荷電交換反応によるスピン物理

～偏極測定と多重極展開によるスピン双極子モードの研究～

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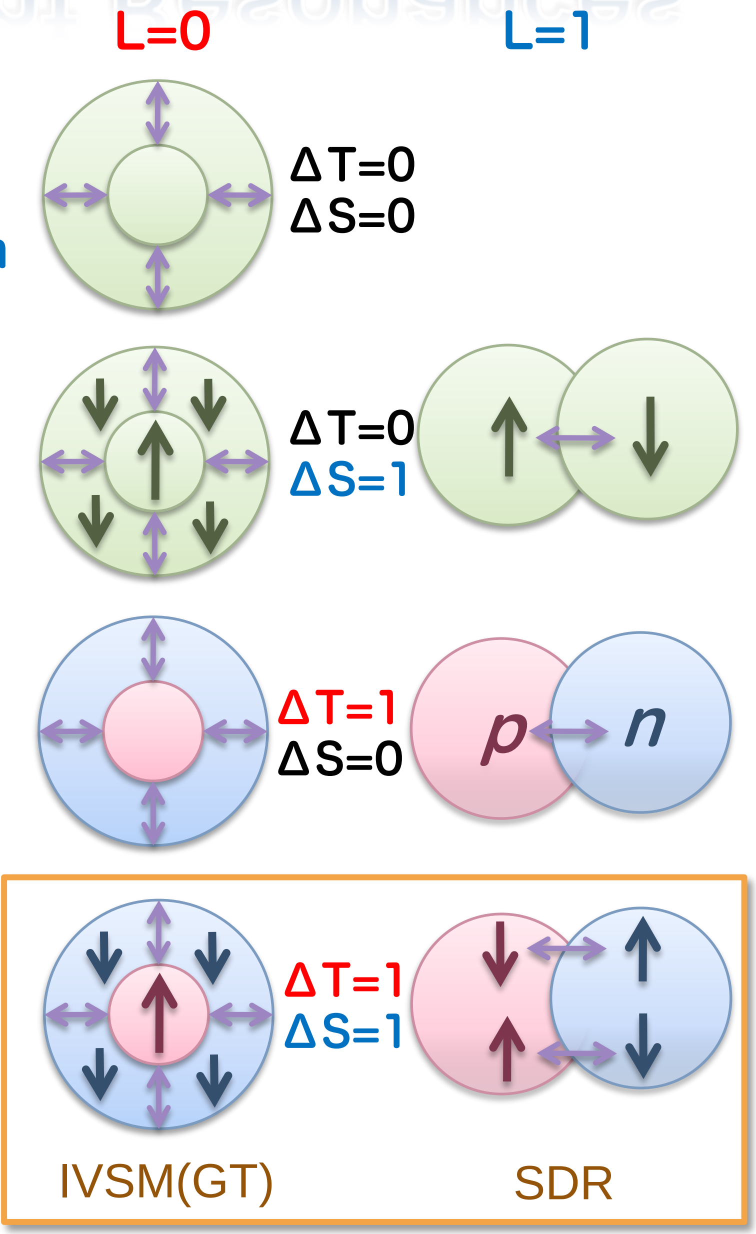
Sum Rule and Giant Resonances

- **Giant resonances**
  - Collective motion
  - Common to many-body quantum system
- **Unique feature of nucleus**
  - Nucleus consists of nucleons with
    - Spin 1/2
    - Isospin 1/2

      → 2×2=4 degrees of freedom
- **Resonance strength depends on**
  - Number of participating nucleons
  - Size of the system

    → Sum-rule depending on g.s. properties
- **Compare GR strength to sum-rule**
  - Residual interaction (distribution)
  - Quark degrees of freedom (quenching)



Spin-Isospin Modes and Sum Rule

- **Spin-isospin transition operators**

Spin-scalar $$O_J^{\tau^\pm} = \sum_{i=1}^{A} r_i^L Y_L(\hat{r}_i) t_i^\pm$$

Spin-vector $$O_J^{\sigma\tau^\pm} = \sum_{i=1}^{A} r_i^L \left[Y_L(\hat{r}_i) \otimes \vec{\sigma}_i\right]_J t_i^\pm$$

- **Model-independent sum-rule**

$$S_J^- - S_J^+ = \frac{(2J+1)}{4\pi}\left(N\langle {r_n}^{2J}\rangle - Z\langle {r_p}^{2J}\rangle\right)$$ ($\sim S^-_J$ for $N \gg Z$)

n-radius *p-radius*

- **Fermi and GT sum rule**

Fermi

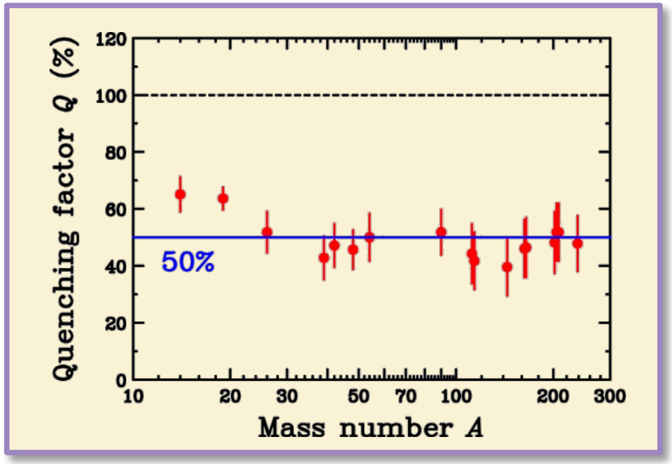
$$S^-(\mathrm{F}) - S^+(\mathrm{F}) = N - Z$$

Gamow-Teller

$$S^-(\mathrm{GT}) - S^+(\mathrm{GT}) = 3(N - Z)$$

50% quenching of GTGR

- 2p2h (Config. Mix.)
- Quark (Δ)

