GT and SDR Studies for Stable Nuclei and Perspective for Unstable Nuclei

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Contents

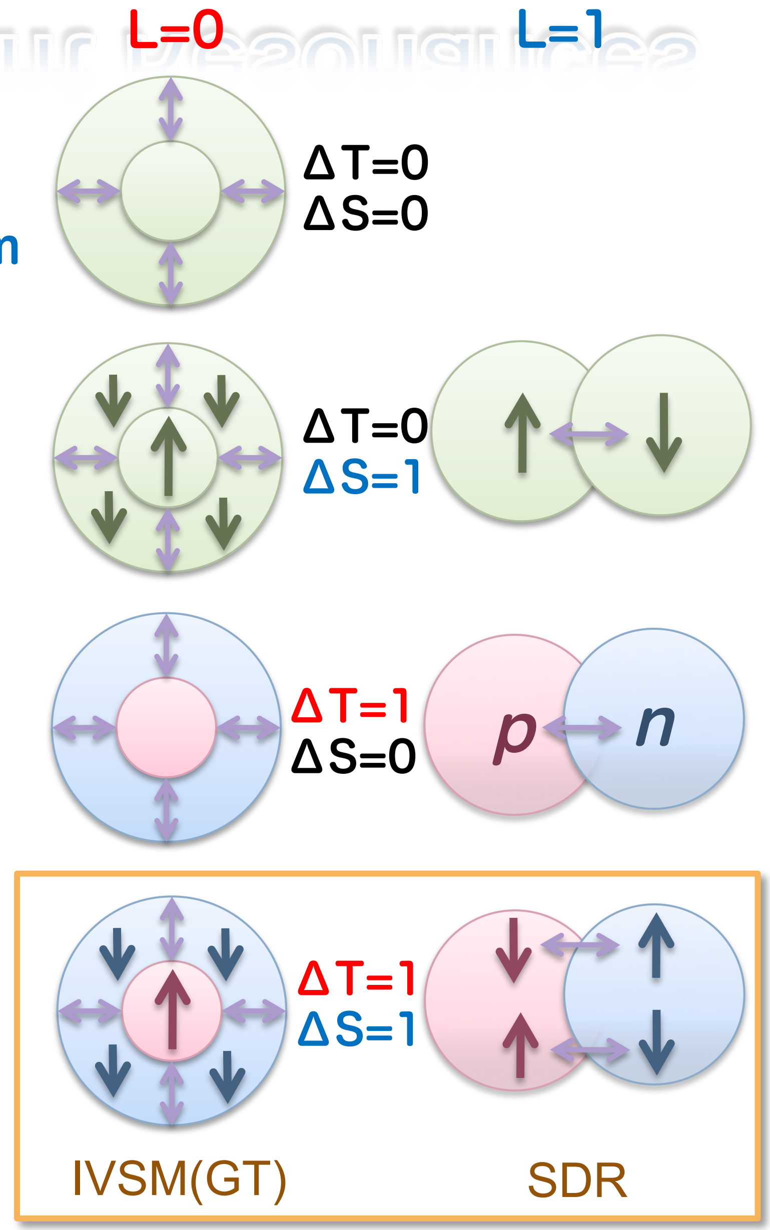
- GT study for ^{90}Zr
  - Unified understanding of spin-isospin responses
    - $\pi + \rho$+g' model
    - Two free parameters: g'_{NN} and $g'_{N\Delta}$
  - Peak position → g'_{NN} (short-range repulsion in NN)
  - Strength (quenching) → $g'_{N\Delta}$ (short-range repulsion in NΔ)
  - No free parameter in $\pi + \rho$+g' model
- GT/SD study for ^{208}Pb
  - Comparison with predictions in $\pi + \rho$+g' model
  - Quantitative reproduction by $\pi + \rho$+g' model
- Perspective for unstable nuclei
  - Can we deduce GT/SD strengths ?
    - Without performing multipole decomposition
    - Without normalizing to beta-decay strengths
  - Predictions for Zr and O isotopes in $\pi + \rho$+g' model

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≫Z)

n-radius *p-radius*

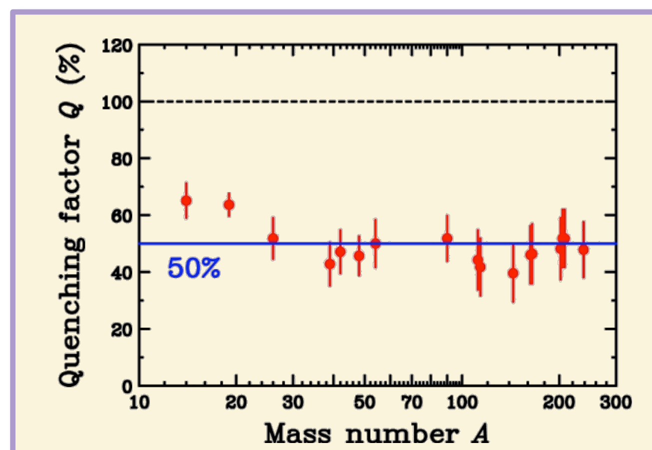
- **Fermi and GT sum rule**

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)

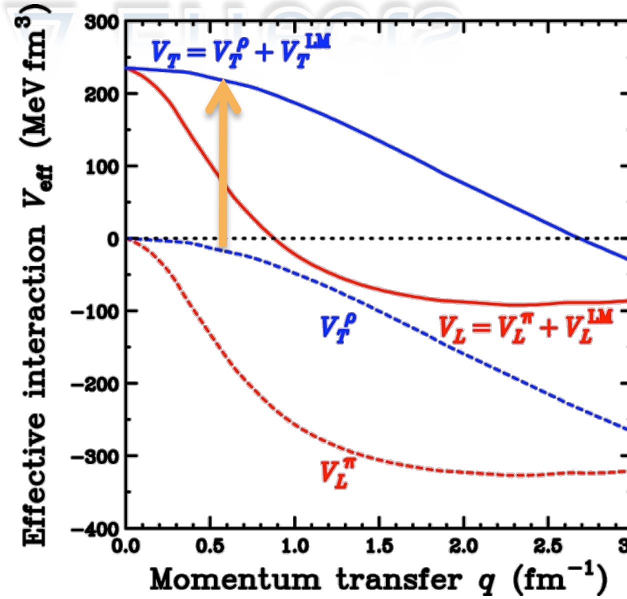
π+ρ+g' model and Δ Effects

- **Effective Interaction**

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

Longitudinal (π) Transverse (ρ)

- **π+ρ+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.

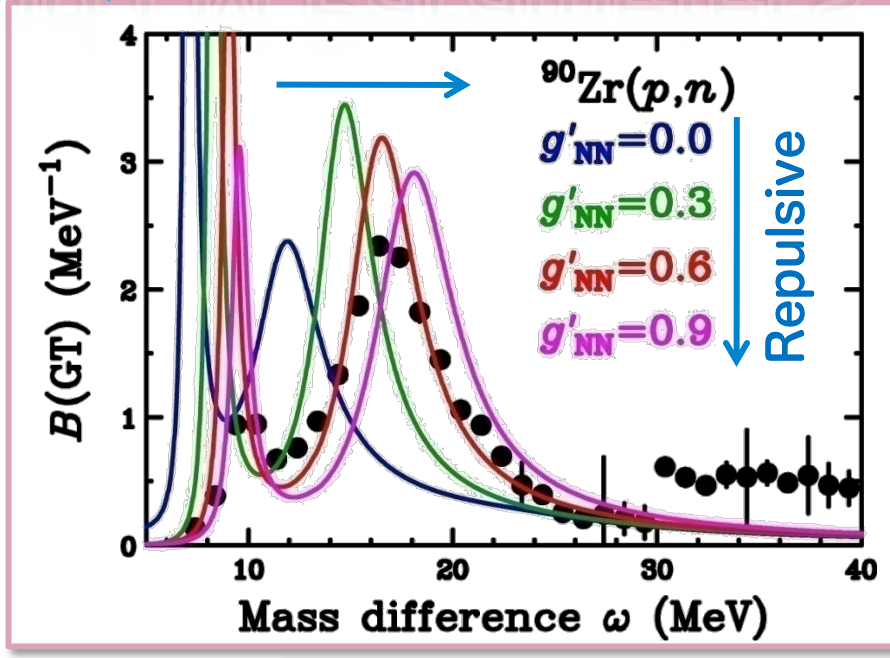
- g' dependence on GTGR
  - RPA(1p1h) by Ichimura group
  - GTGR peak position
    - Strongly depends on g'_{NN}

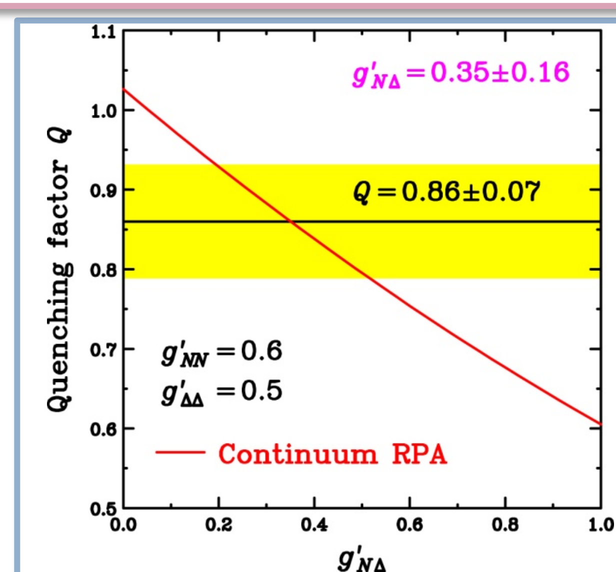
$$g'_{NN} = 0.6 \pm 0.1$$

    - 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.)

