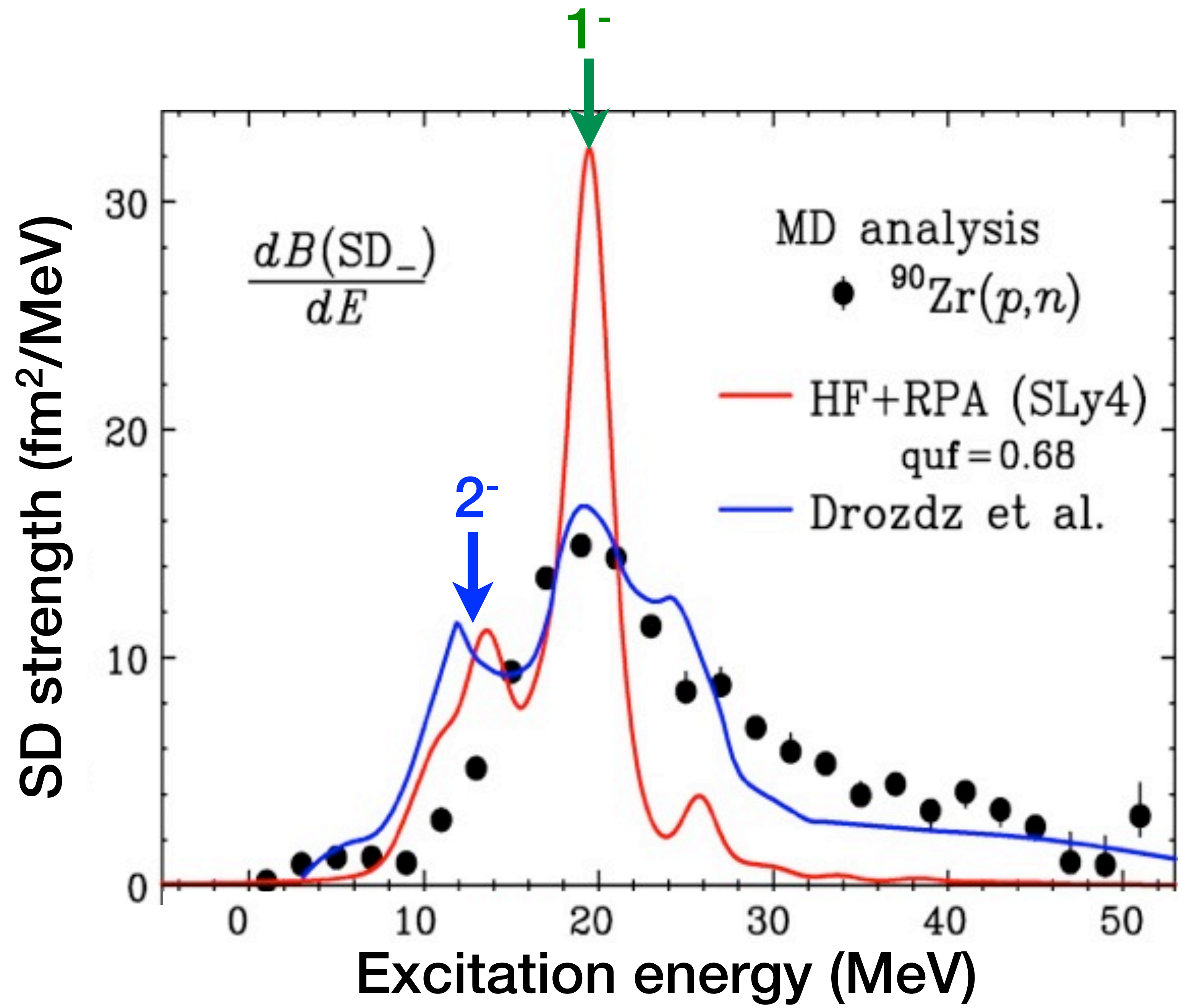
- Extends up to 50 MeV
  - Configuration mix.
- SIngle bump

HF+RPA (1p1h)

- Underestimation at E_x > 25 MeV
  - 2p2h is important
- Three bumps
  - $E_x(2^-) > E_x(1^-)$

Second-order RPA

- Reasonably reproduce in whole region
- Three bumps



Each ΔJ$^\pi$ (0^-, 1^-, 2^-) distributions → Inconsistent (tensor correlation?)

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

Tensor force effects in nuclei

Shell-structure due to tensor force

- Due to tensor correlations, excess neutrons ($j_>$)
  - Pull-down proton orbit with $j_<$
- Experimental data for Sb are well reproduced

Tensor effects in Skyrme int.

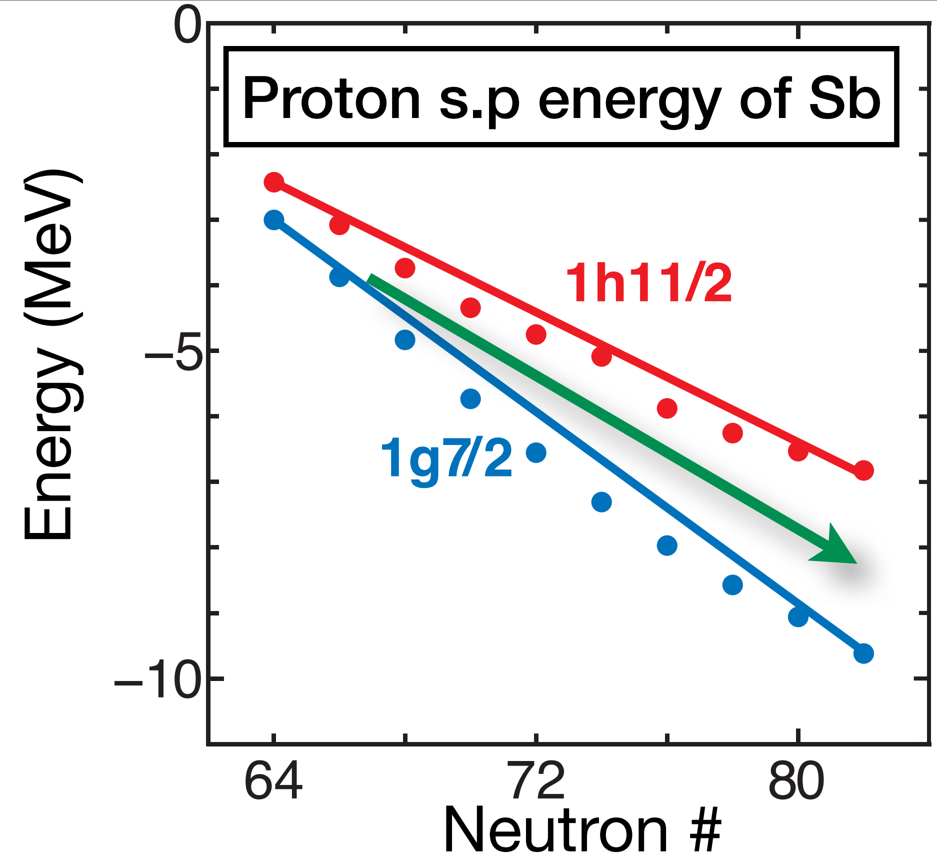
- Additional contribution to normal spin-orbit pot.

central ex. / tensor (pp); central ex. / tensor (pn)

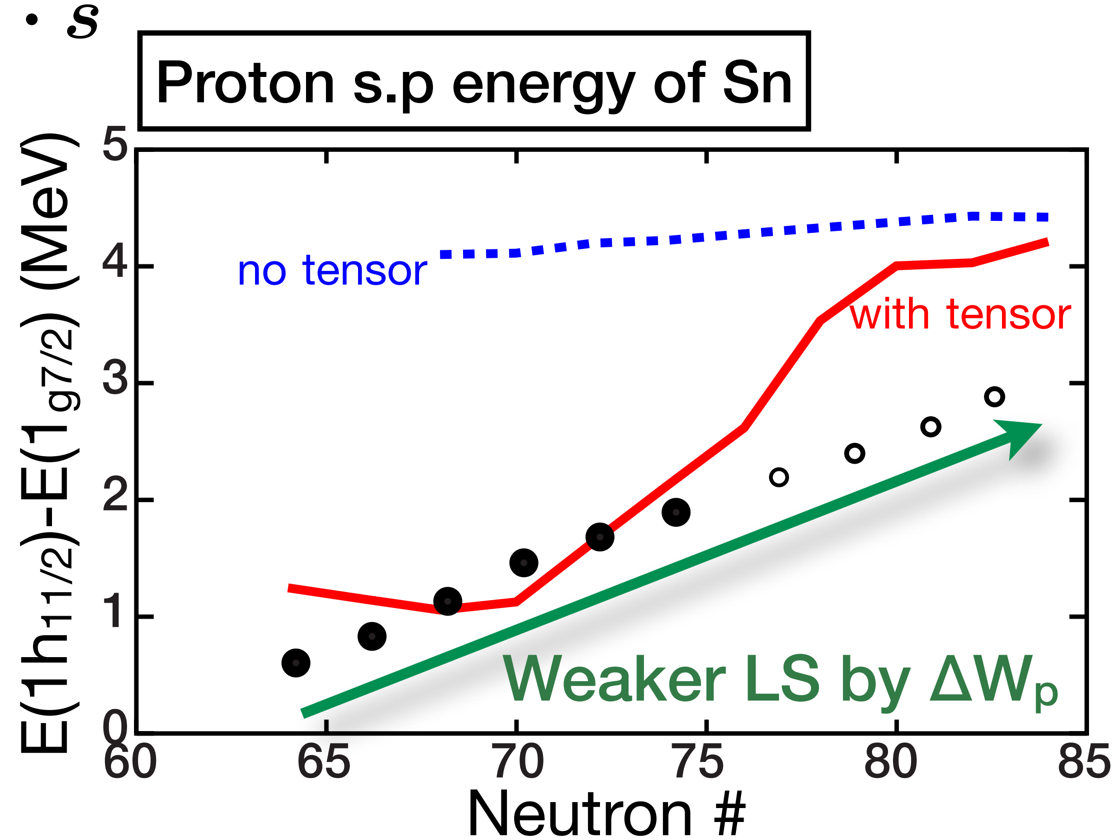
$$\Delta W_p = [\underbrace{(\alpha_C + \alpha_T) J_p}_{pp} + \underbrace{(\beta_C + \beta_T) J_n}_{pn}]\vec{l}\cdot\vec{s}$$

  - $\beta \equiv \beta_C + \beta_T \simeq 120\,\mathrm{MeV}\cdot\mathrm{fm}^5$
  - $\alpha \equiv \alpha_C + \alpha_T \simeq 120\,\mathrm{MeV}\cdot\mathrm{fm}^5$
- Tensor terms depend on central-ex. terms
- Negative α values are also proposed

Further exp. informations are important



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



D.M. Brink and FL. Stancu, PRC 75, 064311(2007).