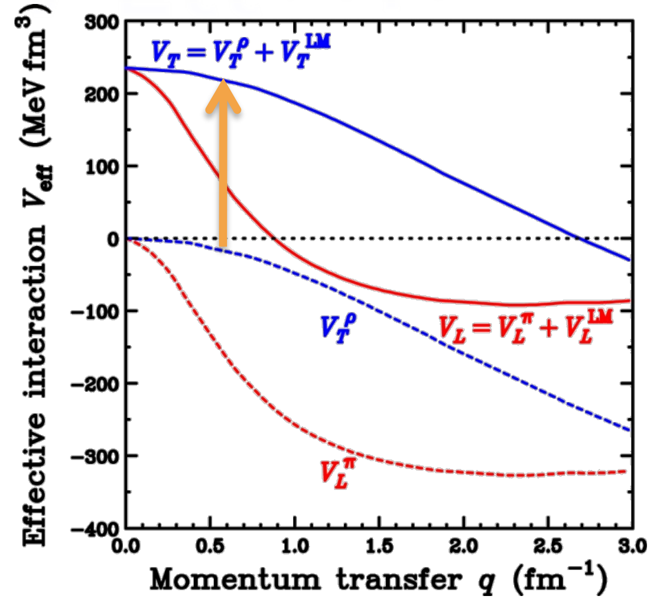


$\pi+\rho$+g' model and Δ Effects

- **Effective Interaction**

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

Longitudinal (π) Transverse (ρ)



- **$\pi+\rho$+g' model**
  - Spin-longitudinal $V_L = V_L^\pi + V_L^{\rm LM}$
  - Spin-transverse $V_T = V_T^\rho + V_T^{\rm LM}$
- **NN(p-h) effective Interaction**

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

π-exchange Short-range repulsion

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

ρ-exchange

- **Extension to N+Δ system for LM interaction**

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

g'$_{NN}$: Strength "distribution"
g'$_{N\Delta}$: Strength "quenching"

GT Strength and LM Parameters

K.Yako et al., PLB 615(2005)193. T.W. et al., PRC 72(2005)067303.

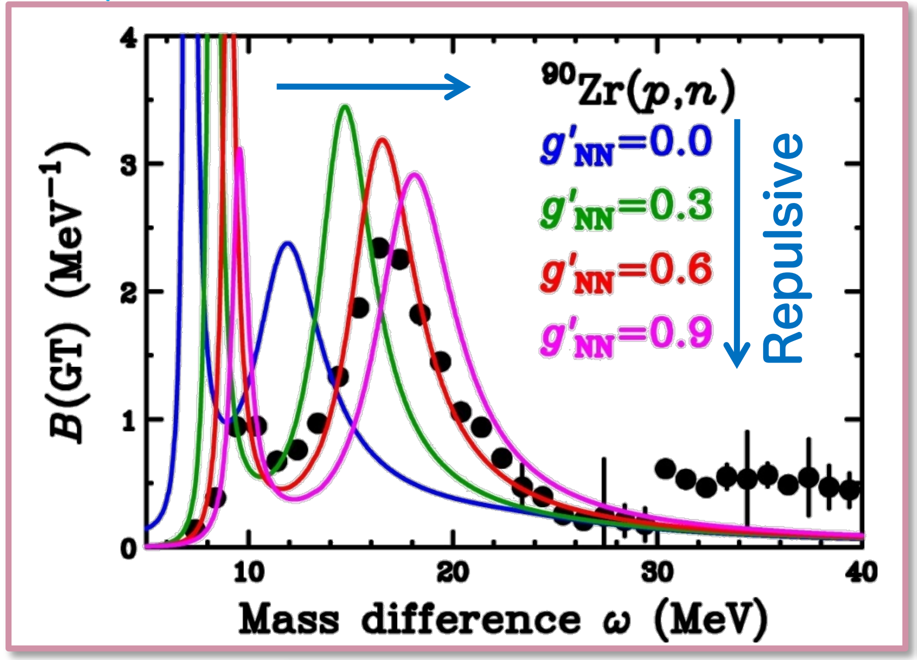
- g' dependence on GTGR
  - RPA(1p1h) by Ichimura group
  - GTGR peak position
    - Strongly depends on g'_{NN}

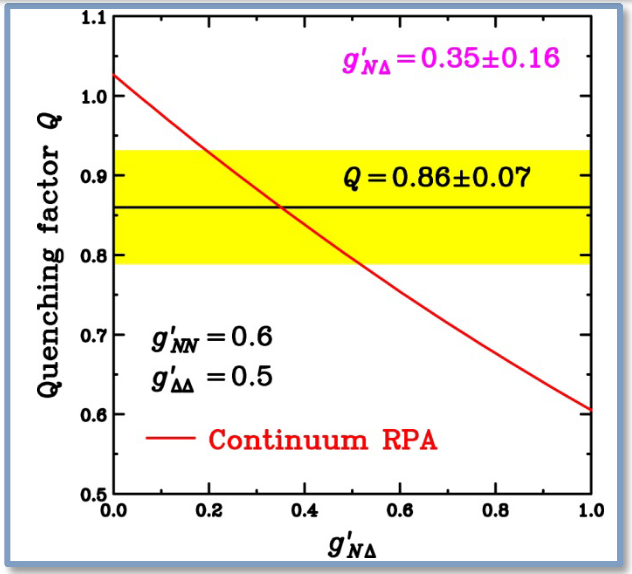
$$g'_{NN} = 0.6 \pm 0.1$$

    - Weak $g'_{N\Delta}$ dependence
- $g'_{N\Delta}$ dep. on GT quenching Q
  - Q=0.86±0.07
    - 2p2h effects are dominant
  - Q evaluated in RPA
    - Strongly depends on $g'_{N\Delta}$

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

- How about other modes (resonances)
  - Quenching (?)
  - Distribution (Information on residual Int.)