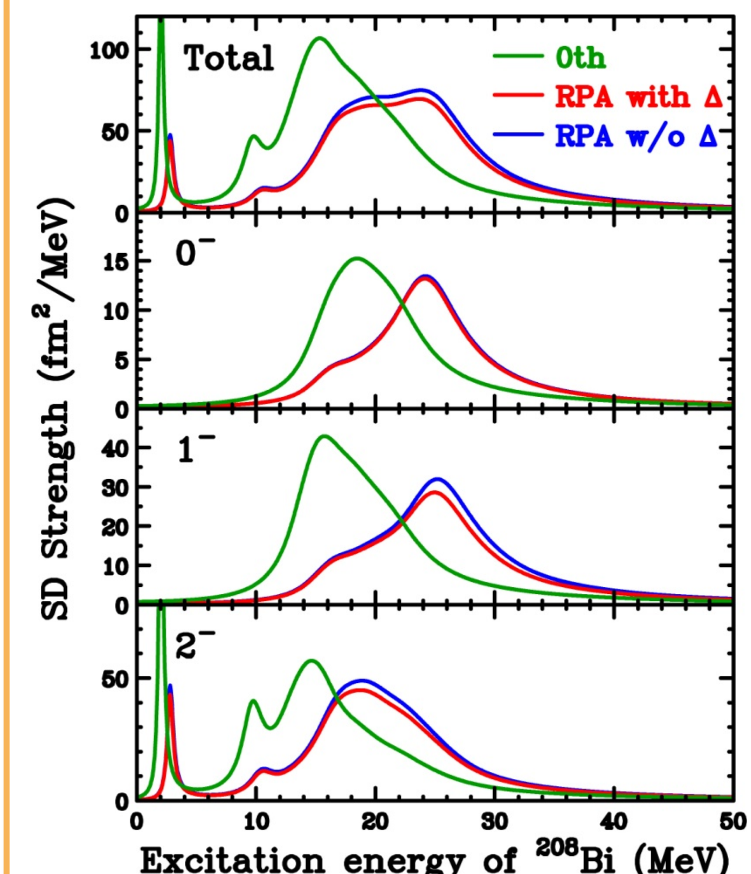




Correlation and Δ Effects on SDR

- **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

$^{208}Pb(p,n)$



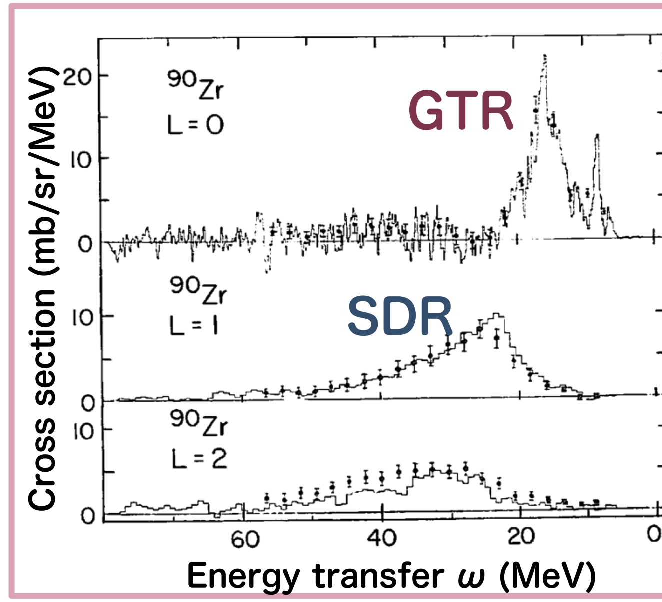
Previous Studies of SDR

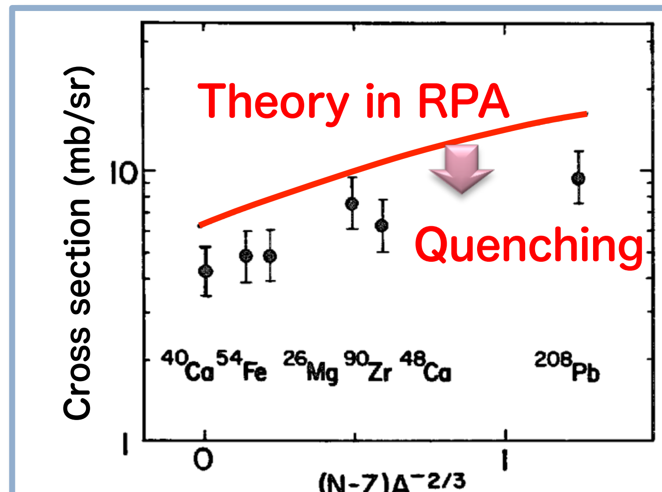
- Multipole decomposition of $^{90}Zr(^3He,t)$ at 900 MeV

Exp. Fit DW calc.

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

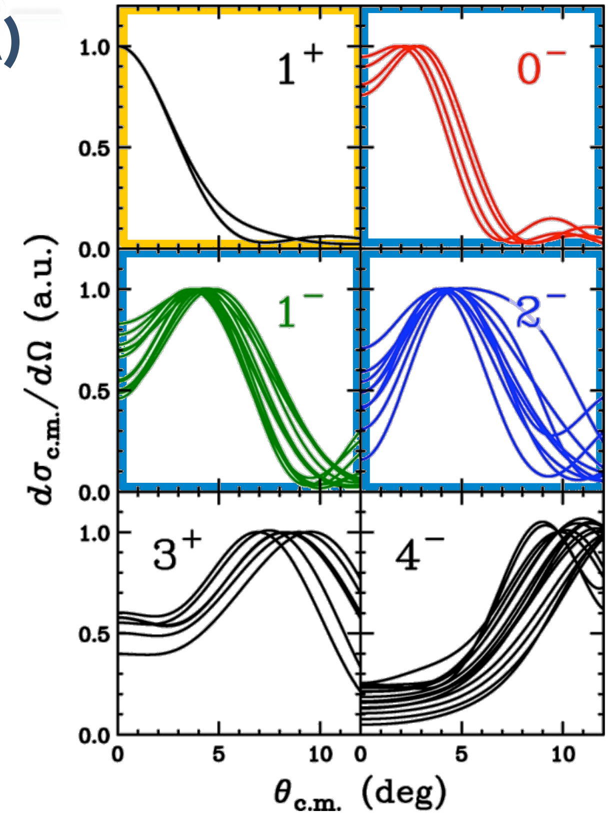
  - θ=0.25° ～4.25°
- SDR cross section
  - Quenching (～30%) from RPA(1p1h)
    - 2p2h (Configuration mixing)
    - Other mechanism
  - Spin-parities could NOT be separated
    - Similar angular distributions of $0^-,1^-,2^-$
- NOT conclusive for quenching
  - Rough estimation for distortion effects (NOT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



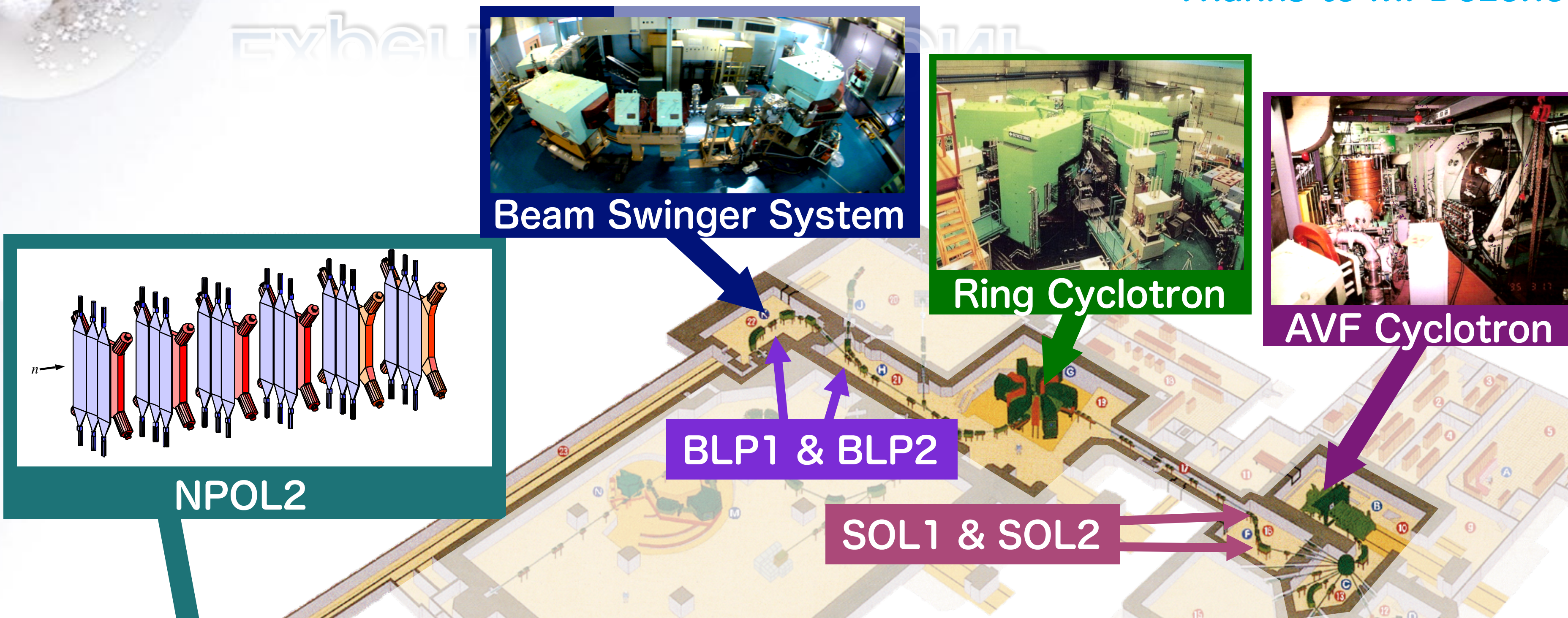
	$D_{NN}(4.0°)$	$D_{LL}(4.0°)$
0^- (SDR)	-1.00	-1.00
2^- (SDR)	-0.17	-0.41
1^- (SDR)	+0.19	-0.16
1^- (GDR)	+0.96	+0.95

MDA with D_{ij}

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

Experiment at RCNP

Thanks to M. Dozono



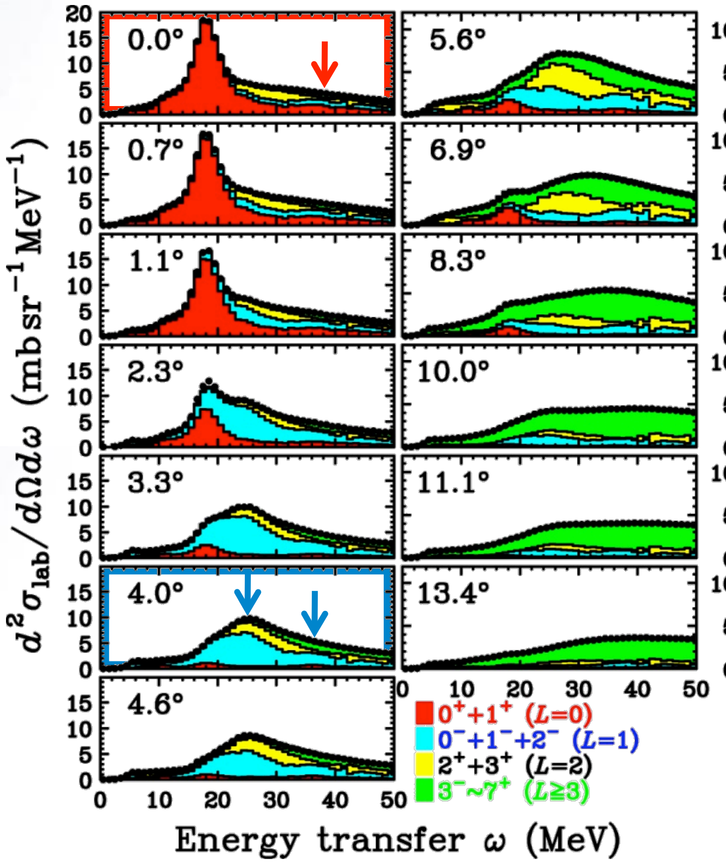
- Beam swinger
  - Cover $\theta = 0^\circ \sim 13.4^\circ$
- Measured data (33 data sets)
  - σ : 13 angles
  - A_y : 12 angles
  - D_{NN} : 4 angles(0,4,7,10deg)
  - D_{LL} : 1 angle(0deg)
  - P : 3 angles(4,7,10deg)