Tensor force effects on SD strengths

HF+RPA prediction for ^{208}Pb

- HF : Tensor forces hardly change LS splitting [(nn/pp contribution) + (np contribution) ~ 0]

- RPA : Tensor effects depend on J^{π}

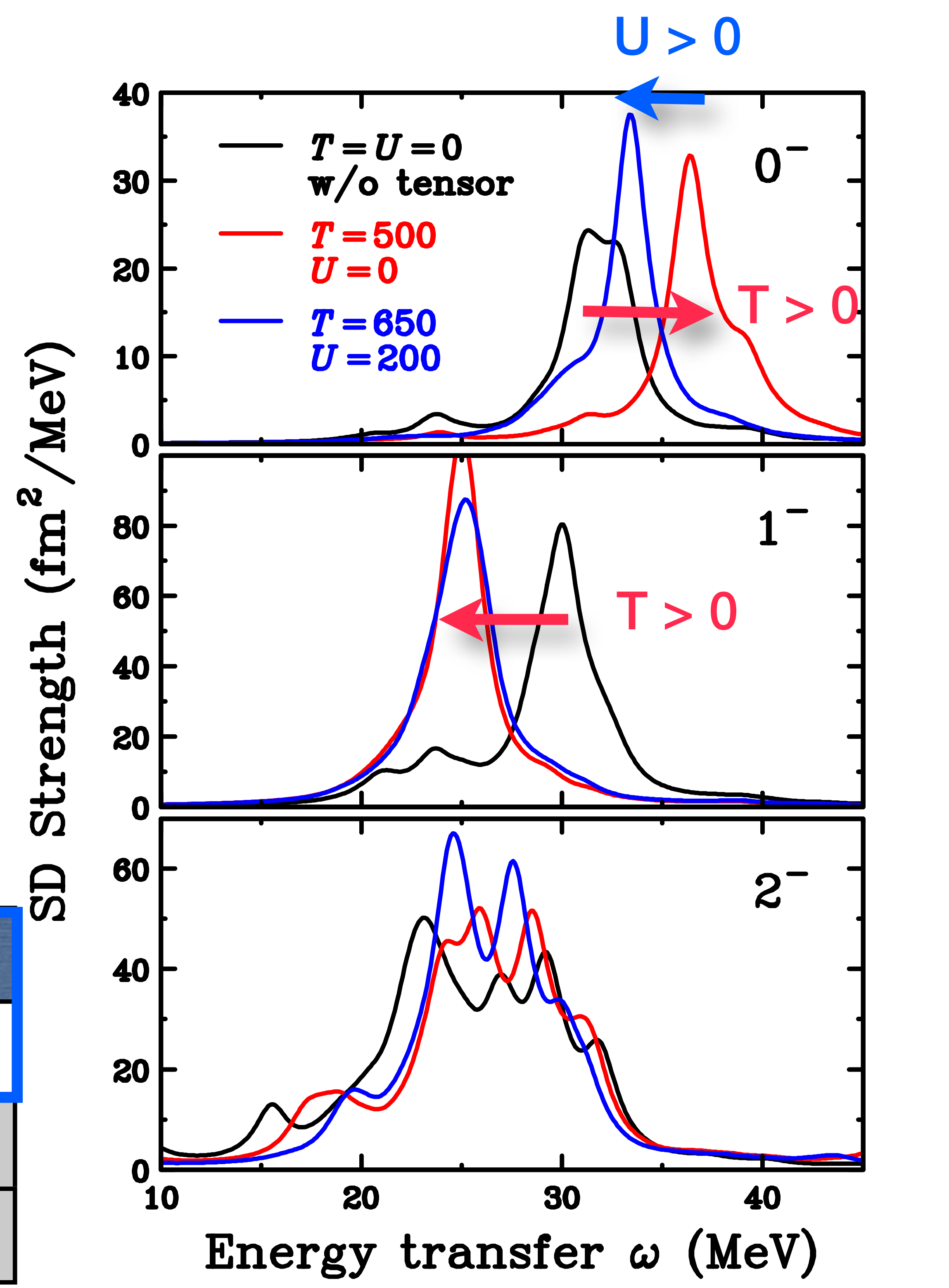
$$V^T \propto \underline{T(\mathrm{TE})} + \underline{U(\mathrm{TO})}$$

triplet-even triplet-odd

$$\alpha_T = \frac{5}{12} U \text{ for } nn/pp$$

$$\beta_T = \frac{5}{24} (T + U) \text{ for } np$$

	T>0 (β_T>0)	U>0 (α_T>0)	U<0 (α_T<0)
0^-	hardening	softening	hardening
1^-	softening	insensitive	
2^-	insensitive		



Separated SD strengths would constrain both T and U (α_T and β_T)

This "experimental" work for ^{208}Pb(p,n)

New data and analysis for ^{208}Pb(p,n)

- Cross sections and analyzing powers at $\theta = 0.0° \sim 10.0°$ (11 angles)
- Complete sets of polarization transfers at $\theta = 0.0° \sim 7.0°$ (5 angles)

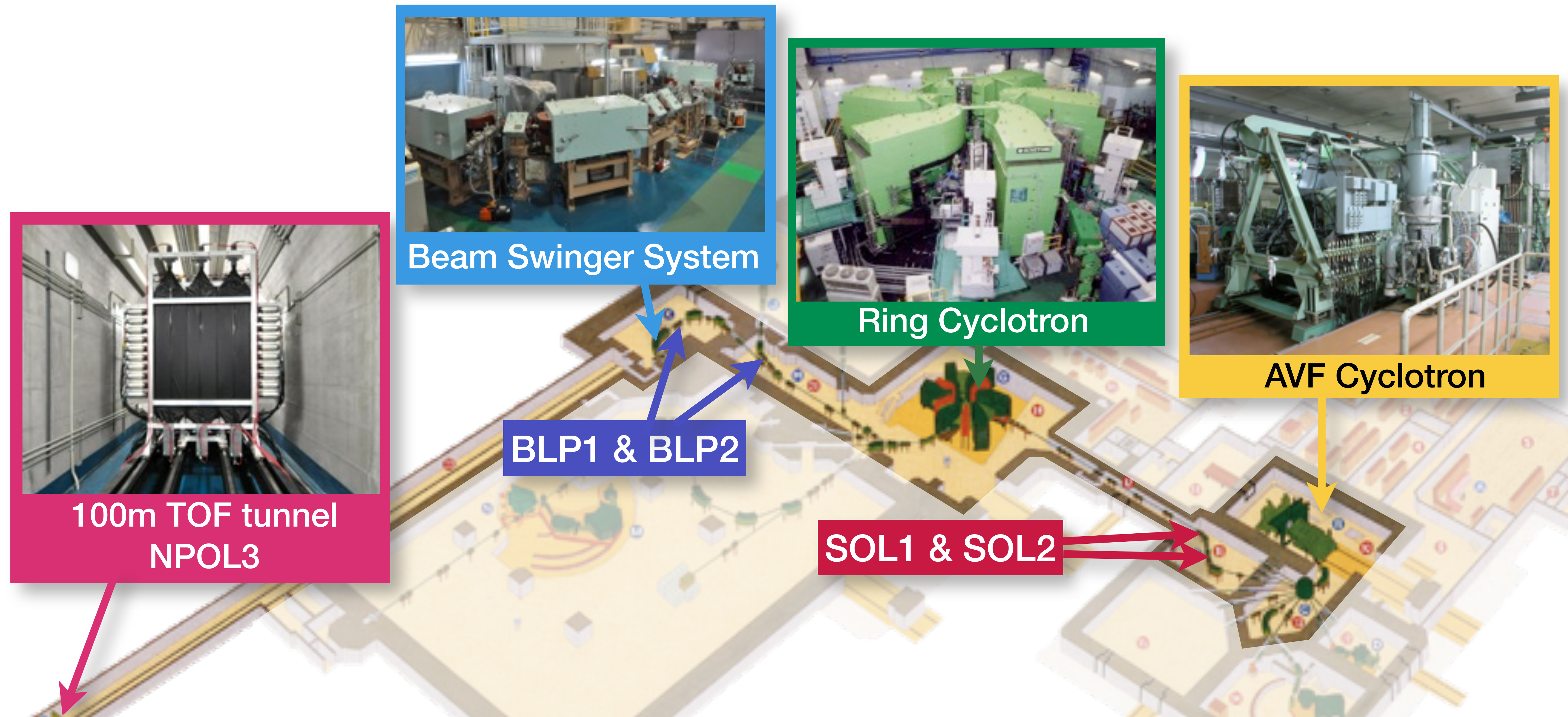
Goal

- Spin-parity J^π separated SD strengths for ^{208}Pb
  - Distribution of separated SD strengths
    - Tensor correlation effects on SD strengths
  - Quenching of separated SD strengths
    - J^π dependence
      (c.f. total SD strength is not quenched for ^{90}Zr)

Tools

- Polarization transfer D_{ij}
  - Sensitive to ΔJ^π (0^-, 1^-, 2^-)
- Multipole decomposition analysis (MDA) with D_{ij}
  - Based on reliable DWIA+RPA calculations

Ring Cyclotron Facility @ RCNP, Osaka



300 MeV polarized protons

- Smallest distortion

Beam polarization

- Controlled by two solenoids
- Measured by two BLPs (p+p)