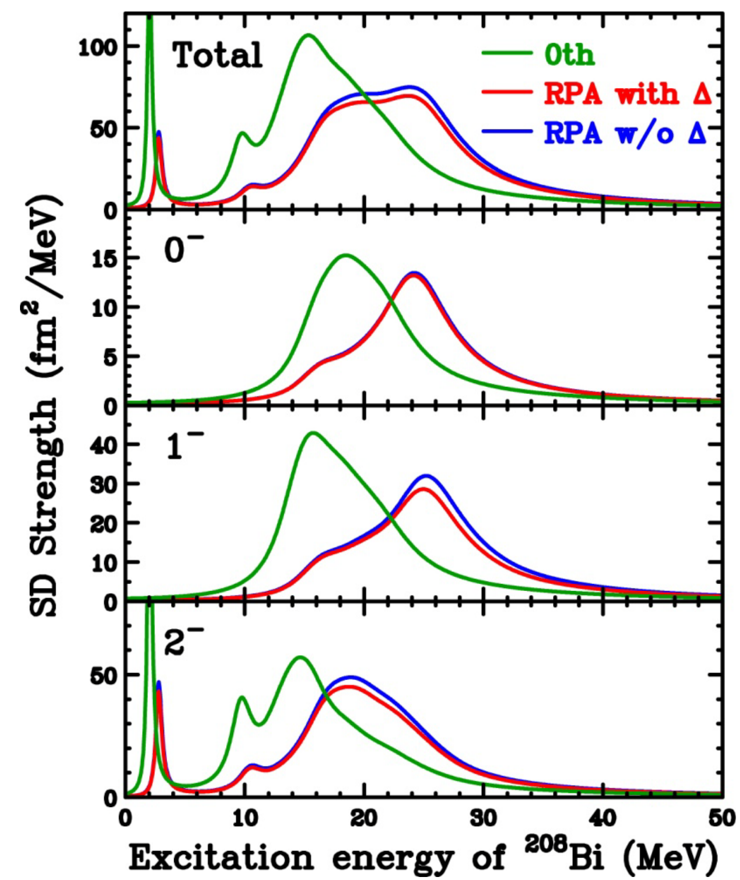




Correlation and Δ Effects on SDR

- SDR in 0^{th}
  - $E_x(2^-) < E_x(1^-) < E_x(0^-)$
  - Reflecting shell-structure
    - B.E.($j_>$) > B.E.($j_<$)
- SDR in RPA
  - NO free parameters
    - Same g' determined by GT
  - $E_x(2^-) < E_x(1^-) < E_x(0^-)$
    - Same as 0^{th}
  - Move strengths to higher E_x
    - Repulsive p-h int.
- Δ effects
  - Very small in SDR

^{208}Pb(p,n)



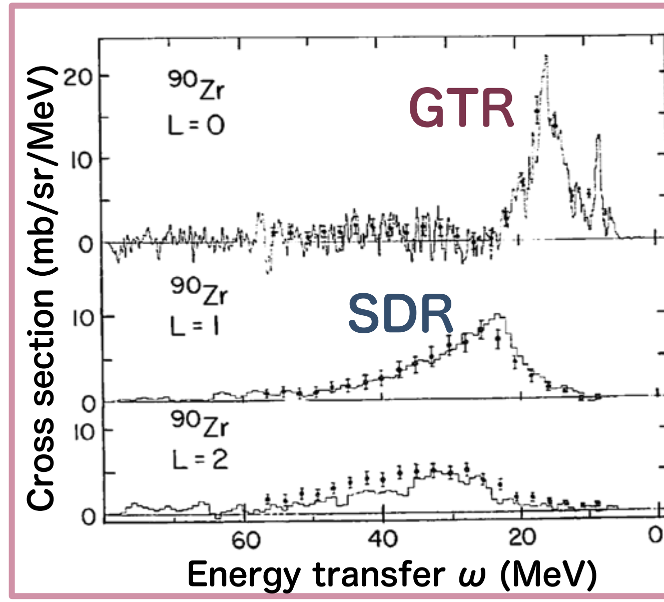
Previous Studies of SDR

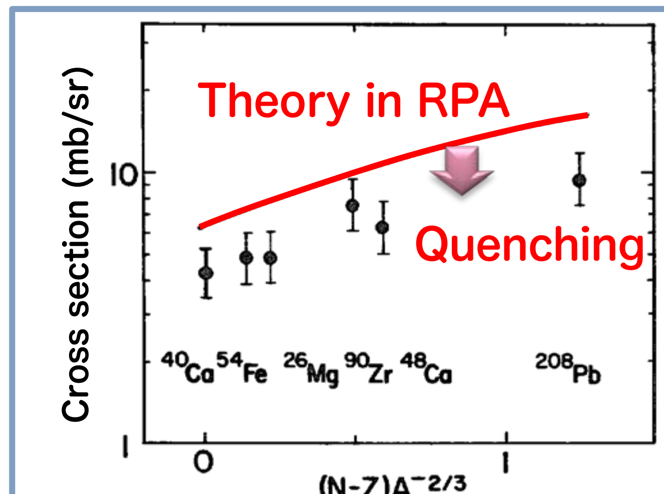
- Multipole decomposition of $^{90}Zr(^{3}He,t)$ at 900 MeV

Exp. Fit DW calc.

$$\sigma(\omega,\theta) = a_0(\omega)\sigma_{L=0}(\theta) + a_1(\omega)\sigma_{L=1}(\theta) + a_2(\omega)\sigma_{L=2}(\theta)$$

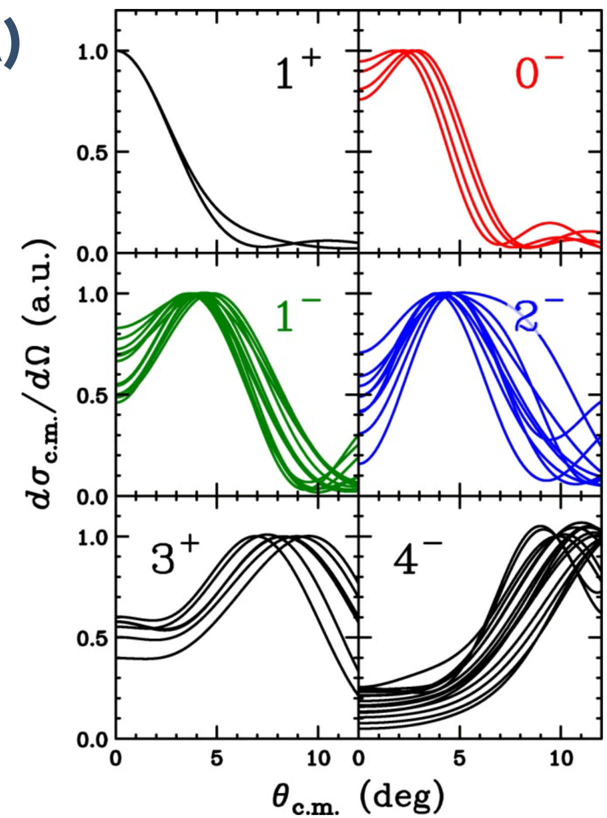
  - θ=0.25° ～4.25°
- SDR cross section
  - Quenching (～30%) from RPA(1p1h)
    - 2p2h (Configuration mixing)
    - Other mechanism
  - Spin-parities could NOT be separated
    - Similar angular distributions of $0^-, 1^-, 2^-$
- NOT conclusive for quenching
  - Rough estimation for distortion effects (NOT in full DWIA)
  - RPA in g' only (w/o π/ρ-exchange)
  - Angular distributions in $(^{3}He,t)$ are steep