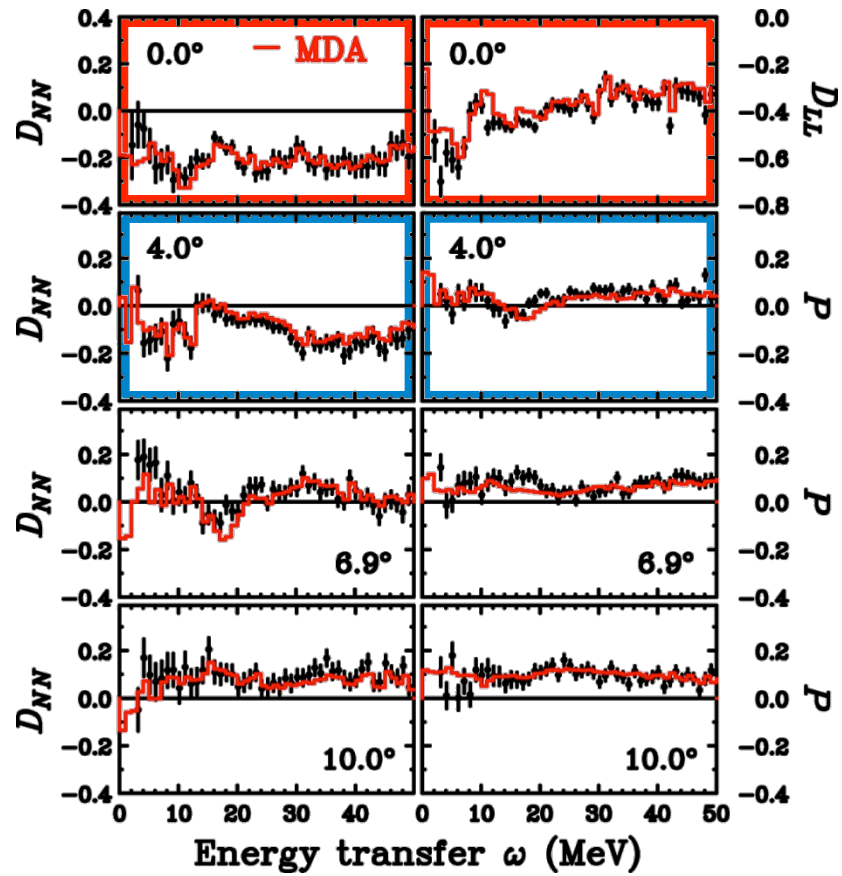
- 295 MeV Polarized protons
  - Predominantly excite GT and SDR
- Beam polarization
  - Control with 2-sets of solenoids
  - Measure with 2-sets of BLP by p-p

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

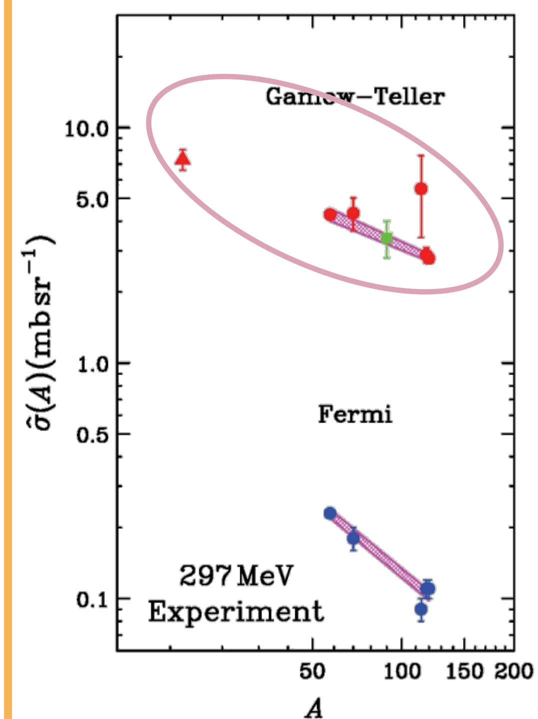
$$\Rightarrow \frac{\sigma^{\mathrm{Exp}}(\mathrm{GT}+\mathrm{IVSM})}{\sigma^{\mathrm{Theor}}(\mathrm{GT}+\mathrm{IVSM})} = \frac{B^{\mathrm{Exp}}(\mathrm{GT})}{B^{\mathrm{Theor}}(\mathrm{GT})}$$

  - 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%



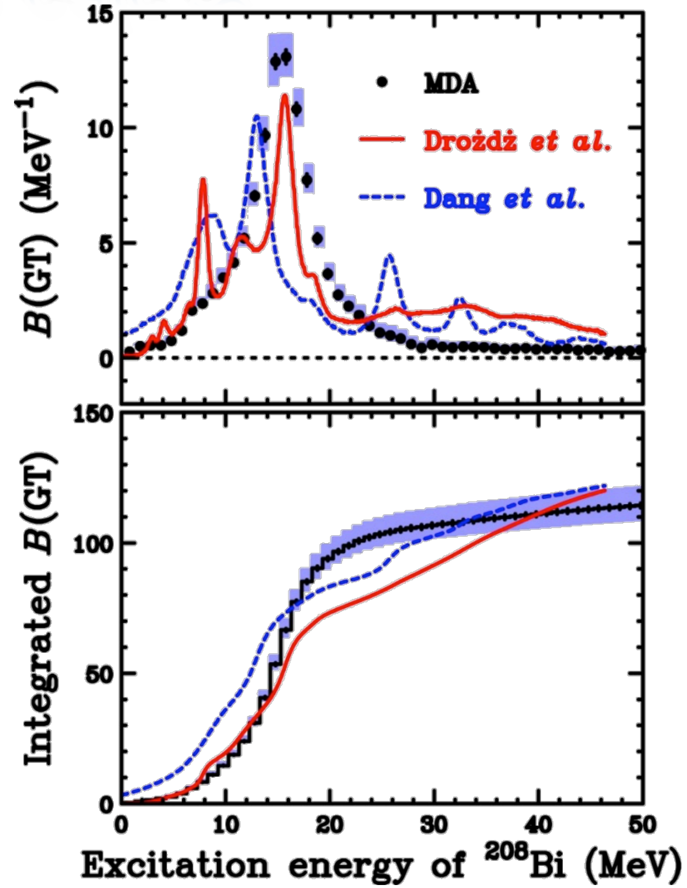
M.Sasano et al.,
PRC 79, 024602 (2009)

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

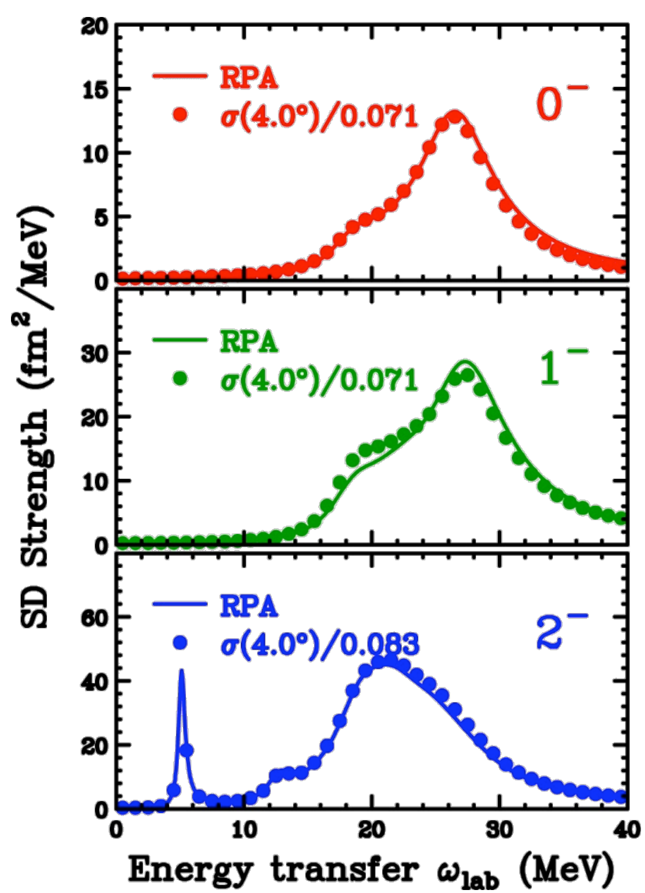
$$\underbrace{\sigma_{\mathrm{SD},J^\pi}(4.0^\circ)}_{\text{MDA}} = \underbrace{\hat{\sigma}_{\mathrm{SD},J^\pi}}_{\text{Unit c.s.}} \underbrace{B(\mathrm{SD})}_{\text{Strength}}$$

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

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

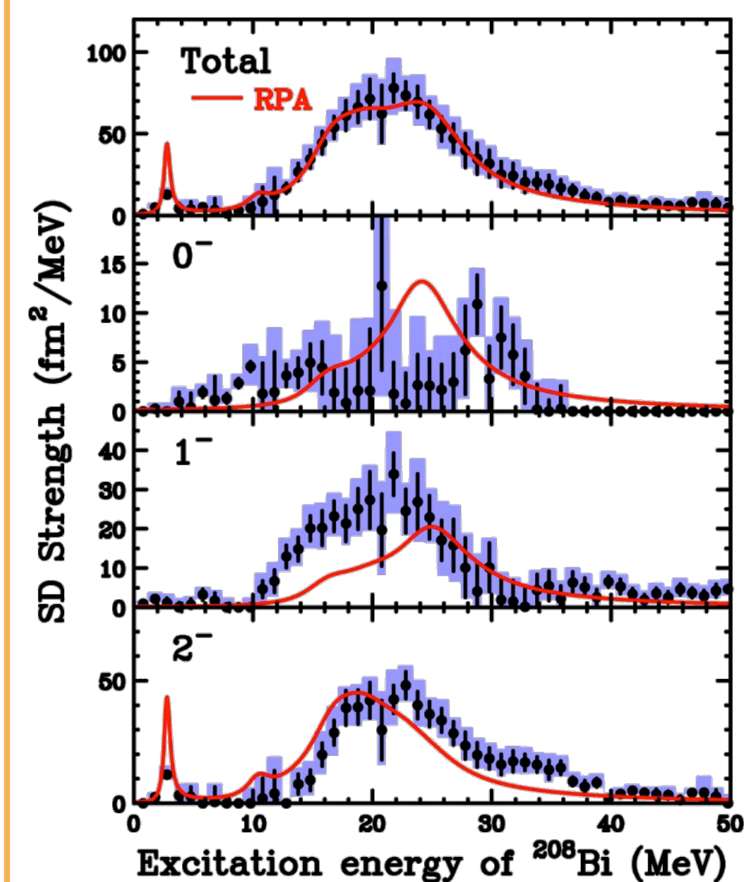
based on DWIA+RPA calc.