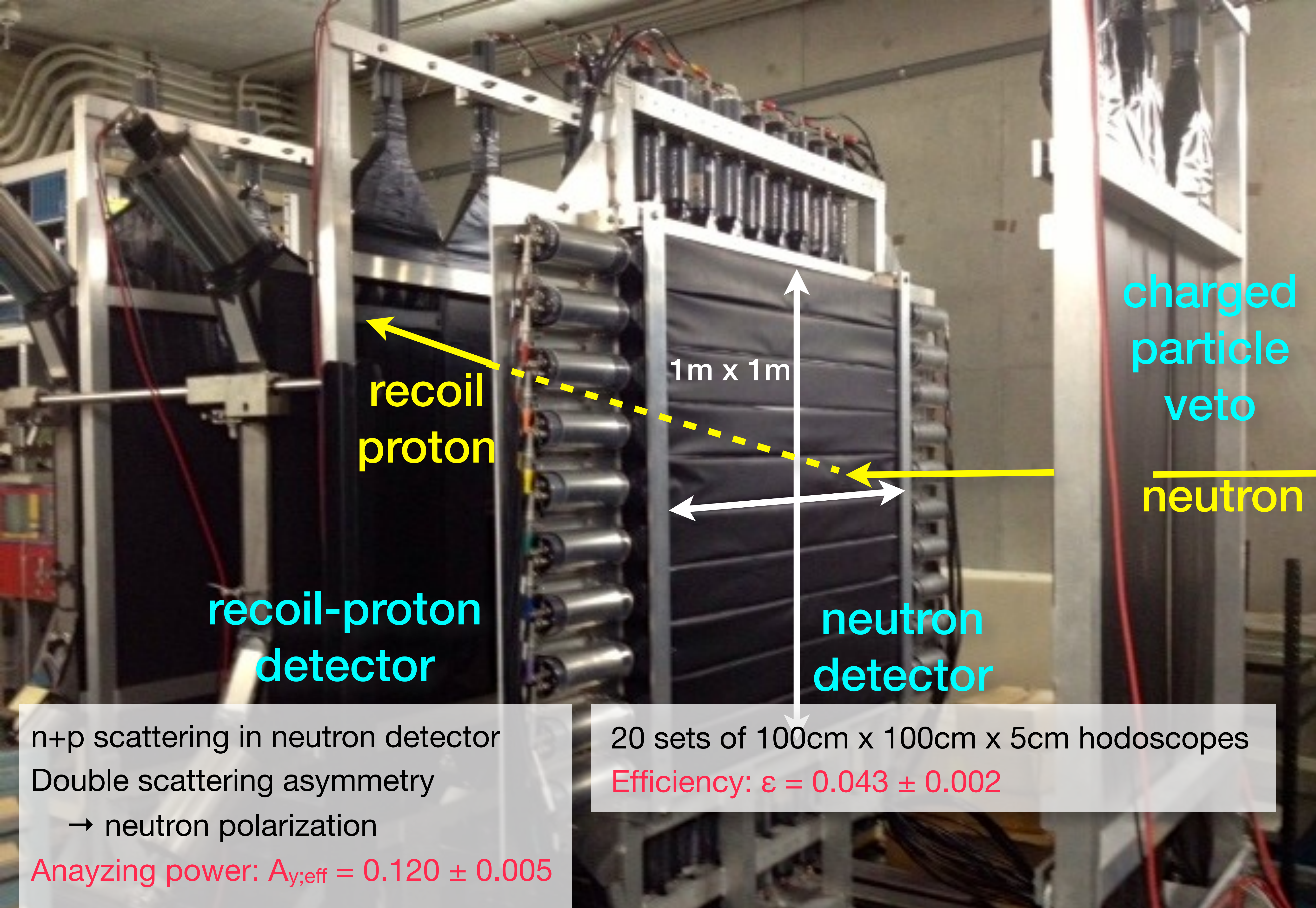
Beam swinger

- $\Theta = 0° - 10°$

Neutron measurement

- NPOL3 with 70m TOF
- D_{ij} measurement with NSR

Neutron detector/polarimeter NPOL3



n+p scattering in neutron detector
Double scattering asymmetry
→ neutron polarization
Anayzing power: $A_{y;eff} = 0.120 \pm 0.005$

20 sets of 100cm x 100cm x 5cm hodoscopes
Efficiency: $\varepsilon = 0.043 \pm 0.002$

Results —Polarized cross section—

Separate into 3 components using D_{ij}

$$I = \boxed{ID_0} + \boxed{ID_L} + \boxed{ID_T}$$

non-spin longitudinal transverse

- ID_L : unnatural parity (0^- and 2^- for SD)
- ID_T : both parities (1^-, 2^- for SD)
- 0^- contributes to ID_L only (special case)

Example at 0°

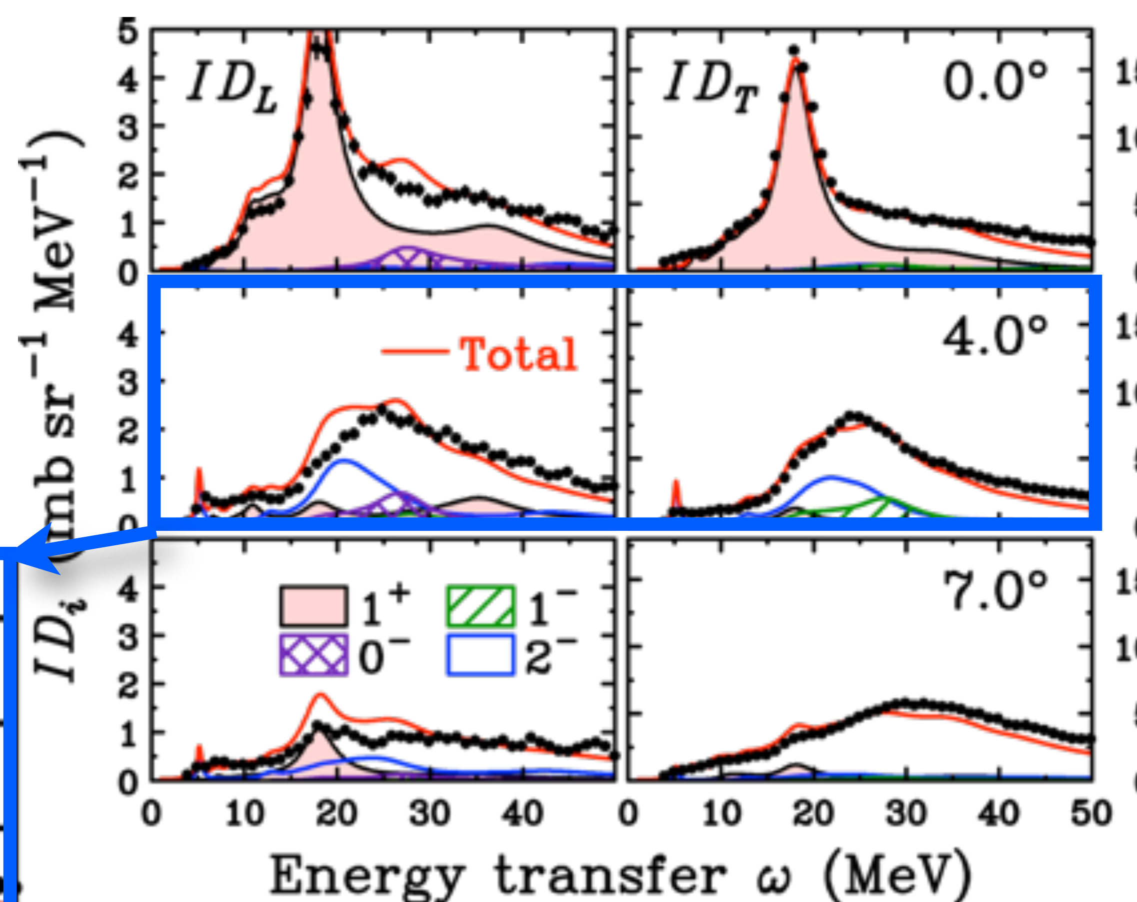
$$ID_L = \frac{I}{4}(1 - 2D_{NN} + D_{LL})$$

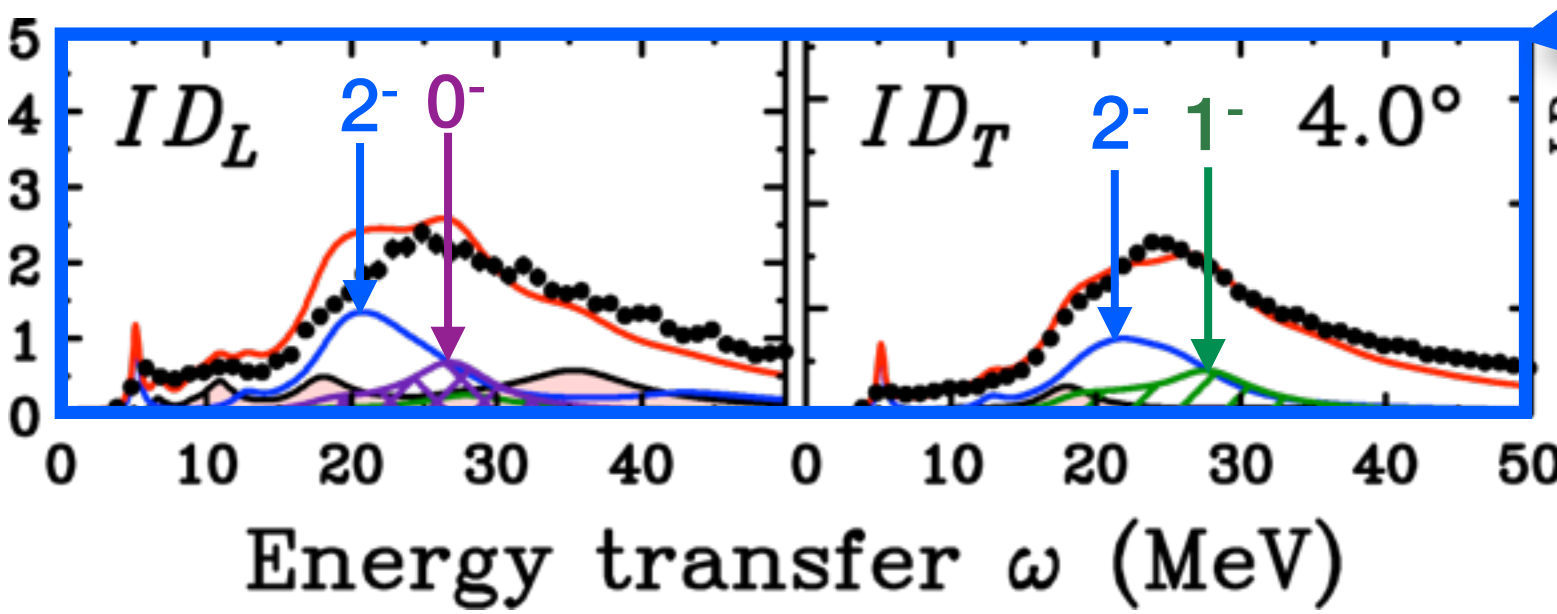
$$ID_T = \frac{I}{2}(1 - D_{LL})$$

Comparison with DWIA+RPA at 4°

- Exp: Narrow bump in both ID_L and ID_T
- Theory : Broad bump [$\omega(2^-) < \omega(1^-) \sim \omega(0^-)$]