MD Analysis for SD
—Difficulties and Solutions—

- **Multipole Decomposition Analysis (MDA)**
  - L-dependence of angular distributions
    - Insensitive to J^{π}
- **MDA for GT**
  - 0^{+} and 1^{+} for L=0
    - 0^{+} strength → IAS (Easily removed)
- **MDA for SD**
  - 0^{-}, 1^{-}, 2^{-} for L=1
    - Separation is difficult with σ
  - GDR and SDR for 1^{-} could not be separated
- **Polarization transfer D_{ij} for SD**



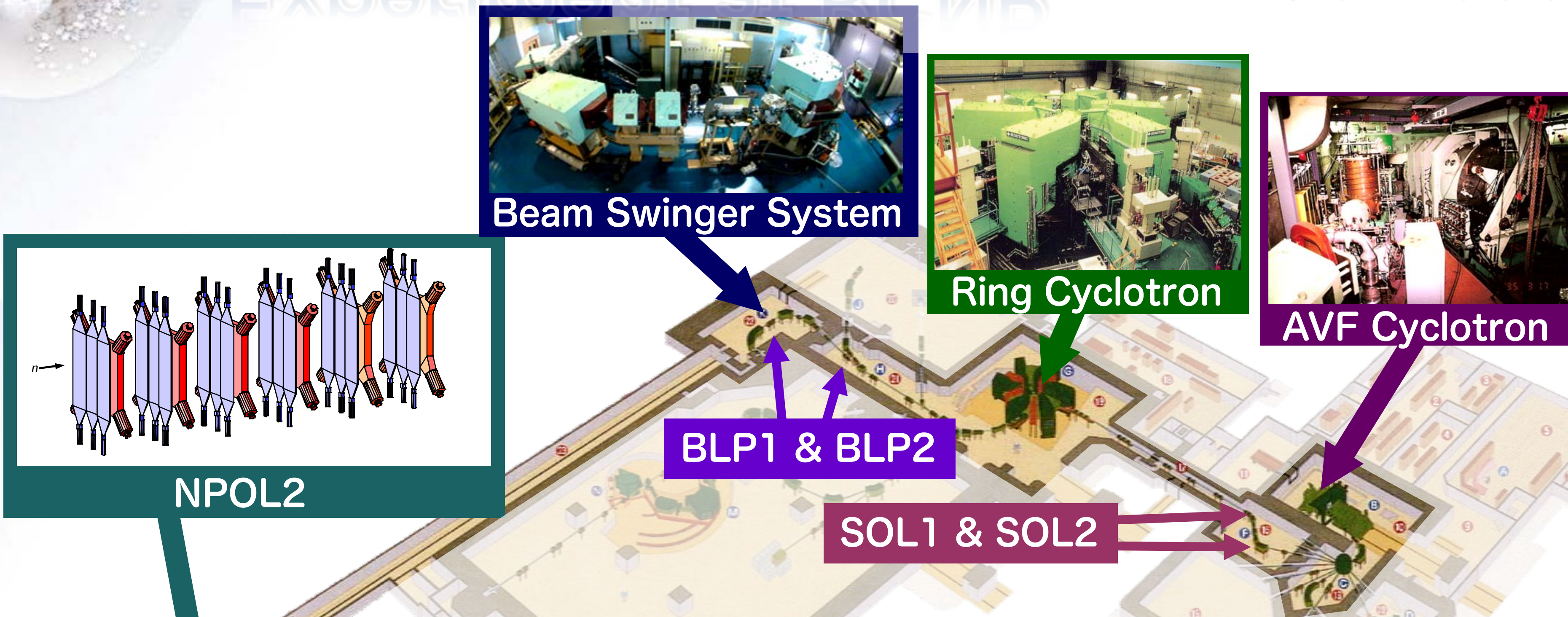
	$D_{NN}(4.0°)$	$D_{LL}(4.0°)$
0^{-} (SDR)	-1.00	-1.00
2^{-} (SDR)	-0.17	-0.41
1^{-} (SDR)	+0.19	-0.16
1^{-} (GDR)	+0.96	+0.95