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



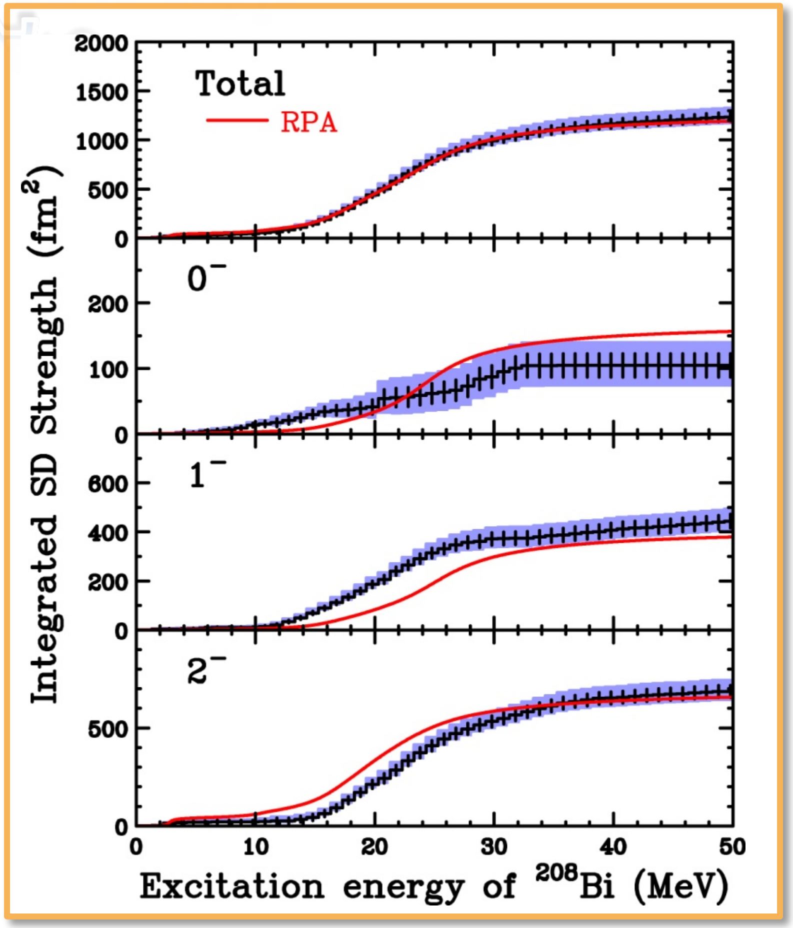
SD Strength Distributions
~Comparison with RPA~

- **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～

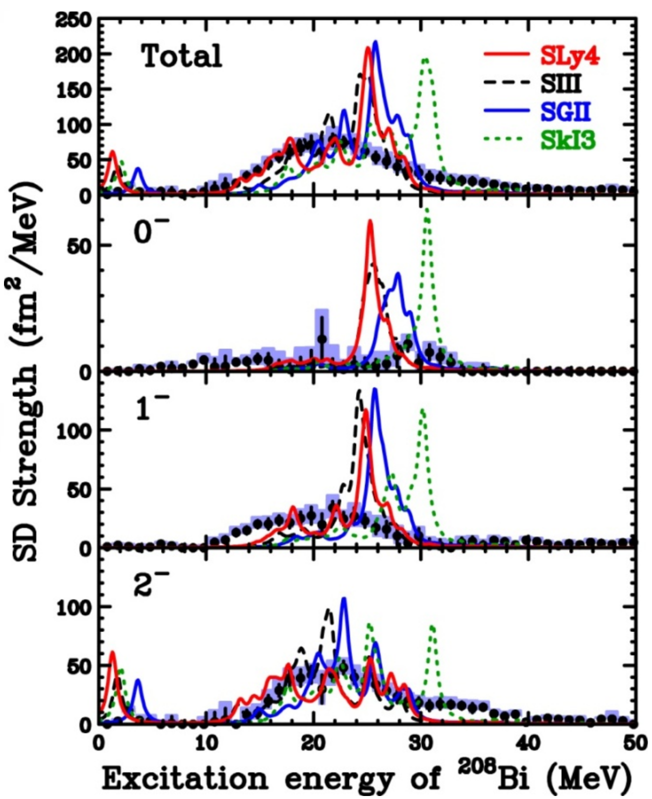
- **Experimental B(SD) from MDA**
  - Uncertainties
    - —— : Statistical uncertainty
    - ▭ : MDA uncertainty
    - ～10% systematic uncertainty from σ_{SD}
- **Comparison with RPA**
  - 0^- : Slightly small (NOT significant)
  - 1^- : Consistent (Softened)
  - 2^- : Consistent (Hardened)
  - Total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

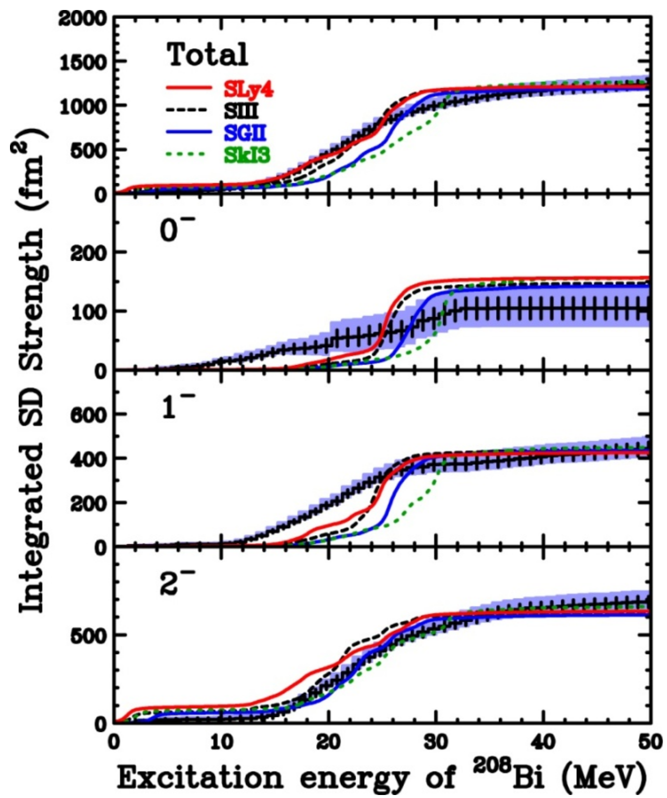


SD strengths are NOT quenched
➢ SD distribution of each J^π is different from theoretical predictions
➢ J^π decomposition in MDA with polarization data is successful