→ MDA should be performed





Separation of SDR into each J^{π}

Separation of SDR (L=1) into 0^-, 1^-, 2^- is important

- Tensor effects depends on J^{π}

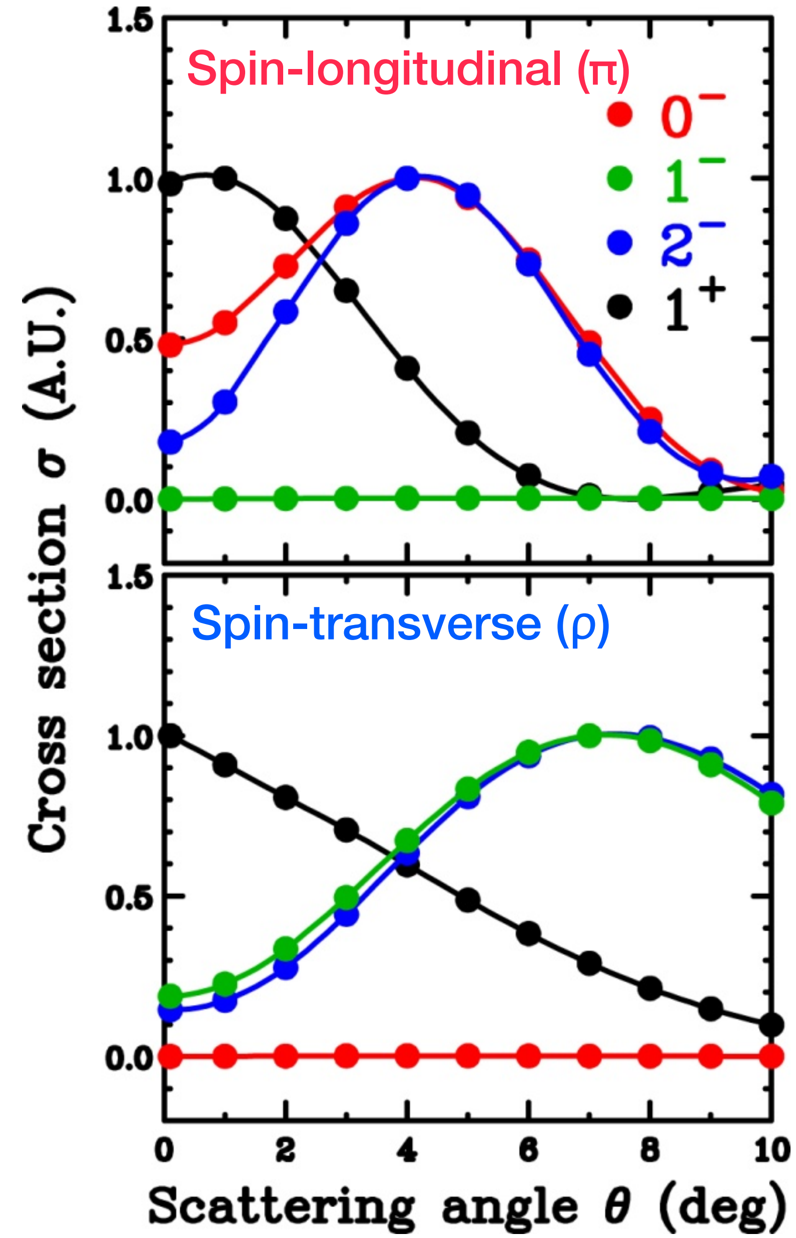
Normal multipole decomposition

- 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

DWIA prediction

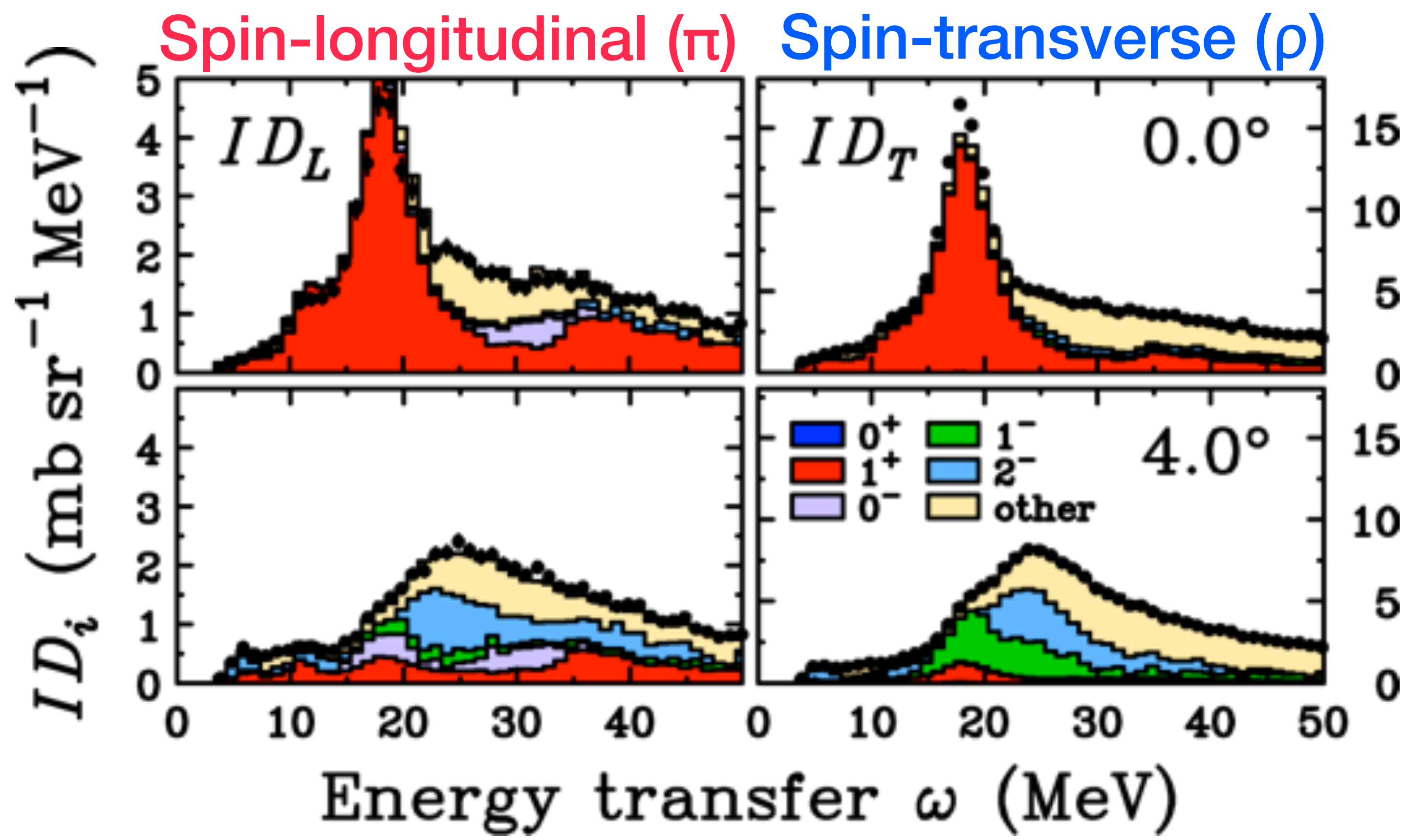


Multipole decomposition for longitudinal (π) and transverse (ρ) c.s.
→ Can separate/specify not only L, but also J^{π}

Results of multipole decomposition

L=0 (GT) contribution

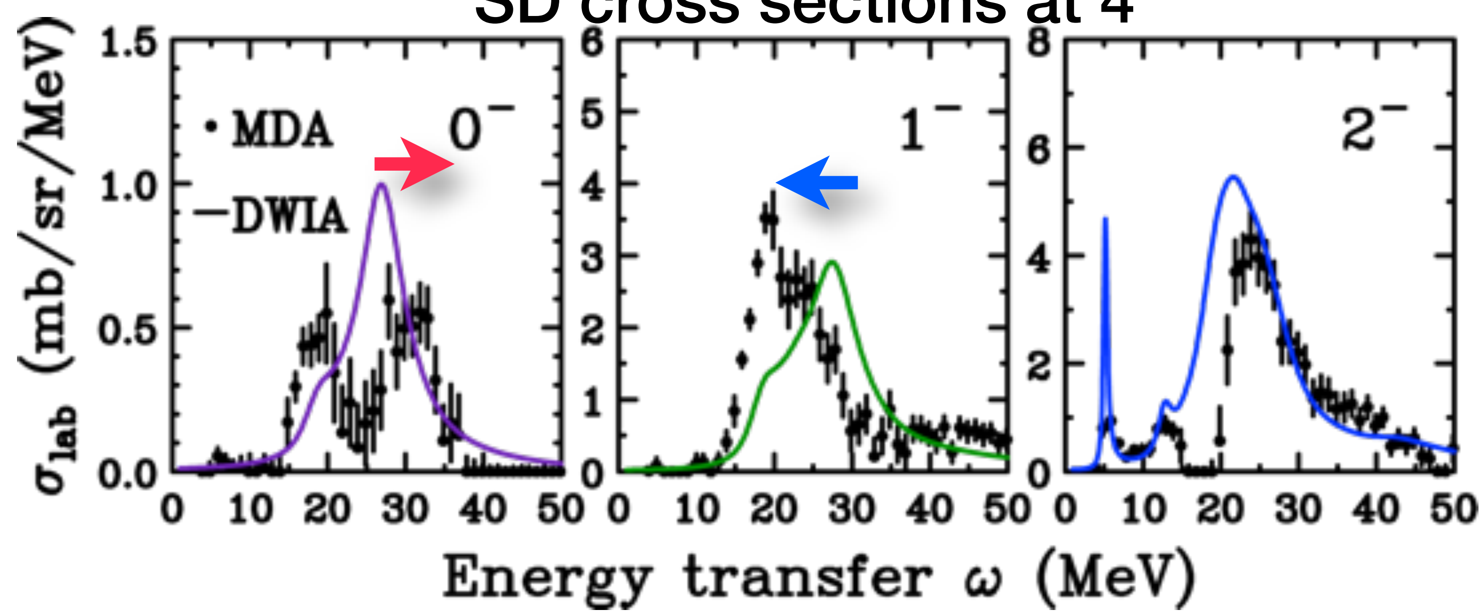
- Large contribution up to 50 MeV
  - Configuration mixing (2p2h)
  - IVSM contribution



L=1 SD (0^-, 1^-, 2^-) contributions

- Theory : $\omega(2^-) < \omega(1^-) \sim \omega(0^-)$
- Exp. : $\omega(2^-) \sim \omega(1^-) < \omega(0^-)$
- Softening on 1^-

SD cross sections at 4°



- Multipole (J^π) decomposition is successful
- J^π dependence on SD resonances could not be reproduced
  - Signature of tensor force effects ?

SD strengths and tensor force effects

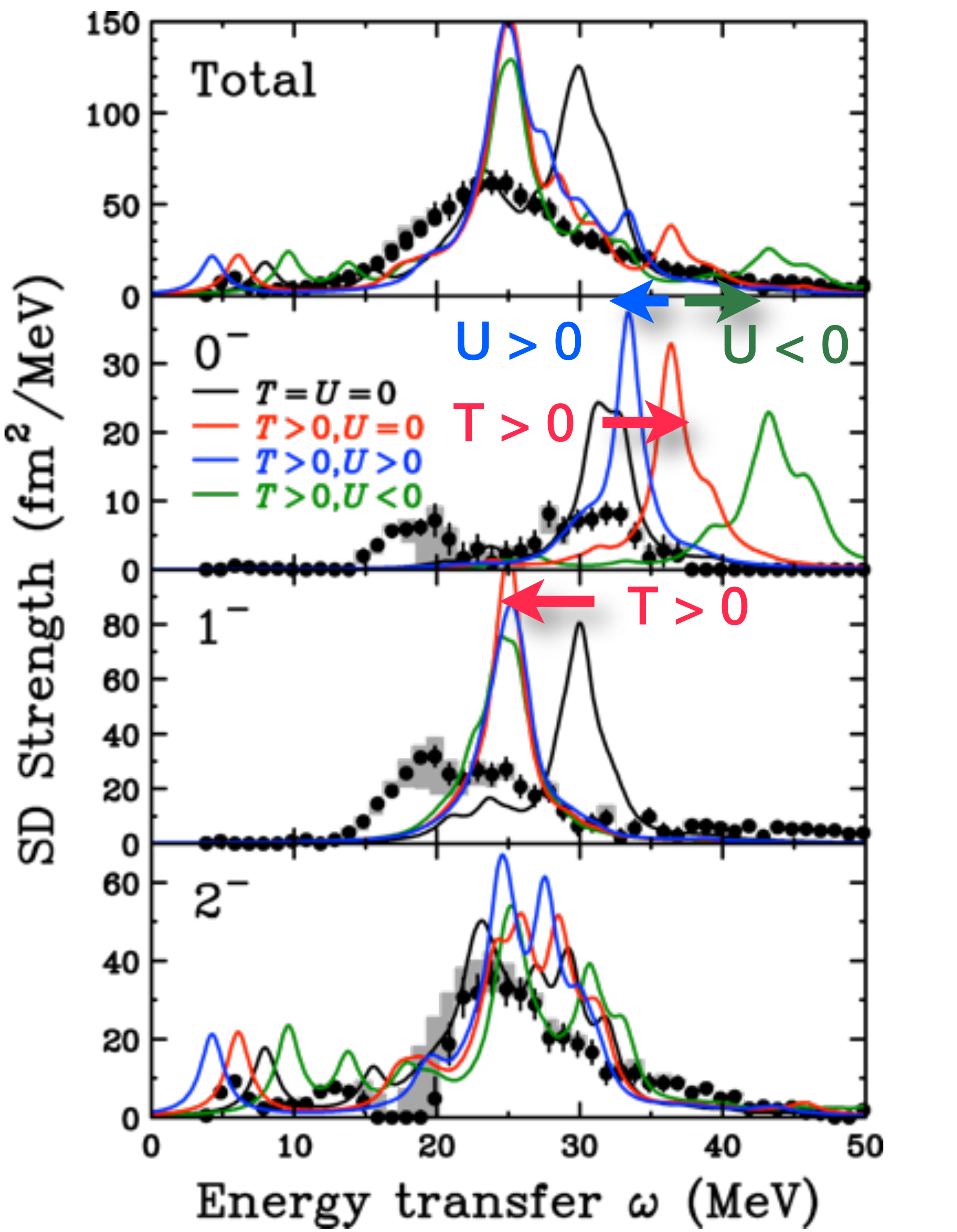
Tensor force effects on SDR

$$V^T \propto \underline{T(\mathrm{TE})} + \underline{U(\mathrm{TO})}$$

triplet-even triplet-odd

	T>0	U>0	U<0
0-	hardening	softening	hardening
1-	softening	insensitive	
2-	insensitive		