MDA with D_{ij}

- ✓ Separate 0^{-}, 1^{-}, 2^{-}
- ✓ Separate GDR and SDR

Experiment at RCNP

Thanks to M. Dozono

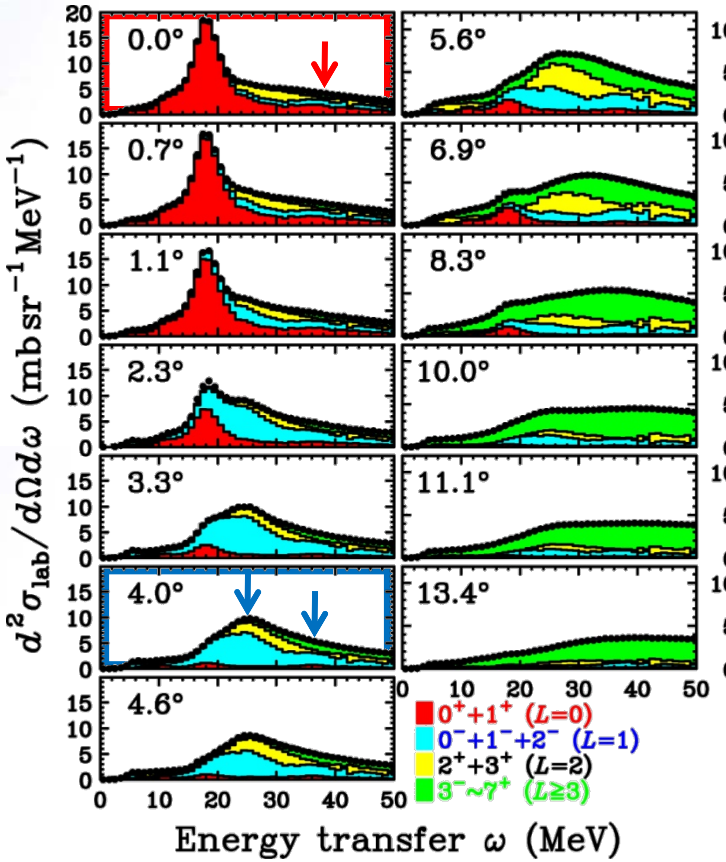


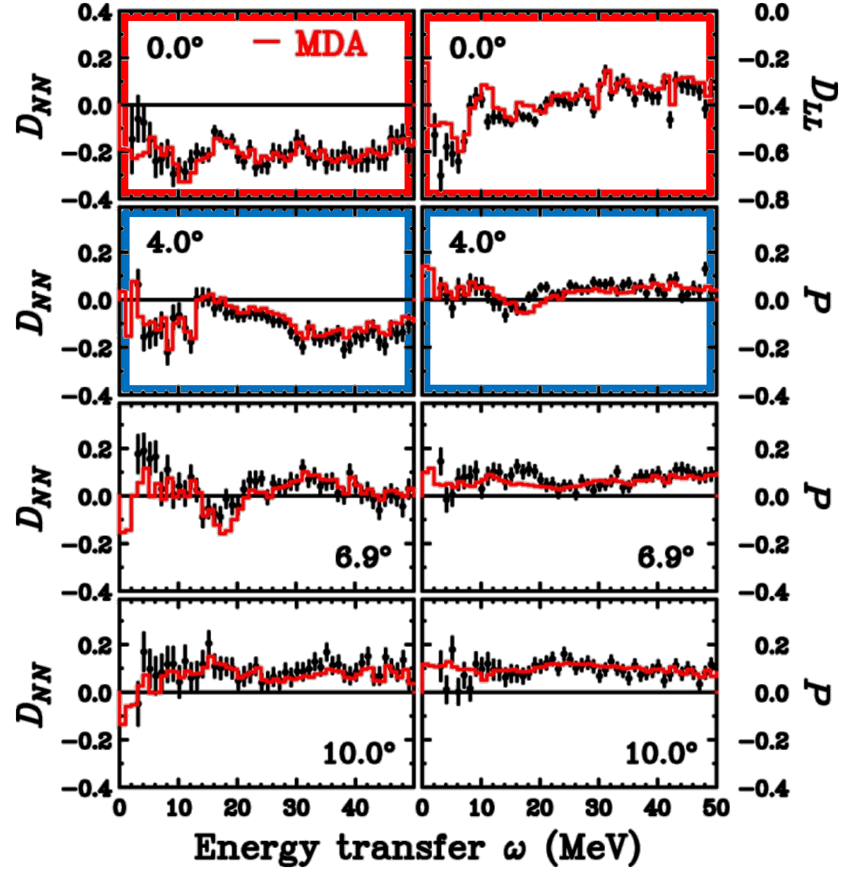
- Beam swinger
  - Cover $\theta = 0^\circ \sim 13.4^\circ$
- Measured data **(33 data sets)**
  - σ : 13 angles
  - A_y : 12 angles
  - D_{NN} : 4 angles(0,4,7,10deg)
  - D_{LL} : 1 angle(0deg)
  - P : 3 angles(4,7,10deg)

- 295 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

Results of MDA
~First MDA with Polarization Data~

- **MDA (up to 7⁺(L=6))**
  - Both cross section and polarization data are well reproduced
  - At 0° : Significant L=0 (GT+IVSM) up to 50 MeV
  - At 4° : Significant L=1 (SDR) around 20 and 35 MeV (2p2h?)





Gamow-Teller Strength B(GT)

- MDA could not separate GT from IVSM
  - Assumption
    - Proportionality between GT/IVSM strength and cross section

$$\underbrace{\sigma(\mathrm{GT}+\mathrm{IVSM})}_{\text{MDA}} = \underbrace{\hat{\sigma}_{\mathrm{GT}}}_{\text{GT unit c.s.}}[B(\mathrm{GT})+B(\mathrm{IVSM})]F(q,\omega)$$

    - Weak interference between GT and IVSM
    - Similar quenching effects on IVSM

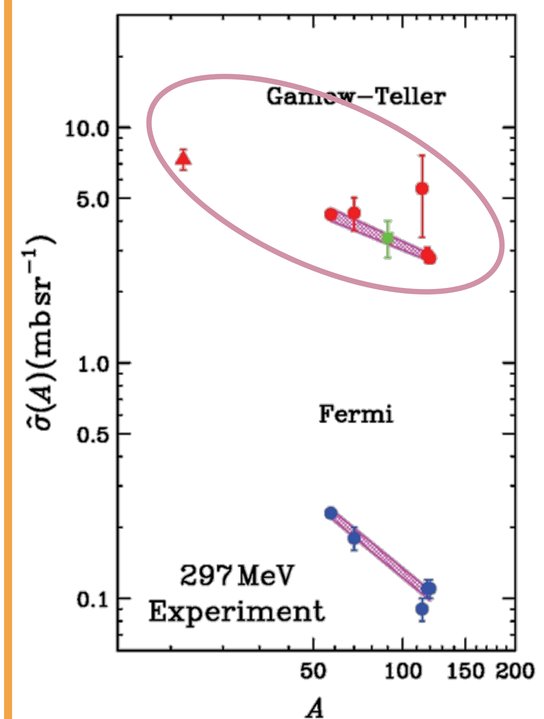
$$\Rightarrow \frac{\sigma^{\mathrm{Exp}}(\mathrm{GT}+\mathrm{IVSM})}{\sigma^{\mathrm{Theor}}(\mathrm{GT}+\mathrm{IVSM})} = \frac{B^{\mathrm{Exp}}(\mathrm{GT})}{B^{\mathrm{Theor}}(\mathrm{GT})}$$