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



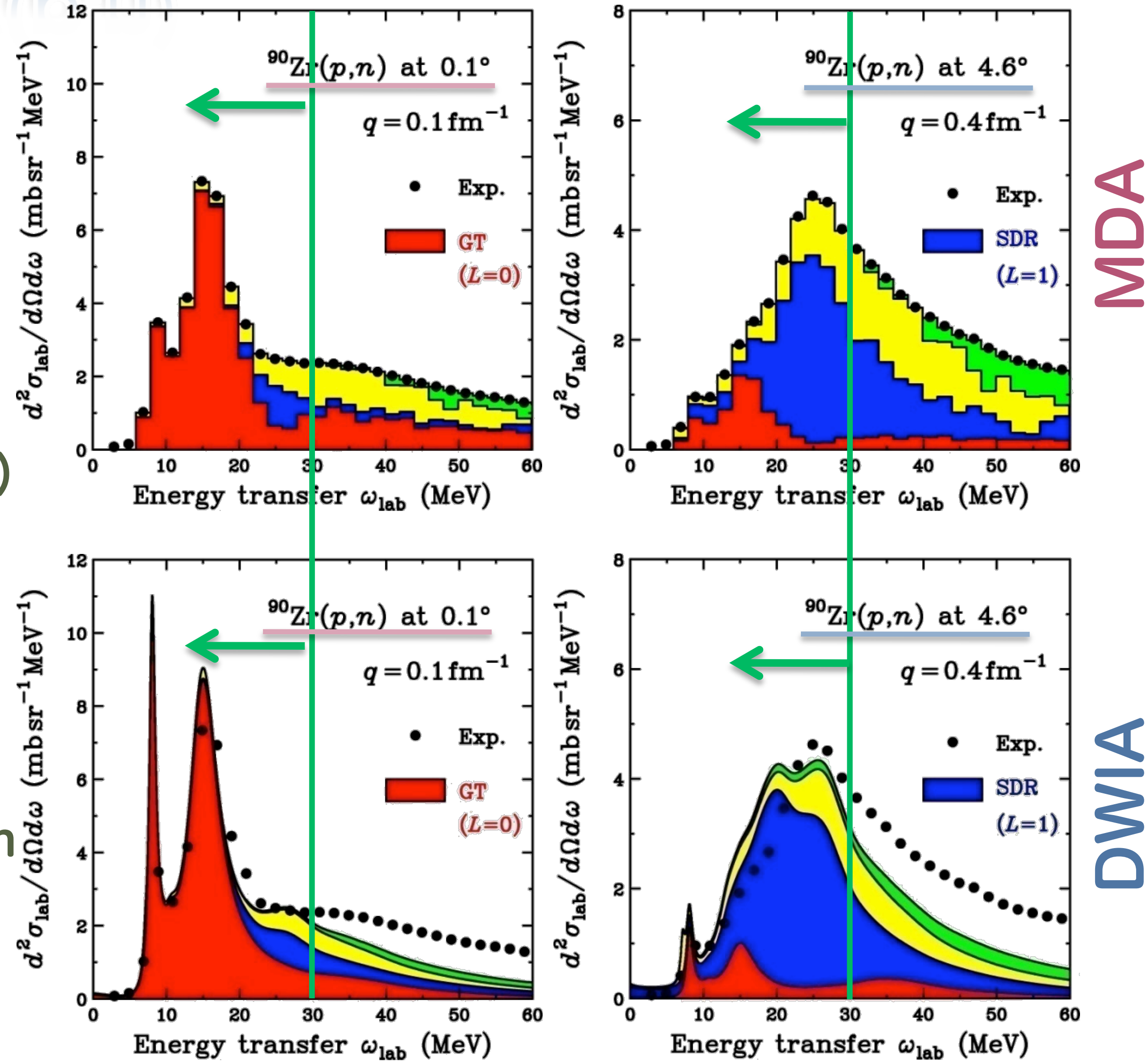


Summary for GT/SD strengths of Stable Nuclei

- **Gamow-Teller strength**
  - Peak position → $g'_{NN} \sim 0.60$
  - Strength (quenching) → $g'_{N\Delta} \sim 0.35$
  - Pionic correlations at large q are also reproduced with these g'
- **Spin-Dipole strengths**
  - Total SD strengths are well reproduced with present g' values
    - Spin composition (0^-, 1^-, 2^-) seems to be different
- **Extension to GT/SD strengths of unstable nuclei**
  - MDA would be unsuccessful due to poor statistics
    - GT/SD strength without MDA ?
      - Physical background in cross section
  - Connection from cross section to GT/SD strength
    - Can DWIA reproduce absolute values of cross sections?
      - YES → Strengths could be deduced from cross sections
- **Predictions for Zr and O isotopes**

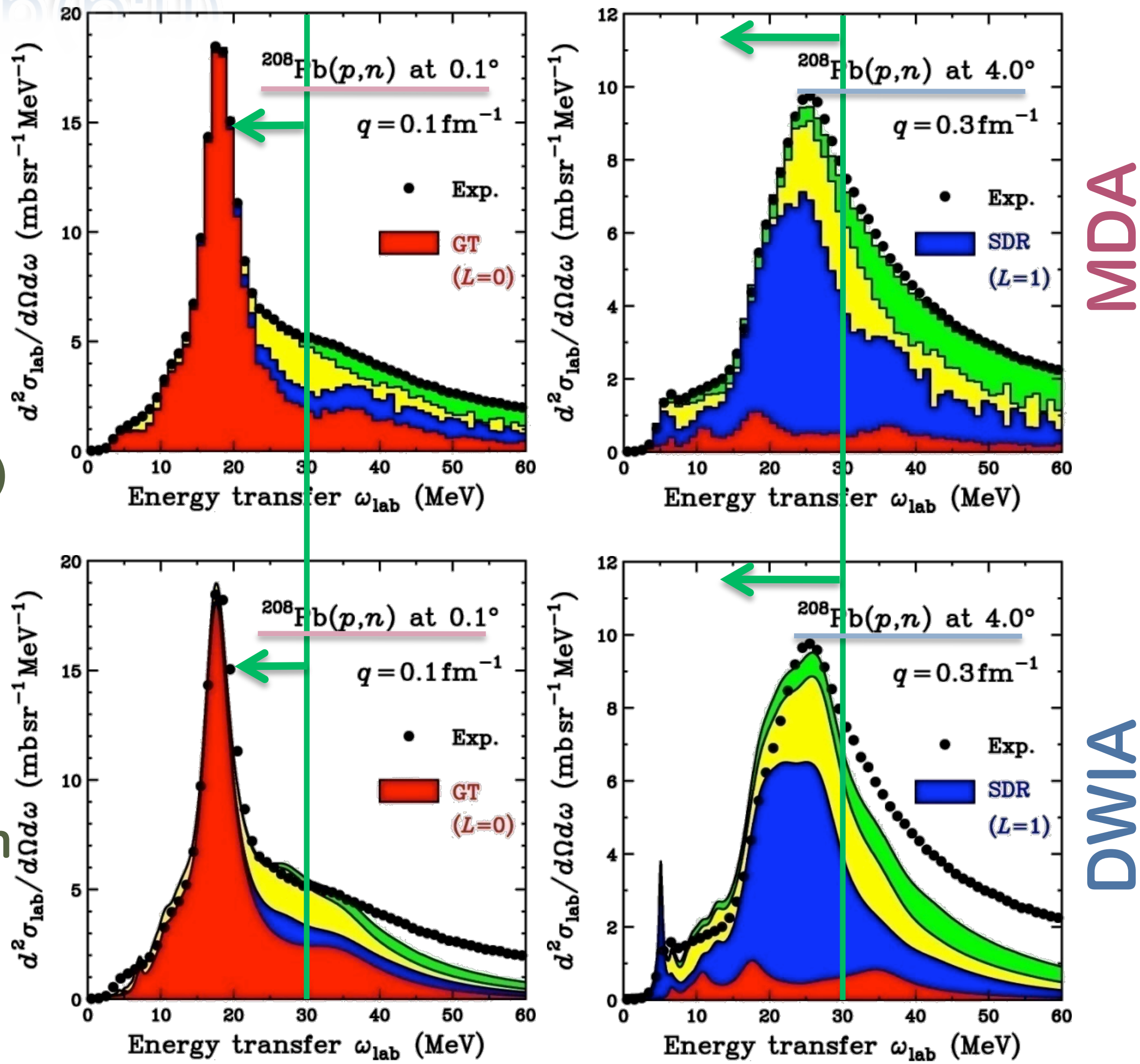
Comparison with MDA and DWIA for ^{90}Zr(p,n)

- MD vs. DWIA
  - Consistent
  - B(GT) and B(SD) can be deduced
  - Negligible 2p-2h effects at ≦ 30 MeV
- GT
  - Negligible B.G. (L≧1) in GTGR
  - B(GT) can be deduced w/o MDA (Not S(GT))
- SD
  - Small (10-20%) BG in SDR
  - B(SD) would be deduced w/o MDA with ～10% error



Comparison with MDA and DWIA for ^{208}Pb(p,n)

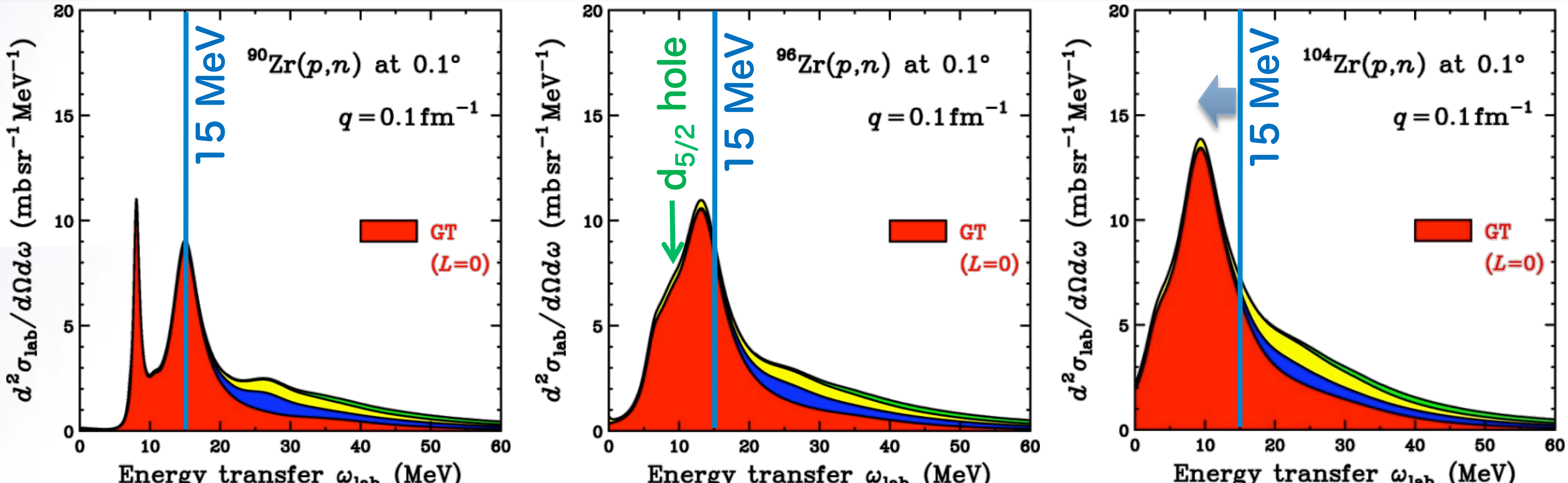
- MD vs. DWIA
  - Consistent
  - B(GT) and B(SD) can be deduced
  - Negligible 2p-2h effects at ≦ 30 MeV
- GT
  - Negligible B.G. (L≧1) in GTGR
  - B(GT) can be deduced w/o MDA (Not S(GT))
- SD
  - Small (10-20%) BG in SDR
  - B(SD) would be deduced w/o MDA with ～10% error



Isotope Dependence of GT for Zr

- **Excess neutron effects on GTR**
  - ^{96}Zr : $d_{5/2}$ hole states fill the valley
    → GT states form a single resonance peak
  - ^{104}Zr : Lower GTR peak position
    → Due to lower proton single particle states
    (Larger binding energy for protons)