- T(TE) > 0 tensor interaction
  - **Softening for 1- : $\omega^{calc.} \sim \omega^{exp.}$**
  - Hardening for 0- : $\omega^{calc.} > \omega^{exp.}$
- T(TE) > 0 + U(TO) > 0 tensor interaction
  - **Softening for 0- : $\omega^{calc.} \sim \omega^{exp.}$**
- T(TE) > 0 + U(TO) < 0 tensor interaction
  - Hardening for 0- : $\omega^{calc.} >> \omega^{exp.}$



- **Softening on 1- is reproduced by T>0**
- **Tensor effect on 0- is weak**
  - **Hardening by T>0 should be cancelled by softening by U>0**

•T(TE) ～ 650 MeV fm⁵
•U(TO) ～ 200 MeV fm⁵

Summary

New experimental data for ^{208}Pb(p,n)

- Cross sections and analyzing powers at $\theta = 0.0° \sim 10.0°$ (11 angles)
- Complete sets of polarization transfers at $\theta = 0.0° \sim 7.0°$ (5 angles)

Extended multipole decomposition (MD) analysis

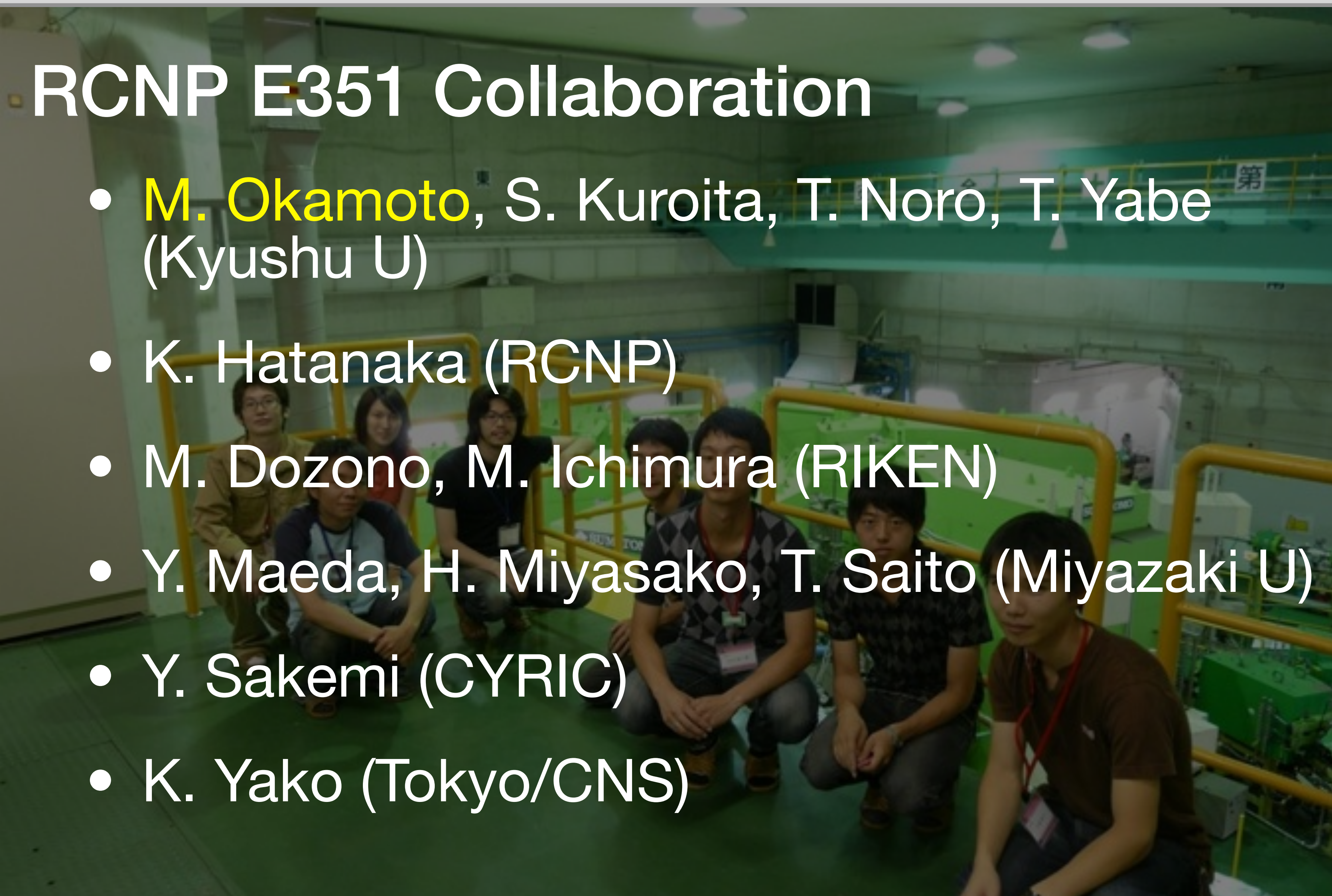
- Polarization observables were used, for the first time, in MD analysis
  - Reasonable agreement with experimental data
- Successful separation into individual J^{π} components

SD strength for ^{208}Pb

- Softening effect for 1^-
  - T(TE) $\sim$ 650 MeV fm^5 ($\beta_T \sim$200 MeV fm^5)
- Small effect for 0^- (= hardening effect by T(TE) is NOT observed)
  - Hardening effect by T should be cancelled by softening effect by U>0
  - U(TO) $\sim$ 200 MeV fm^5 ($\alpha_T \sim$ 100 MeV fm^5)
- Similar to β_T=238 MeV fm^5 and α_T=135 MeV fm^5 by low-q limit of G-matrix calc.

First exp./theor. findings for **"tensor force effects in nuclear spin excitations"**

Neutron Polarimeter “NPOL” Collaboration



RCNP E351 Collaboration

- M. Okamoto, S. Kuroita, T. Noro, T. Yabe (Kyushu U)
- K. Hatanaka (RCNP)
- M. Dozono, M. Ichimura (RIKEN)
- Y. Maeda, H. Miyasako, T. Saito (Miyazaki U)
- Y. Sakemi (CYRIC)
- K. Yako (Tokyo/CNS)

Backup Slides

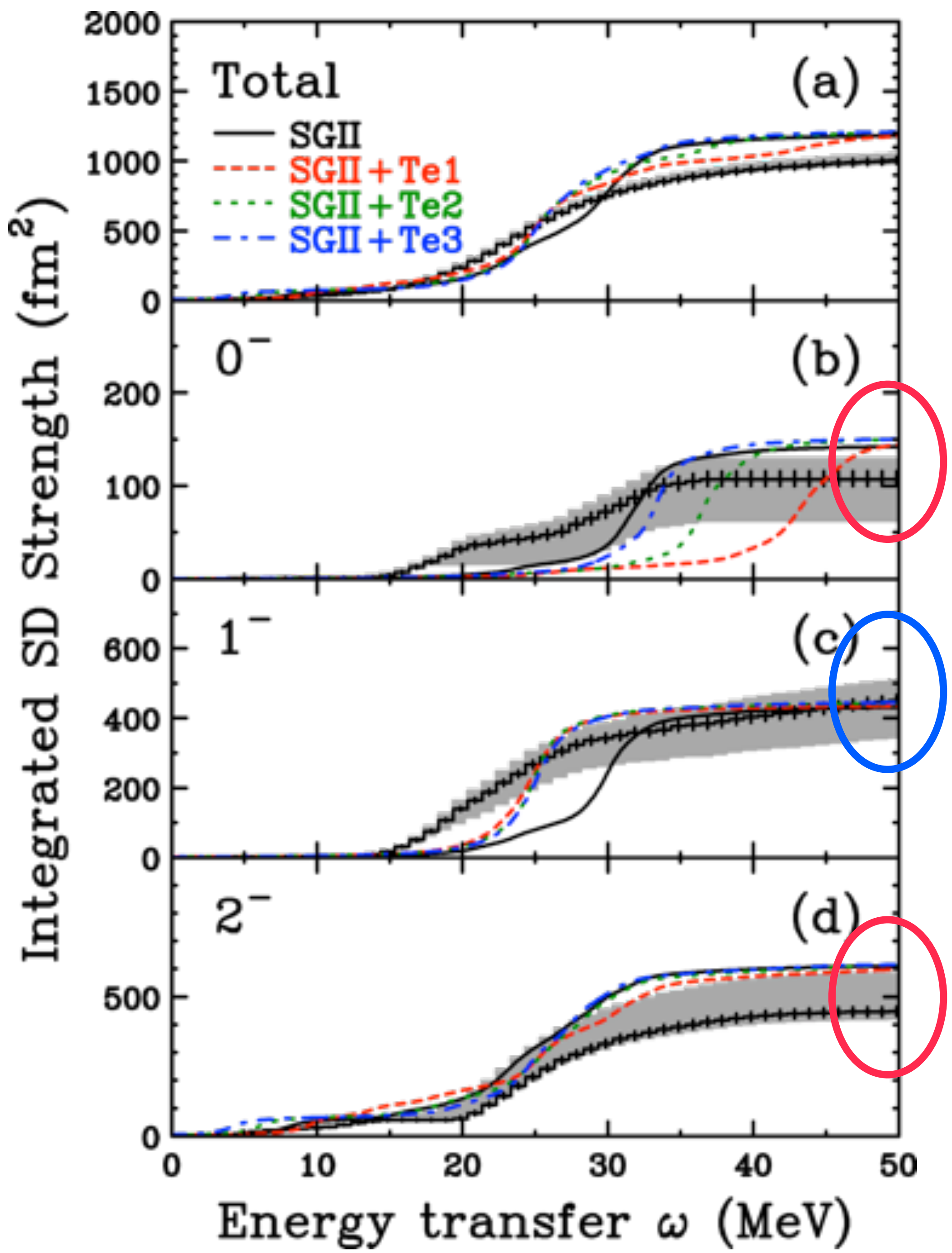
Integrated SD strengths

Integrated strength

$$S_{\mathrm{SD},J^\pi}(\omega) = \int^{\omega} B(\mathrm{SD}, J^\pi)d\omega$$

Total strength (ω < 50 MeV)