  - Reliability for theoretical calculations

$$\hat{\sigma}^{\mathrm{Exp}}_{\mathrm{GT}} = 1.88 \pm 0.17\,\mathrm{mb/sr}$$

$$\hat{\sigma}^{\mathrm{Theor}}_{\mathrm{GT}} = 1.94 \pm 0.16\,\mathrm{mb/sr}$$

Theoretical calculations are reliable
→ Systematic uncertainty of B(GT) ~ 10%



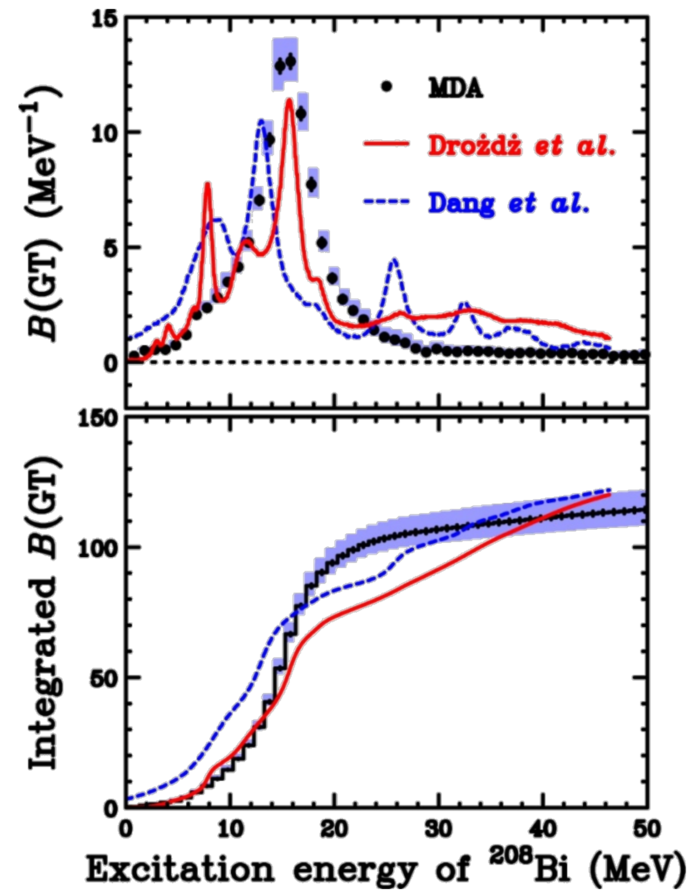
M.Sasano et al.,
PRC 79, 024602 (2009)

GT Strength B(GT) ～Comparison with 2p2h calc.～

- Experimental B(GT)
  - Strength up to 50 MeV
  - Not significant compared with ^{90}Nb

$$S^-(\mathrm{GT}) = 115 \pm 1(\mathrm{stat}) \pm 7(\mathrm{MDA})$$
$$= 87 \pm 5\%$$

  - Configuration mixing is dominant
    - Quark (Δ) effect is small
  - Consistent with Q=0.86 for ^{90}Nb
    - S^+(GT) is expected to be small
- Theoretical calc. with 2p2h
  - S^-(GT) is consistent
  - Different B(GT) distributions
    - Exp: Concentrate in GR region
    - Theory: Significant spread



S.Drozdz et al., PLB 189, 271(1987)
N.D.Dang et al.,PRL 79,1638(1997)

Further studies are required for conclusions

SD Unit Cross Section

C. Gaarde et al., NPA 369, 258 (1981)
K. Yako et al., PRC 74, 051303(R)(2006)

- **Relation between SD cross section and SD strength B(SD)**
  - Proportionality ansatz

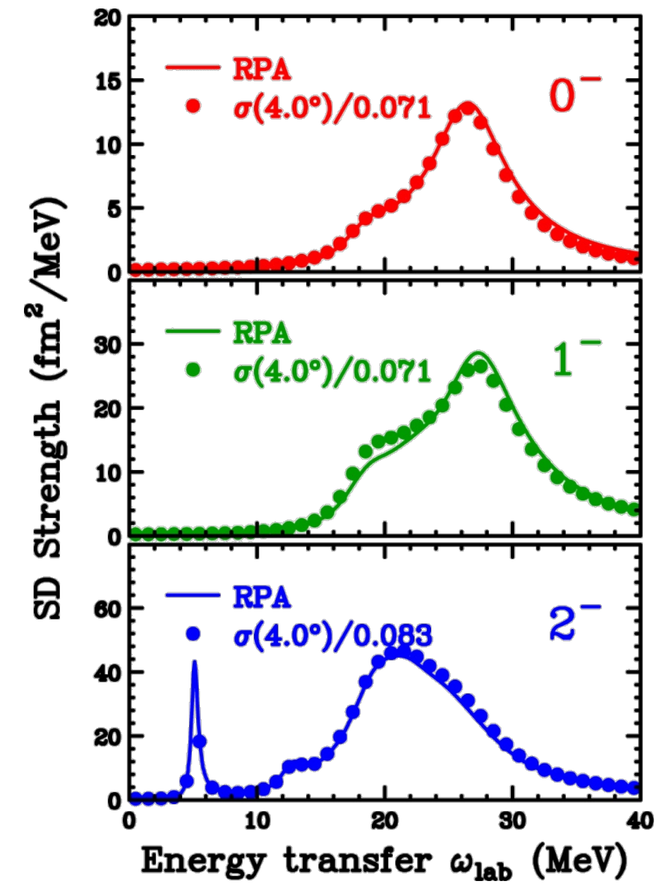
$$\underbrace{\sigma_{\mathrm{SD},J^\pi}(4.0^\circ)}_{\text{MDA}} = \underbrace{\hat{\sigma}_{\mathrm{SD},J^\pi}}_{\text{Unit c.s.}} \underbrace{B(\mathrm{SD})}_{\text{Strength}}$$

    - Proportionality : ~10%
  - Differences from constant unit c.s.
    - q-dep. (q is a function of ω)
    - Structure (radial W.F.)
    - Tensor int. (structure dep.)

$$\hat{\sigma}_{\mathrm{SD},J^\pi} \rightarrow \hat{\sigma}_{\mathrm{SD},J^\pi}(\omega)$$