Information on s.p. states is important for investigating correlation effects



^{90}Zr
$g_{9/2}$ filled

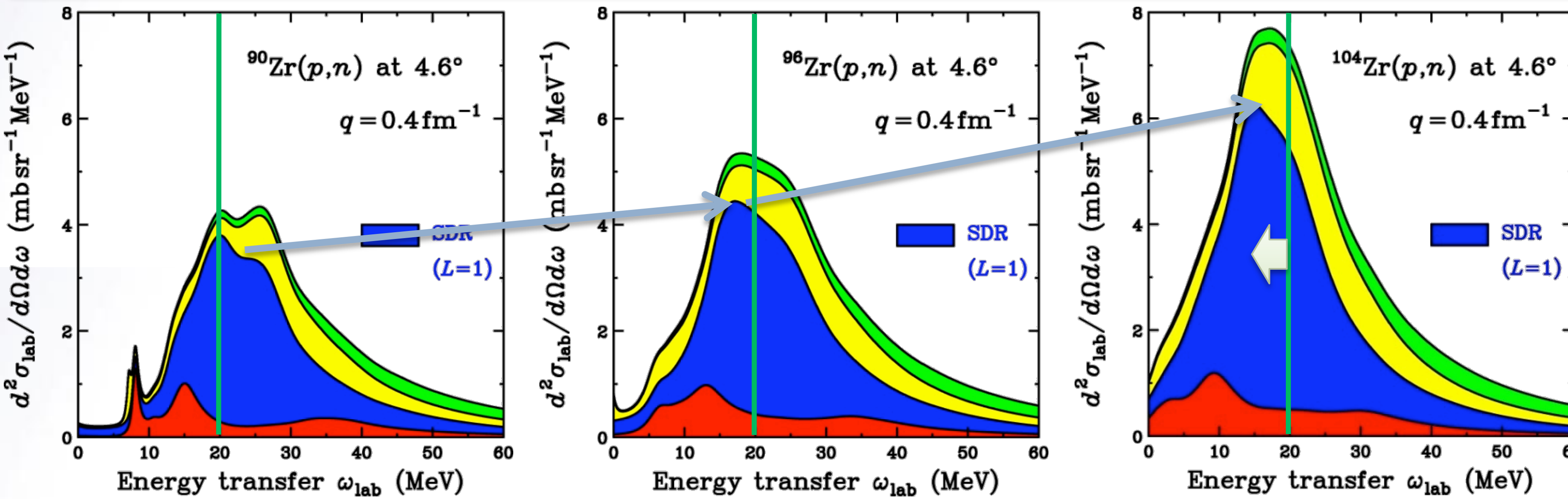
^{96}Zr
$d_{5/2}$ filled

^{104}Zr
$g_{7/2}$ filled

Isotope Dependence of SD for Zr

- **Excess neutron effects on SDR**
  - SDR strengths are increased as a function of (N-Z)
  - SDR peak positions are lowered due to lower proton s.p. energy

SDR strengths could be deduced by using a proportionality ansatz
✓ Neutron skin thickness might be deduced
✓ SDR distributions would give information on interaction beyond $\pi+\rho+g'$



^{90}Zr
$g_{9/2}$ filled

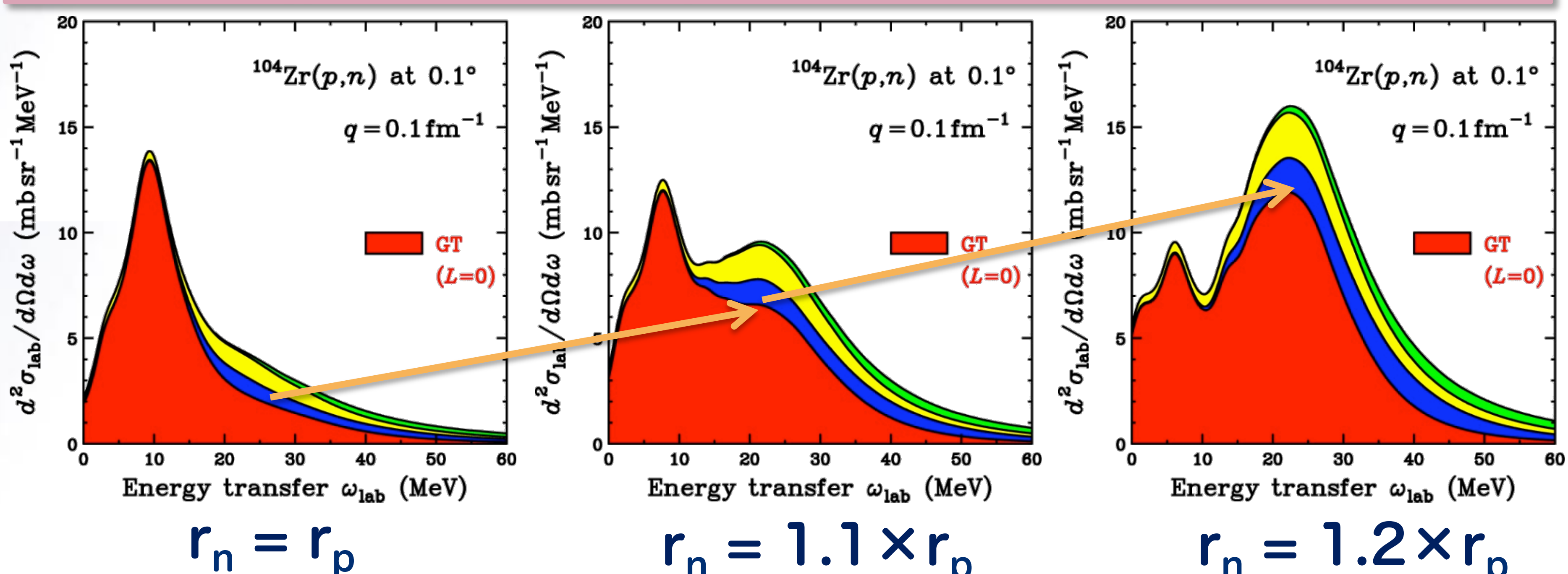
^{96}Zr
$d_{5/2}$ filled

^{104}Zr
$g_{7/2}$ filled

Neutron Skin Dependence of GT for ^{104}Zr

- **Neutron skin effects on GT/IVSM**
  - GT : Peak height would be lowered
    (Interference by IVSM (?))
  - IVSM : Very sensitive to neutron skin thickness

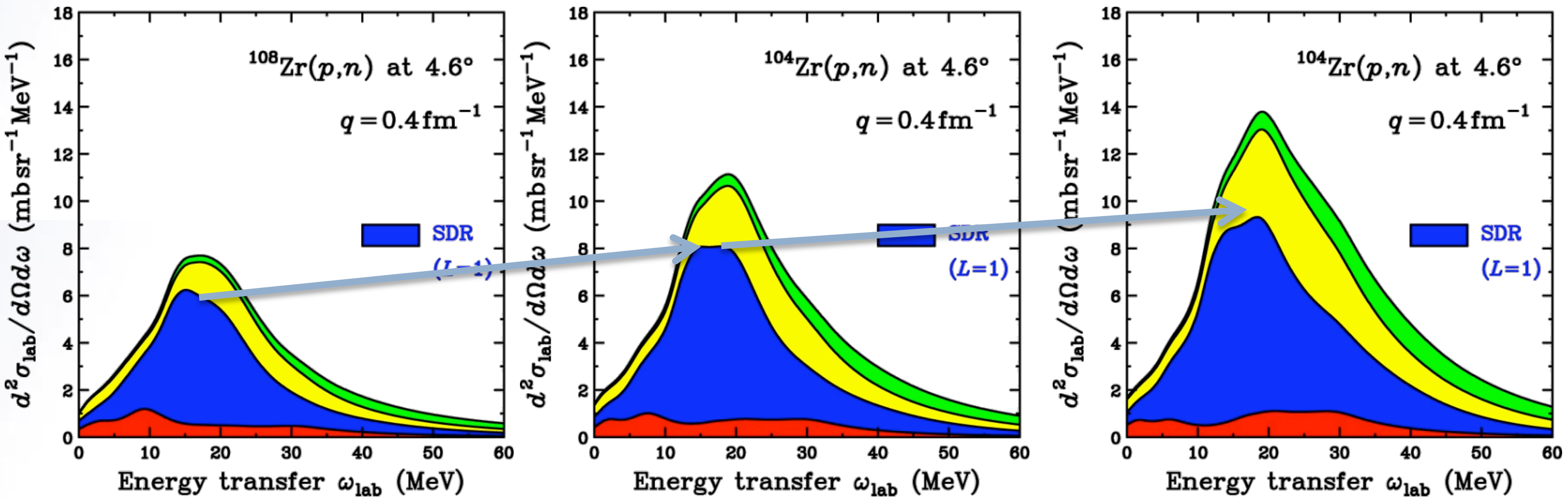
IVSM would be CLEARLY observed for RI with neutron skin
✓ IVSM strength is sensitive to neutron skin thickness
✓ Peak energy $\omega \sim 20$ MeV (Very low compared with stable nuclei)



Neutron Skin Dependence of SD for ^{104}Zr

- **Neutron skin effects on SDR**
  - SDR strengths are increased as a function of $N\langle r_n^2\rangle - Z\langle r_p^2\rangle$
  - Neutron skin effects are NOT so large
    - Effects are comparable with uncertainty of proportionality ansatz

Systematic studies would be required to deduce the neutron skin effects
✓ Compare with the data for normal nuclei/isotope without neutron skin

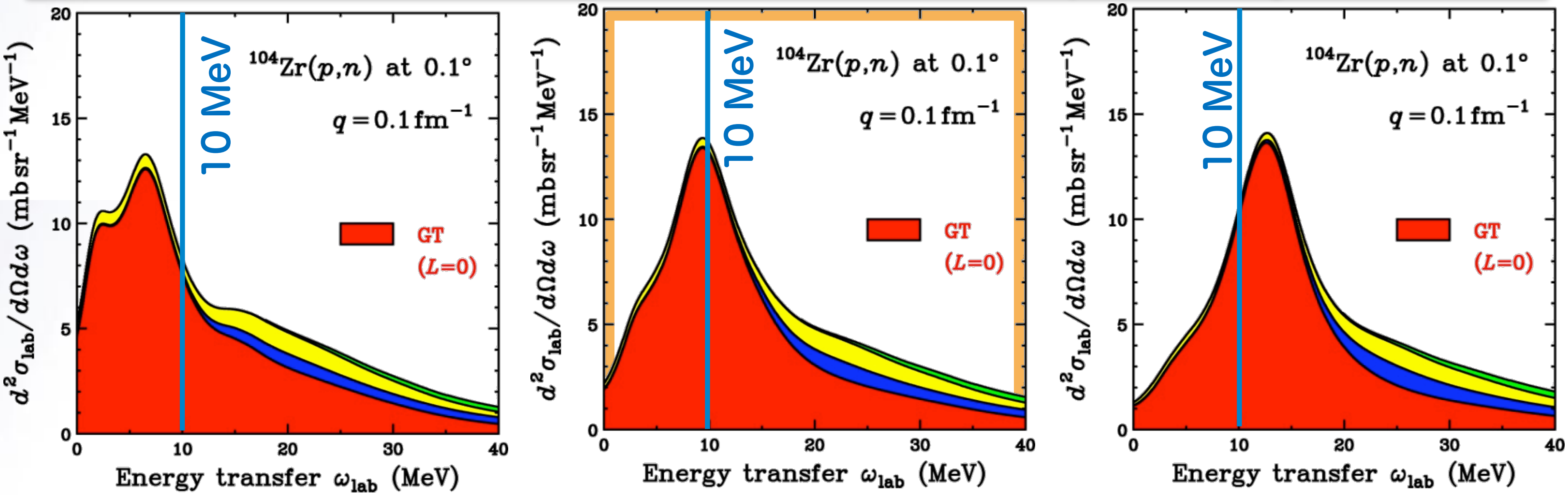


$r_n = r_p$ $\quad$ $r_n = 1.1 \times r_p$ $\quad$ $r_n = 1.2 \times r_p$

g'_{NN} Dependence of GT for ^{104}Zr

- g'_{NN} dependence for GTR
  - GT strength is hardened as a function of g'_{NN}
  - GT strength is ALSO a function of neutron skin thickness