- Exp. : $(1.00 \pm 0.05) \times 10^3$ fm^2
- Theory : $(1.18 - 1.21) \times 10^3$ fm^2
- Quenching fac.: 0.84 ± 0.04
- Systematic uncertainty ∼ 15%



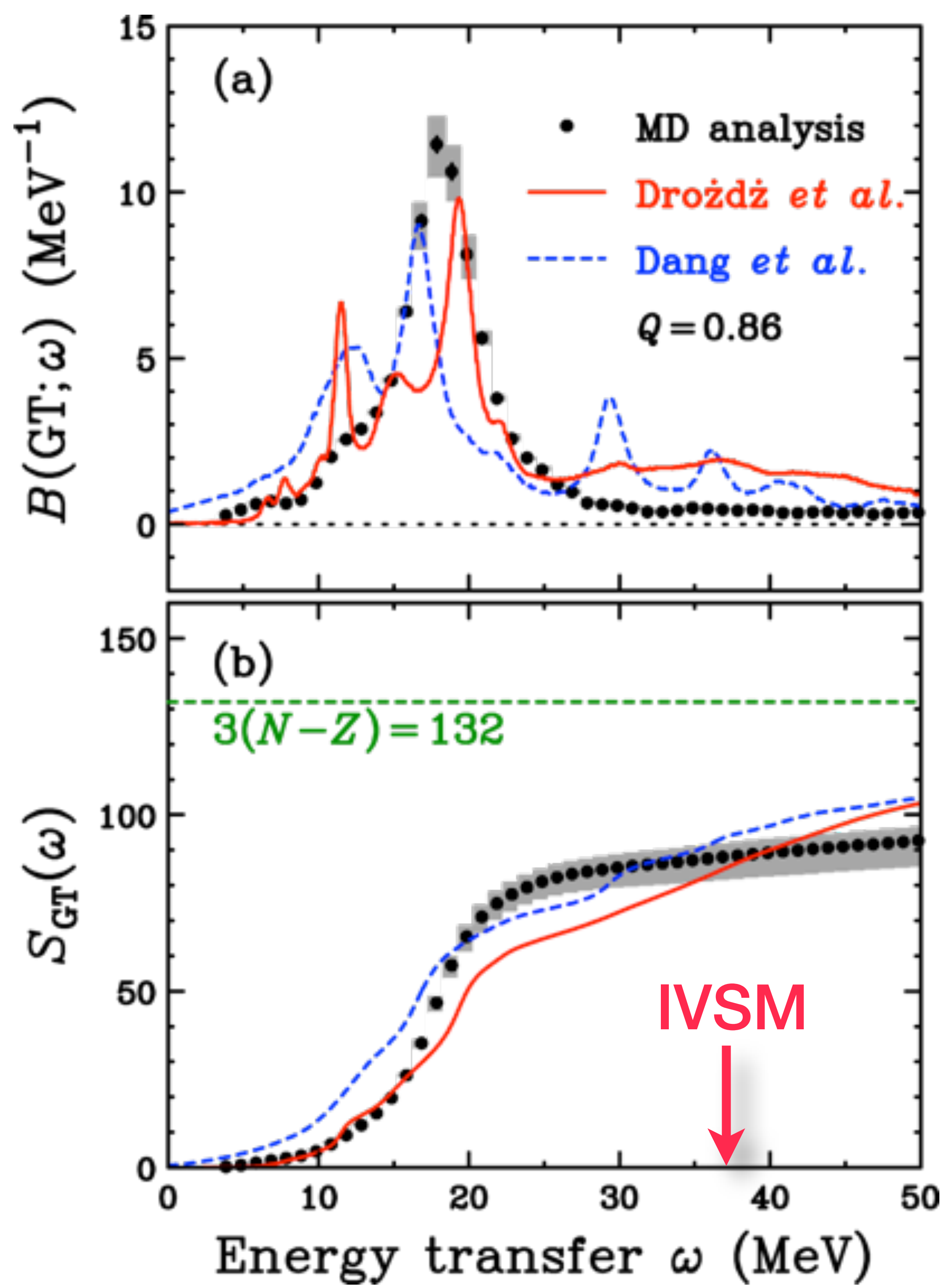
Each J^π strength

- 0^- and 2^- : ∼70% of RPA prediction
- 1^- : ∼100% of RPA prediction
- Systematic uncertainty ∼ 30% (Correlation between each strength)

- 84 ± 4% of total SD strength is found
- Quenching might depend on J^π

} Not conclusive (Large uncertainties)

Gamow-Teller strength



Experimental B(GT)

- B(GT) in GTGR ∼64% of 3(N-Z)
  - Similar to ^{90}Zr(p,n) result
- Significant strength up to 60 MeV
  - Configuration mixing is important
- Total strength
  - Q_{GT} ∼ 70% of 3(N-Z)
  - Systematic uncertainty ∼15%

Comparison with theory

- Two calc. with 2p2h config. mixing
  - Quenched by Q=0.86
  - Δ-h effects from 90Zr(p,n) results
- Significant strength in the continuum
  - Slightly larger than the present results
  - Interference effects between GT and IVSM ? → Should be investigated

Iso-vector spin-monopole strength

Compression mode IVSM

- $\hat{O}_{\mathrm{IVSM}} = \sum_{k=1}^{A} t_{k;-} \sigma_k r_k^2 \quad : \; 0\hbar\omega + 2\hbar\omega$
- $\hat{O}_{\mathrm{IVSM}} = \sum_{k=1}^{A} t_{k;-} \sigma_k [r_k^2 - \langle r^2 \rangle_{\mathrm{excess}}]$

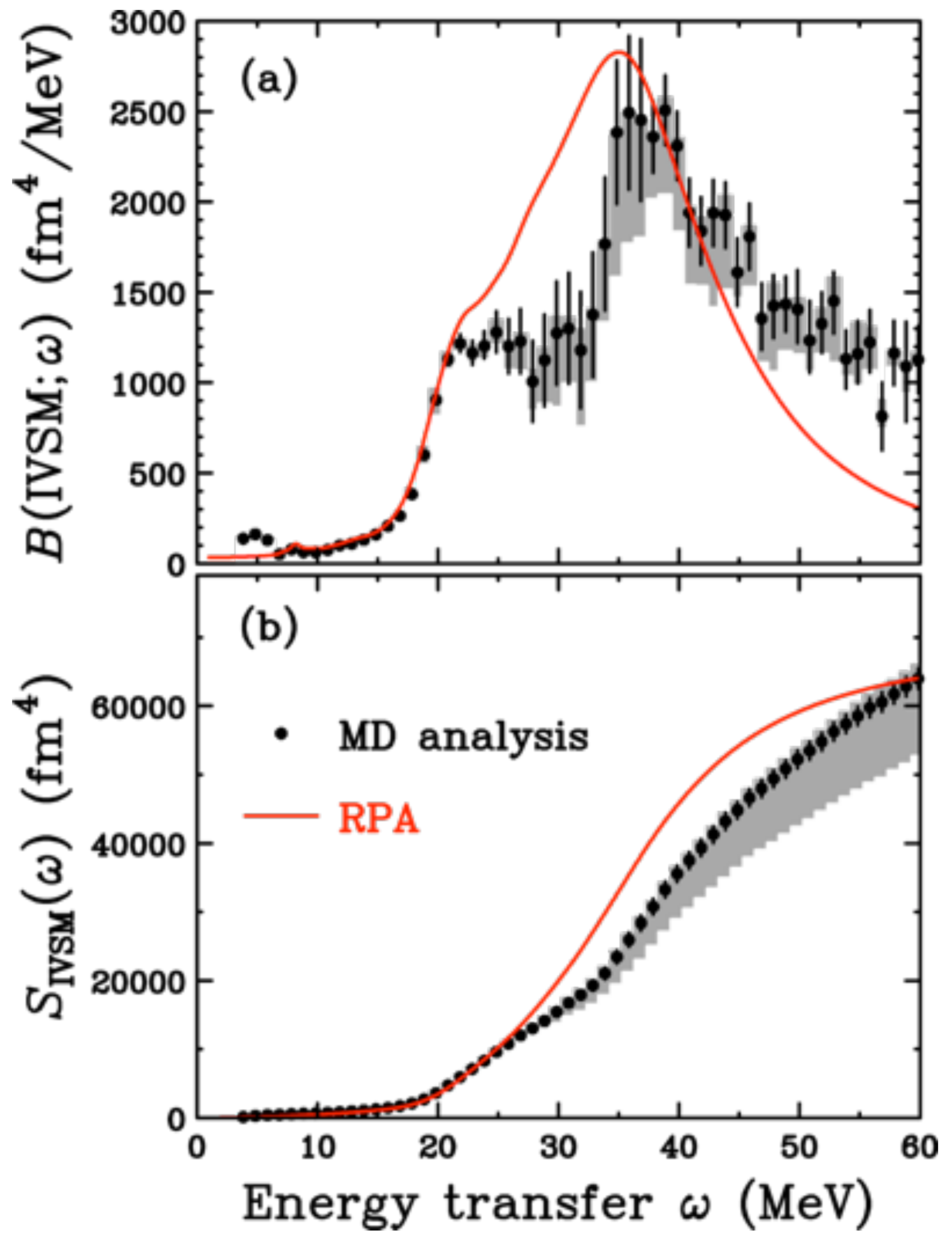
restrict $2\hbar\omega$ compression mode

Experimental results

- E_x = 35 MeV (ω=37 MeV)
  - Consistent with (p,n) and (^{3}He,t) [32 and 37±1]

Comparison with theory/previous work

- $S_{\mathrm{IVSM}} = (6.4 \pm 0.1^{+0.2}_{-1.1}) \times 10^4 \ \mathrm{fm}^4$
  - Consistent with RPA prediction
- Non-energy-weighted sum rule = 7.7×10^4 fm^4
  - $(83 \pm 2^{+3}_{-15})\%$ → Reduced by RPA correlations
  - $(60 \pm 5 \pm 14)\%$ for (^{3}He,t) → Difference between (p,n) and (^{3}He,t) for IVSM?