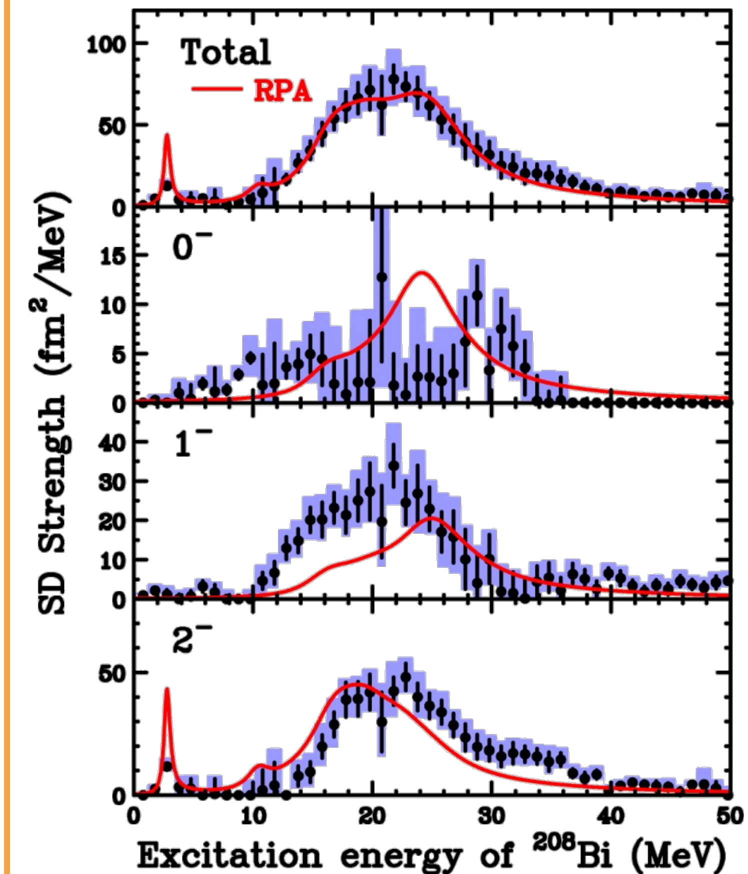
based on DWIA+RPA calc.

- **Unit c.s. depends on DWIA inputs**
  - Optical potential, etc.
    - Uncertainty : ~10%



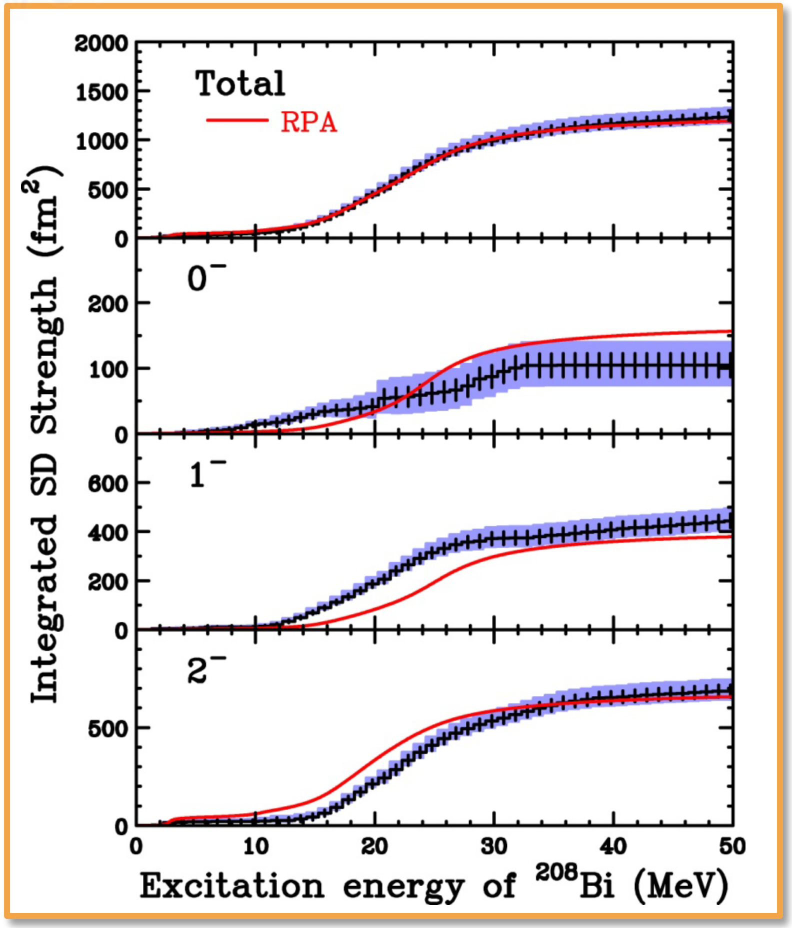
SD Strength Distributions
～Comparison with RPA～

- **Experimental B(SD)**
  - Asymmetric single peak for 1^- & 2^-
    - Tail to higher E_x up to 40 MeV
  - Fragmented 0^- strength
- **Theoretical calc. in RPA**
  - Phenomenological spreading width
    - Effective inclusion of 2p2h (in part)
  - Strength distribution
    - Total strength is consistent
    - 0^- strength is severely fragmented
  - Sequence of SDR peak
    - Exp: $E_x(2^-) \sim E_x(1^-) \sim E_x(0^-)$
    - Theory: $E_x(2^-) < E_x(1^-) < E_x(0^-)$
- **Comment on tensor correlations**
  - Repulsive effect on 1^- : N.G. (attractive effect ?)