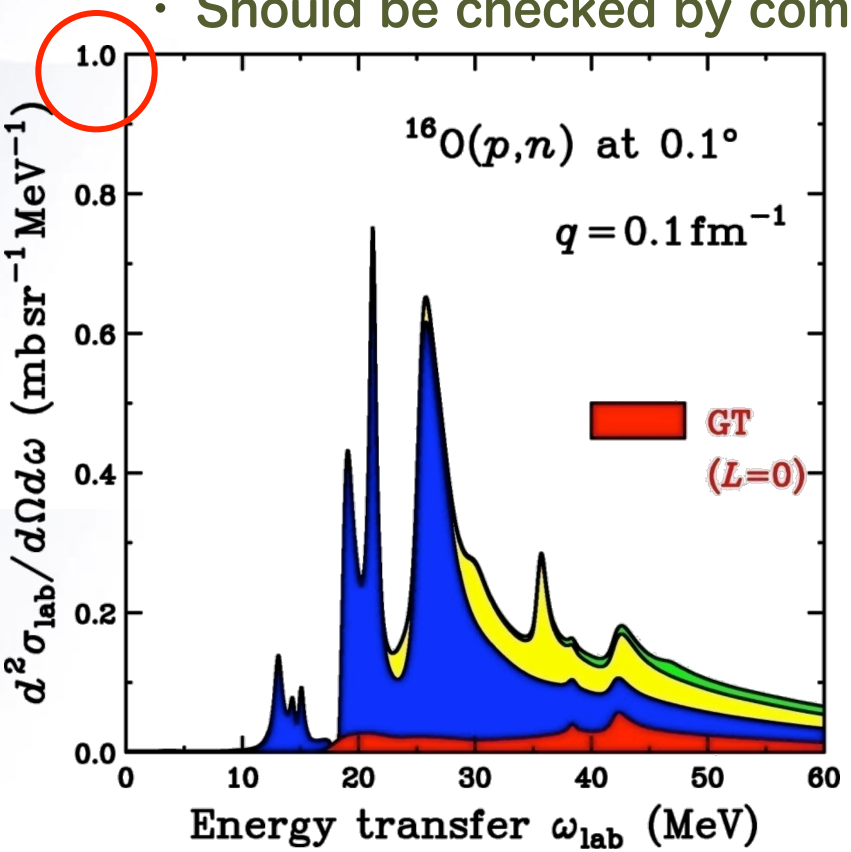
IVSM is sensitive to neutron skin thickness
✓ GTR peak position is NOT sensitive to neutron skin thickness
✓ Simultaneous measurement of GT and IVSM enables us to obtain
- Information on g'_{NN} (nuclear correlation), and
- Information on neutron skin thickness, independentluy



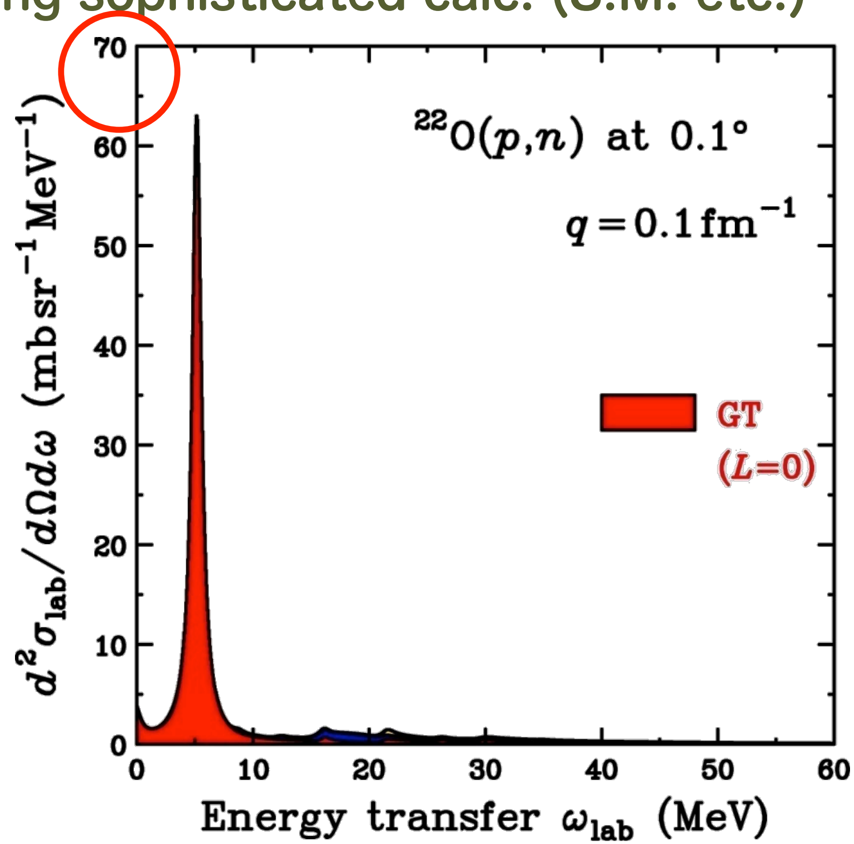
g'_{NN} = 0.3 g'_{NN} = 0.6 g'_{NN} = 0.9

Isotope Dependence of GT for O

- **Excess neutron effects on GT**
  - ^{16}O : GT strength is almost completely suppressed
  - ^{22}O : Prominent GT peak ($d_{5/2}$ hole) is expected
    - Should be checked by comparing sophisticated calc. (S.M. etc.)



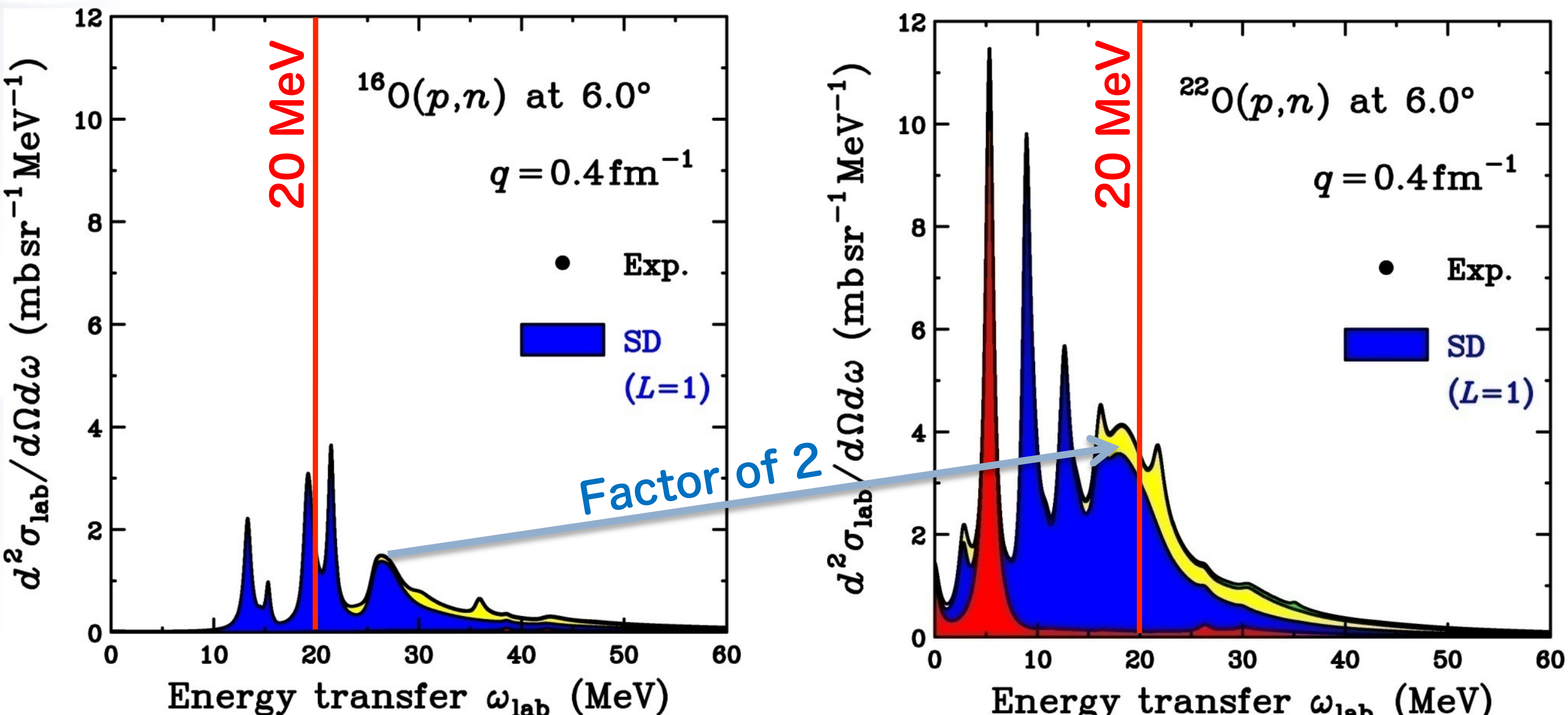
^{16}O : $p_{1/2}$ filled



^{22}O : $d_{5/2}$ filled

Isotope Dependence of SD for O

- **Excess neutron effects on SDR**
  - SDR strengths are increased as a function of (N-Z)
    - Effects are significant compared with Zr due to larger N/Z
    - Neutron skin effects would be more clearly observed
  - SDR peak positions are lowered due to lower proton s.p. energy



^{16}O : $p_{1/2}$ filled

^{22}O : $d_{5/2}$ filled

Summary for Future Perspective

- Proportionality ansatz for deducing GT/SD strengths
  - Reliable at E/A∼300 MeV within ∼10%
- Physical background for deducing GT/SD strengths
  - Less than 10-20% in p-h region (≦30%)
  - Uncertainty of strength ∼ 10-20% without MDA
    - MDA should be performed for total strength S
- Prediction for Zr
  - Excess neutron effects would be observed in GT peak
  - Excess neutron effects would be observed in SD strength
  - IVSM would be clearly observed for nuclei with skin
- Prediction for O
  - Excess neutron effects would be more clear compared with Zr