Advantage at intermediate energies

Smallest distortion

- NN total cross section is minimum
- Clean measurement
- Simple reaction mechanism
  - One-step direct
  - Impulse approximation

Spin-flip (ΔS=1) dominance at q=0

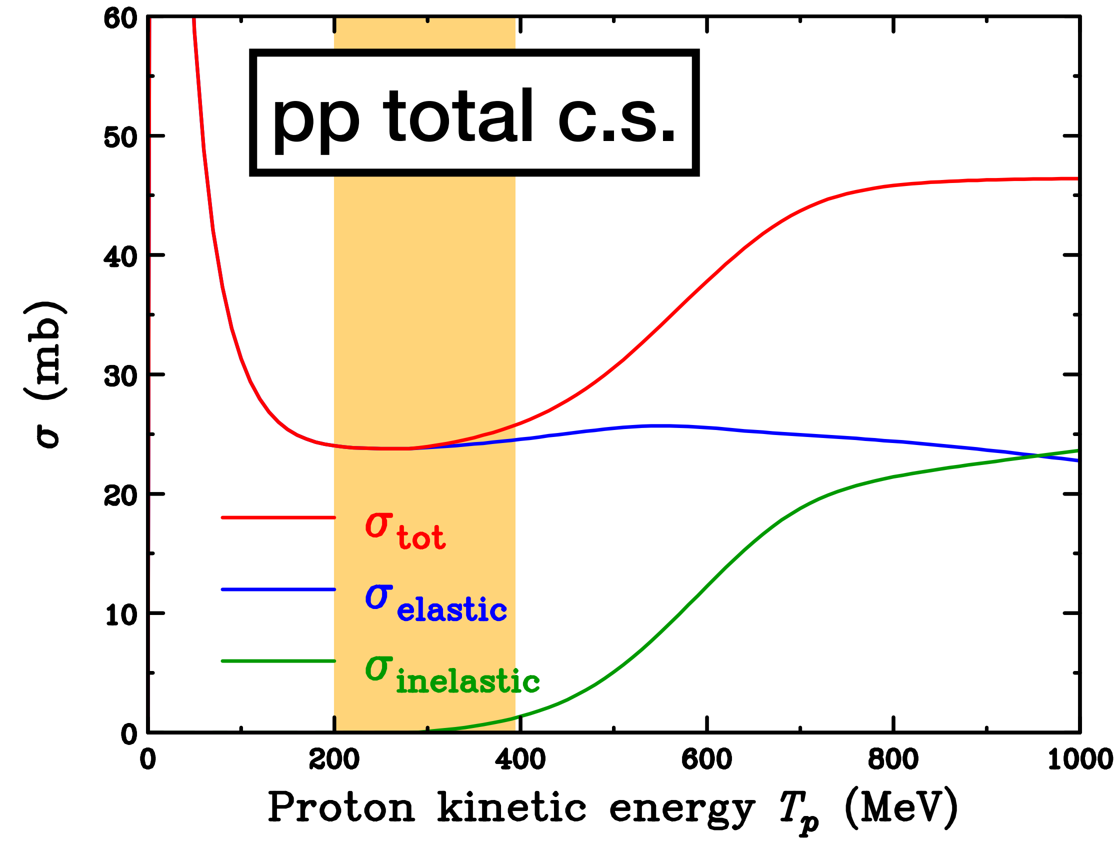
- Spin-vector (στ) > 10 × spin-scalar (τ)
- GT is predominantly excited at 0°

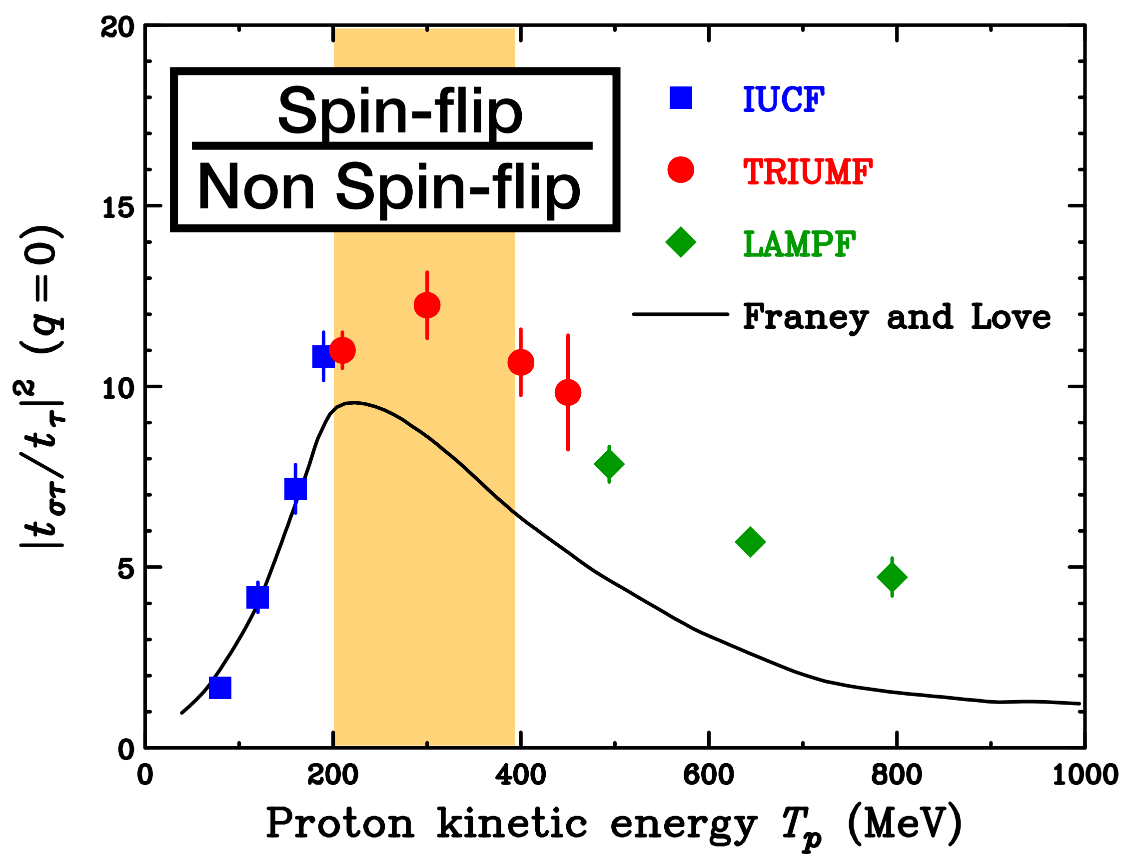
Spin-flip (ΔS=0) dominance at small q

- Spin-flip modes are also dominant
- SD mode is predominantly excited

Smallest tensor interaction

- Proportionality relation is reliable





DWIA+RPA calculations

Computer code: crdw

- Developed by Ichimura group

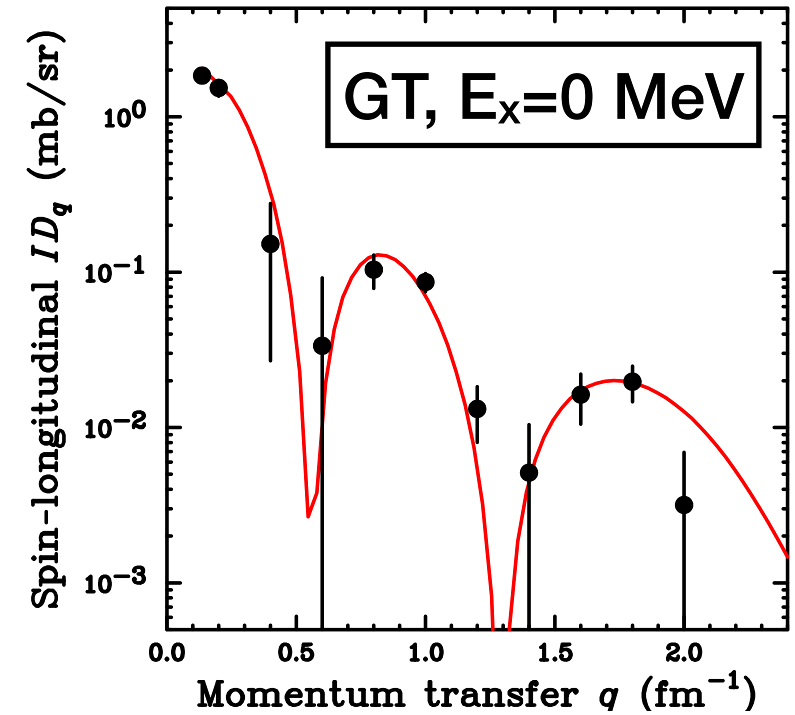
DWIA

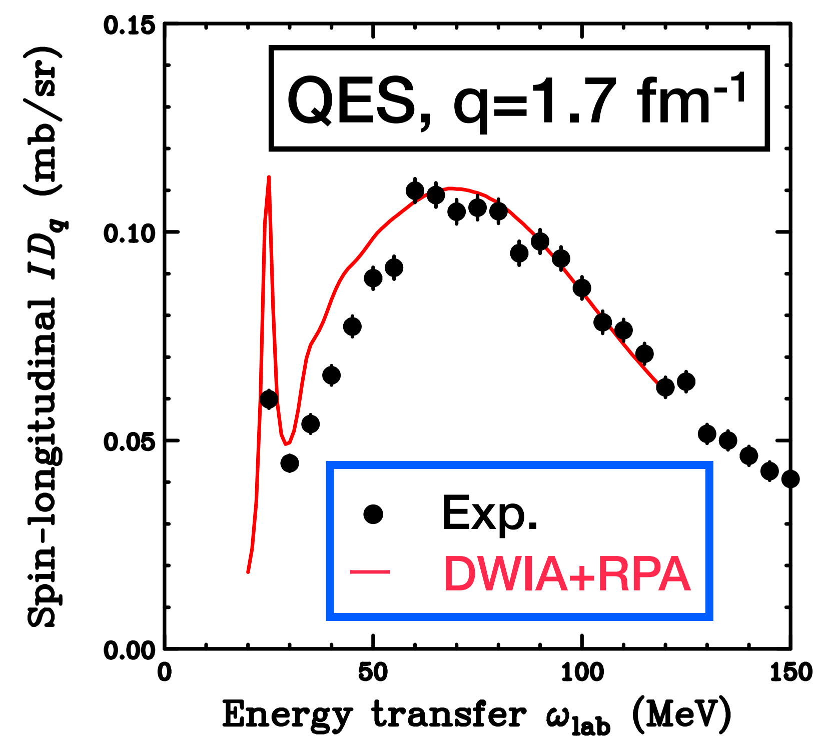
- Global optical potentials for ^{208}Pb
  - Proton: Hama et al.
  - Neutron: Shen et al.
- NN t-matrix
  - Franey and Love t-matrix

RPA

- π+ρ+g' p-h interaction
  - $g'_{NN} = 0.60 \pm 0.10$
  - $g'_{N\Delta} = 0.35 \pm 0.16$