Integrated SD Strength
～Comparison with RPA～

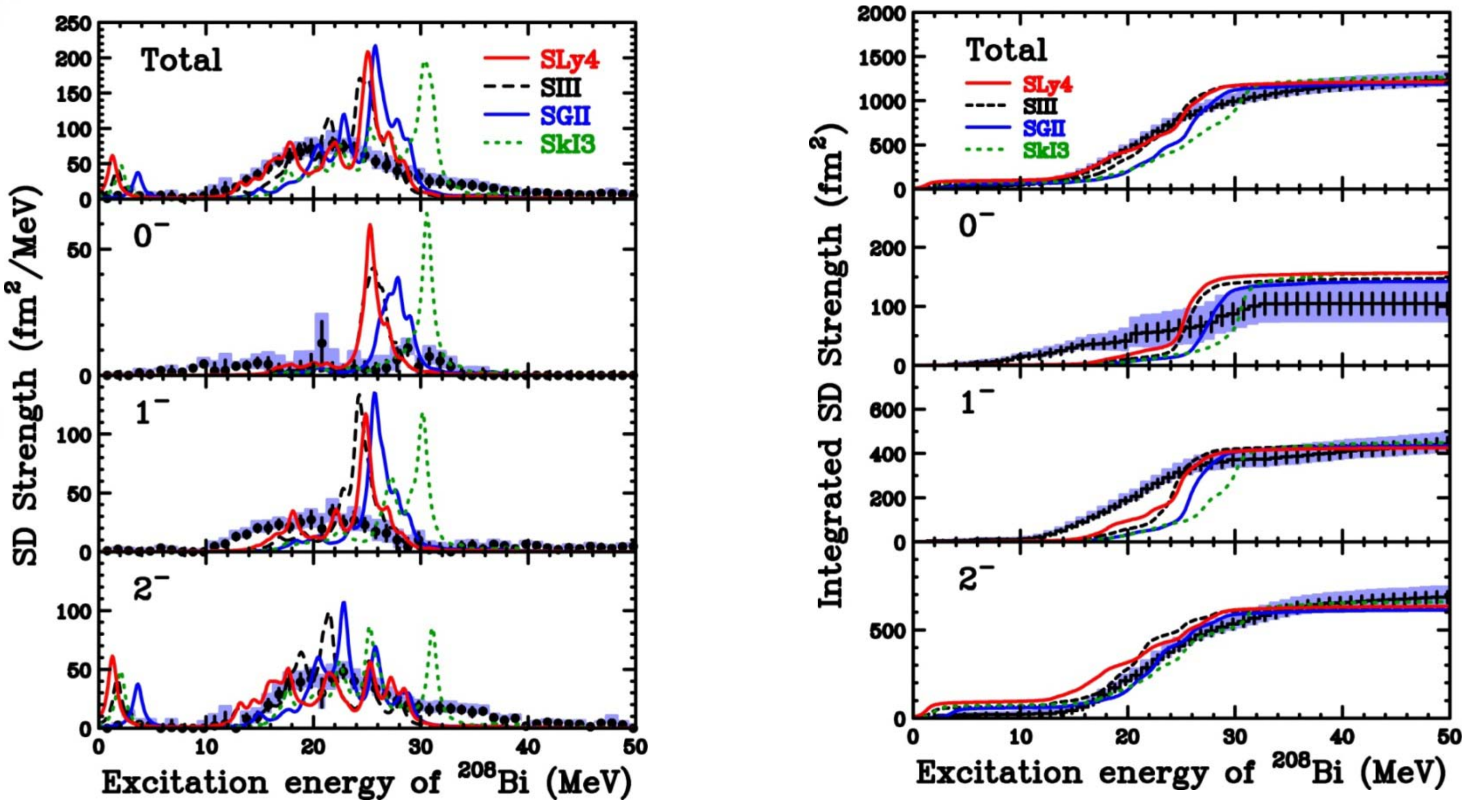
- **Experimental B(SD) from MDA**
  - Uncertainties
    - ── : Statistical uncertainty
    - ▭ : MDA uncertainty
    - ～10% systematic uncertainty from σ_{SD}
- **Comparison with RPA**
  - 0^- : Slightly small (NOT significant)
  - 1^- : Consistent (Softened)
  - 2^- : Consistent (Hardened)
  - Total : Consistent (Similar distribution)



SD strengths are NOT quenched
- ➢ SD distribution of each J^π is different from theoretical predictions
- ➢ J^π decomposition in MDA with polarization data is successful

Comparison with HF+RPA

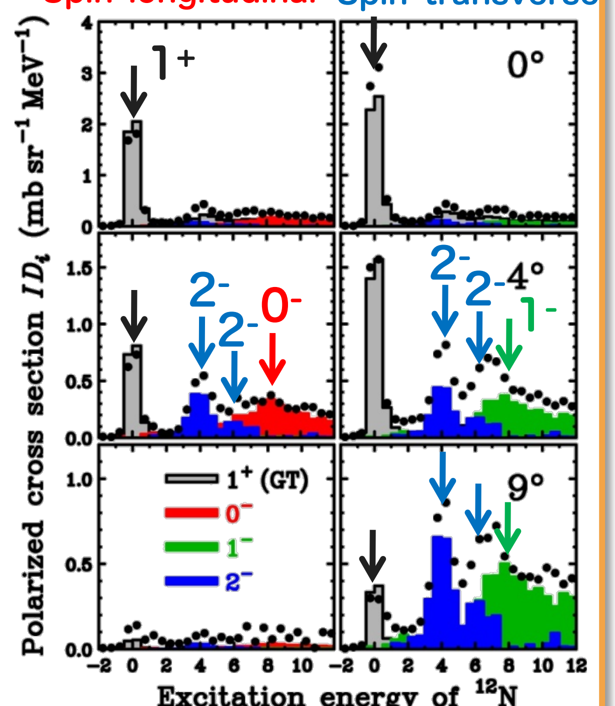
- **HF+RPA calculations by Sagawa-san's group**
  - Skyrme interaction: SLy4, SIII,SGII,SkI3
    - 0^- and 1^- strengths are smeared/fragmented compared with calc.
    - 1^- strength is significantly softened
    - Integrated strengths (each J^π,Total) are consistent



Summary and Future Perspective

- First attempt to perform MDA with polarization data
  - Successful separation of SDR into each J^{π} component
- Information on SD strengths
  - SD strengths are NOT quenched
    - 0^- strength : Fragmented
    - 1^- strength : Softened
      (Inconsistent with tensor effects)
    - 2^- strength : Roughly consistent
- Perspective (In Progress)
  - MDA with "complete" polarization data
    - 0^-,1^-,2^- Separation becomes more reliable
    - We can check the reliability of MDA
  - RCNP-E317 : $^{12}C(p,n)^{12}N$
    - Complete polarization data at 0°,2°,4° 6°,9°,12° (6 angles)

M. Dozono (Doctor work)



Establish method of J^{π} decomposition in continuum by polarization data