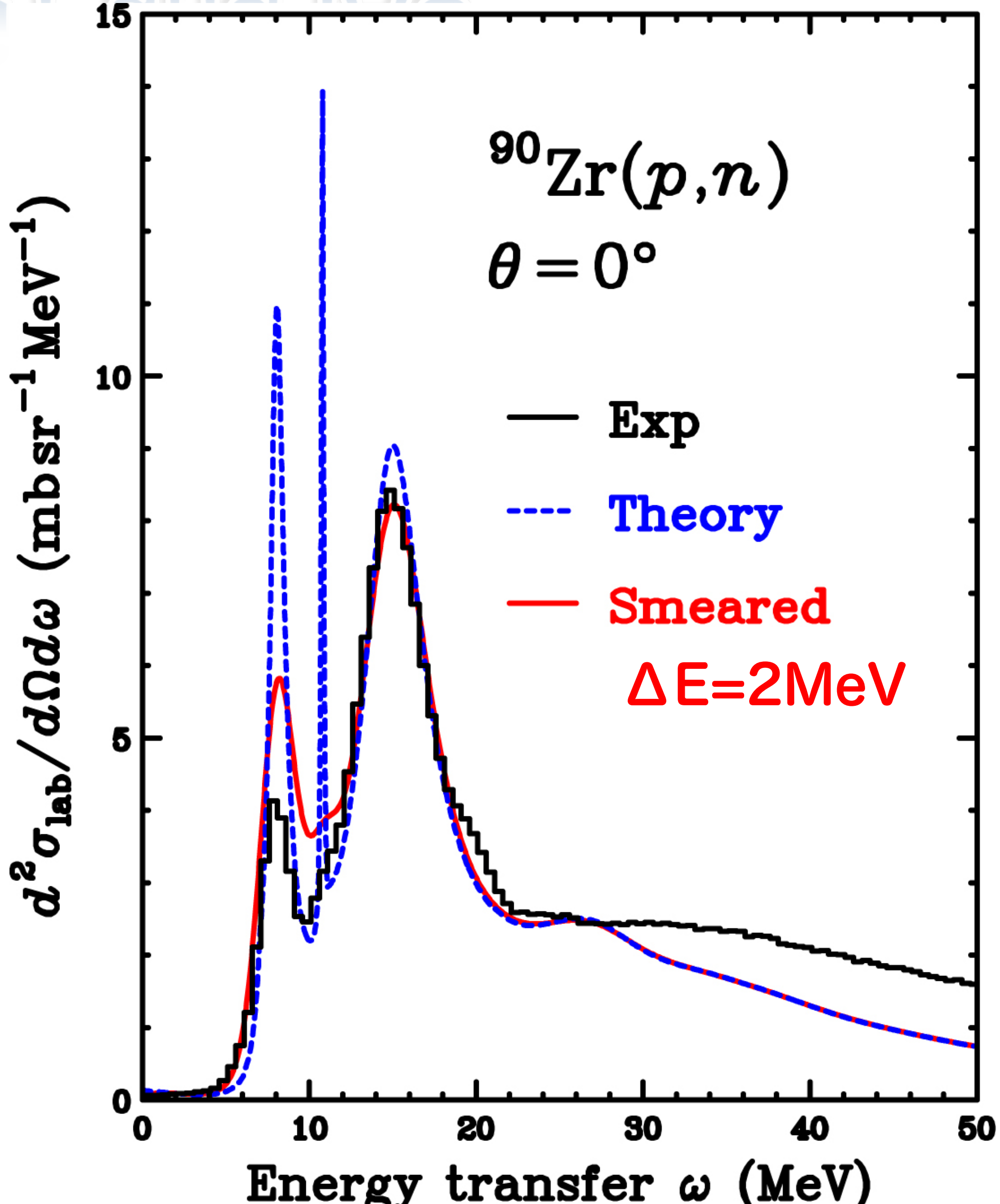
Comment

✓ Elastic scattering data are important for reliable DW calculations

✓ Information on s.p. levels is important for correlation effects

BACKUP

GT and IAS

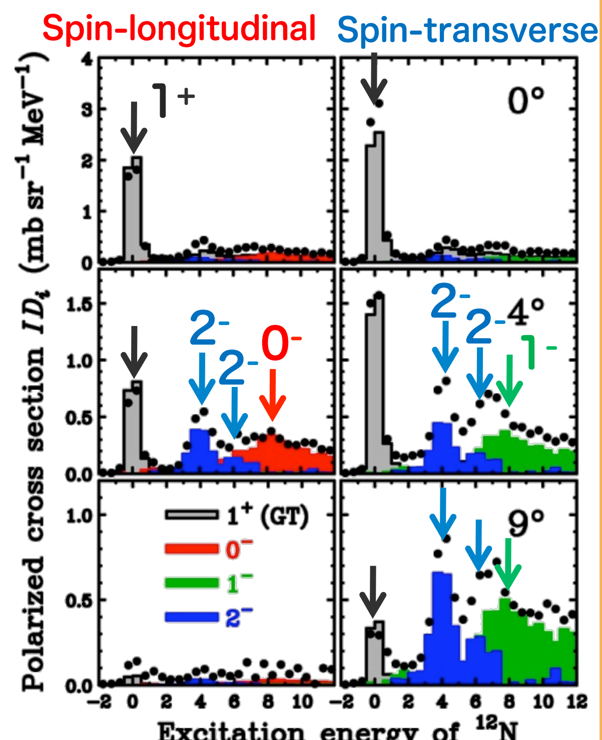


^{90}Zr(p,n)
θ = 0°
Exp
Theory
Smeared
ΔE=2MeV
$d^2\sigma_{lab}/d\Omega d\omega$ (mb sr^{-1} MeV^{-1})
Energy transfer ω (MeV)
0
5
10
15
0
10
20
30
40
50

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

M. Dozono (Doctor work)

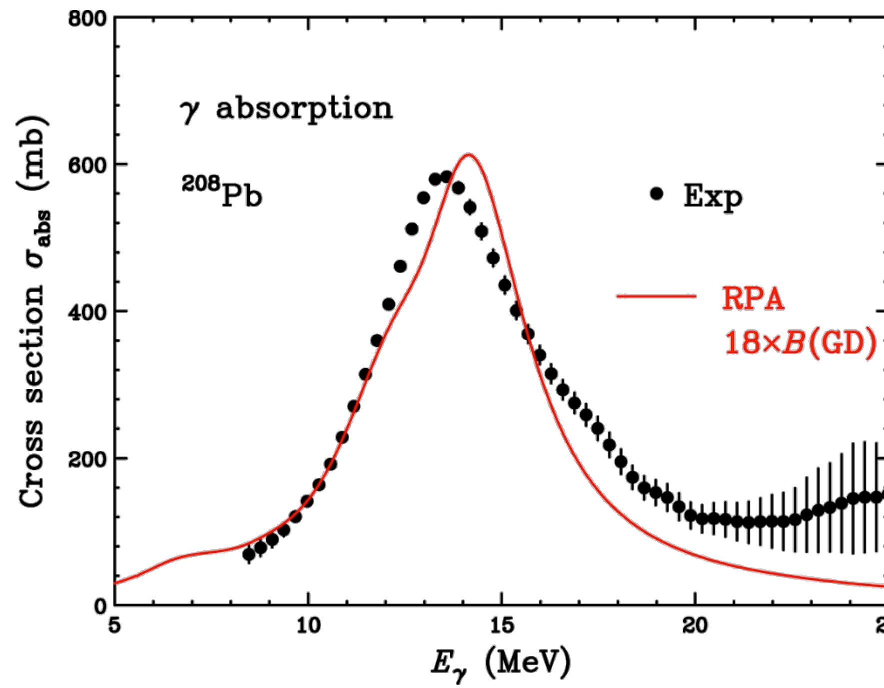


- Perspective (In Progress)
  - MDA with "complete" polarization data
    - 0^-,1^-,2^- Separation becomes more reliable
    - We can check the reliability of MDA
  - RCNP-E317 : $^{12}C(p,n)^{12}N$
    - Complete polarization data at 0°, 2°, 4°, 6°, 9°, 12° (6 angles)

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

Comment on GDR

- **Experimental GDR strength**
  - γ absorption
    - GDR is dominant
  - $E_x \sim 14$ MeV
  - $\Gamma \sim 4$ MeV
- **RPA calculation**
  - NO free parameter
    - f is determined by IAS
  - Phenomenological spreading width
  - (p,n) and (γ,n) difference is properly taken into account
  - Proportionality ansatz
    - $\sigma_{abs} = 18 \times B(GDR)$

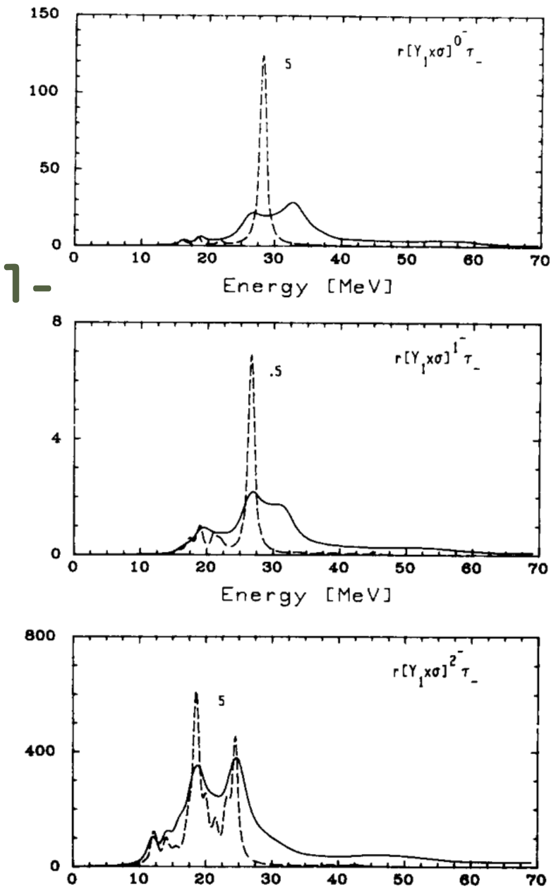


S.N.Belyaev et al., Yad. Phys. 55, 289 (1992).

GDR strength is well described by RPA
→In MDA, GDR (non-spin) component can be fixed to RPA(γ-abs. data)

Previous Studies of SDR

- **Theoretical predictions**
  - 2p2h effects in 2nd-order RPA (SRPA)
    - Smear out RPA distributions
    - Move strengths to higher energies
  - Smearing effects are relatively small in 2-
    - 2- has large config. compared with 0- and 1-
    - 2- strength is fragmented in RPA(1p1h)
    - 0- and 1- strengths → 2p2h effects



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