} ← ^{90}Zr(p,n) data





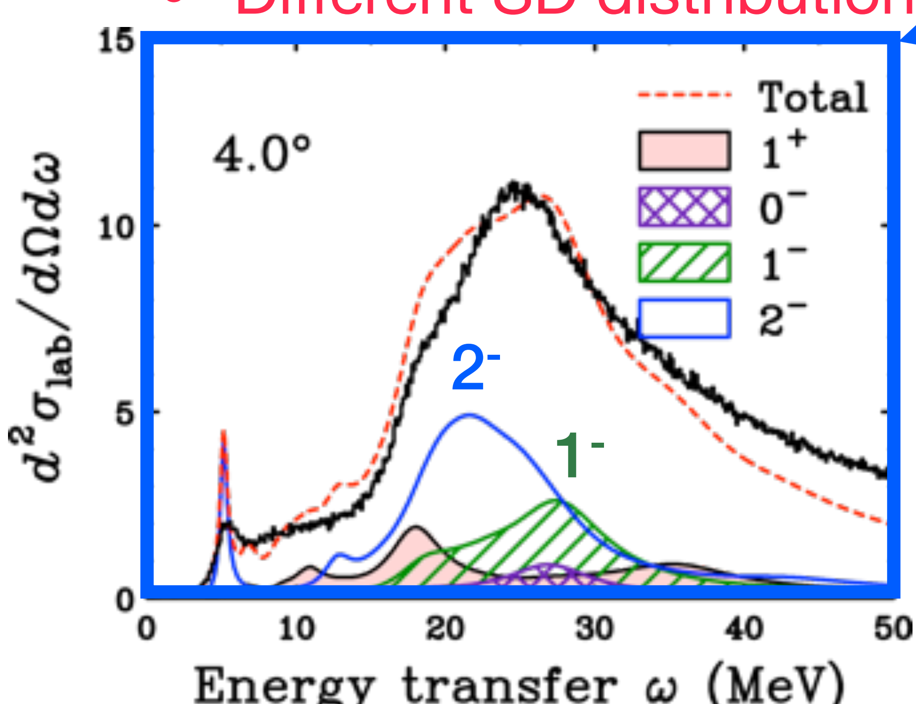
- No free parameter
- Well reproduce pionic modes for ^{12}C(p,n) in wide momentum-transfer region

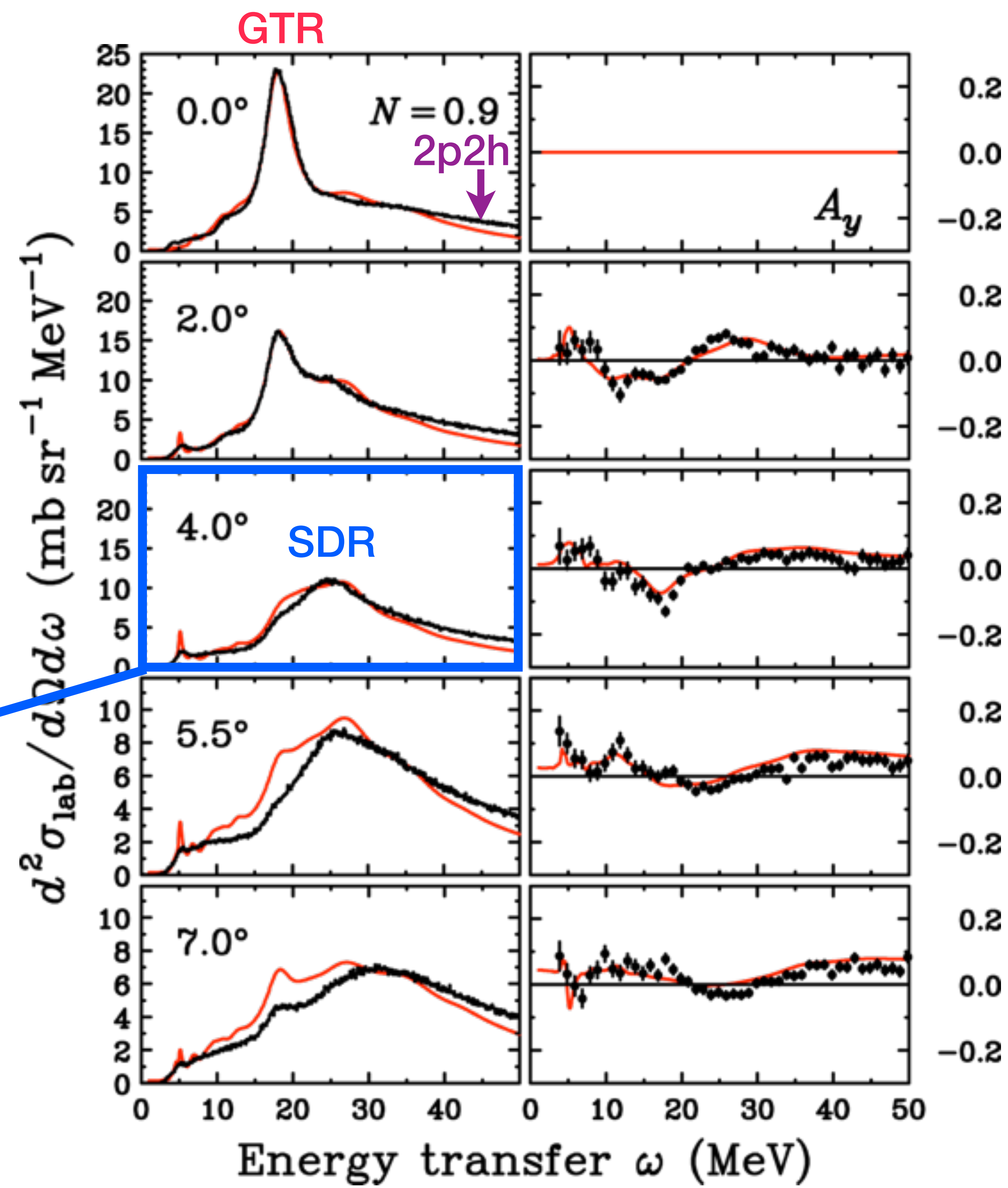
Absolute values are reliable

Results —Cross section and A_y—

Comparison with DWIA+RPA(1p1h)

- Normalization factor N=0.9
  - Quenching by 2p2h
  - Should be re-distributed into continuum
- Reproduce GTR and A_y
- Discrepancy for SDR at 4.0°
  - Theory : Broad bump
    - $E_x(2^-) < E_x(1^-)$
  - Exp. : Narrow bump
    - Different SD distributions?





SD unit cross section and B(SD)

SD unit cross section

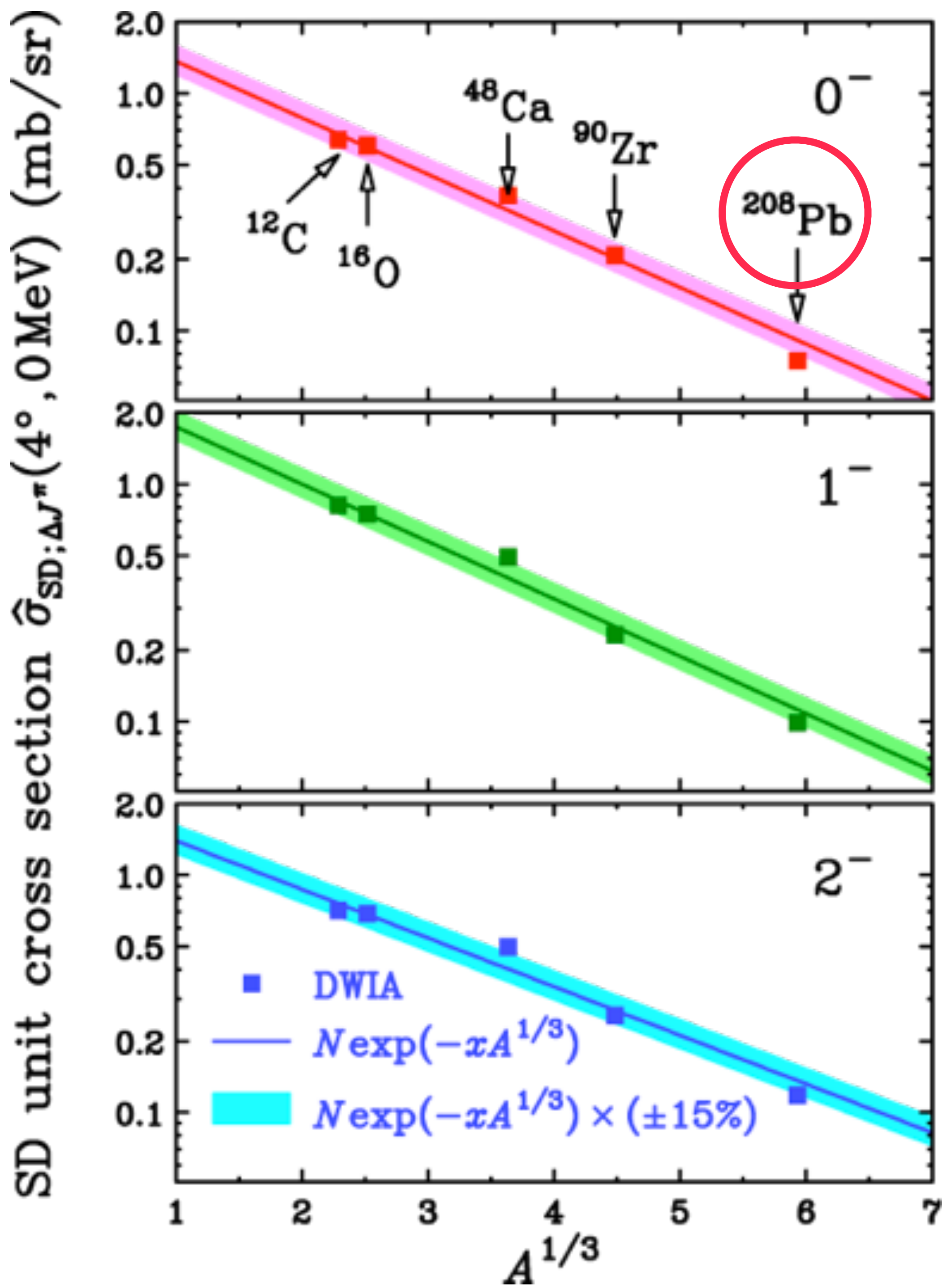
- Maximum cross section at ∼4°
- Proportionality relation
  - $\sigma_{\mathrm{SD};J^\pi}(4^\circ) \simeq \hat{\sigma}_{\mathrm{SD};J^\pi} B(\mathrm{SD}, J^\pi)$

DWIA calculations (▪)

- ^{12}C, ^{16}O, ^{48}Ca, ^{90}Zr, ^{208}Pb
- SD excitation at ω=0 MeV

A-dependence

- $\hat{\sigma}_{\mathrm{SD};J^\pi}(A) = N \exp(-xA^{1/3})$
  - Proper description for A-dep.
  - Reproduce DWIA results within ∼15%



Experimental SD strength

$$\underbrace{B^{\mathrm{exp}}(\mathrm{SD}, J^\pi)}_{\text{Exp}} = \frac{\sigma^{\mathrm{exp}}_{\mathrm{SD};J^\pi}}{\hat{\sigma}_{\mathrm{SD};J^\pi}} = \frac{\sigma^{\mathrm{exp}}_{\mathrm{SD};J^\pi}}{\sigma^{\mathrm{calc}}_{\mathrm{SD};J^\pi} / B^{\mathrm{calc}}(\mathrm{SD}, J^\pi)} = \underbrace{a_{J^\pi}}_{\text{MDA}} \underbrace{B^{\mathrm{calc}}(\mathrm{SD}, J^\pi)}_{\text{RPA}}$$

Comparison with RPA and self-consistent HF+RPA

RPA (used in DWIA+RPA calc.)

- π+ρ+g' residual interaction
- Systematically lower than HF+RPA
  - Different mean field

Self-consistent HF+RPA

- SII (w/o tensor)
- Reproduce 2^- strength
  - c.f. Tensor correlations are insensitive to 2^-
- Significantly higher for 1^-
  - Softening effect by T(TE) ?
- Roughly consistent for 0^-
  - Hardening effect by T(TE)
  - Cancelled by softening effect by U(TO) > 0 ?