Charge exchange spin dipole sum rule and the neutron skin thickness

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NuSYM10, Jul. 27, 2010

Isovector modes of the giant resonance

Giant resonances

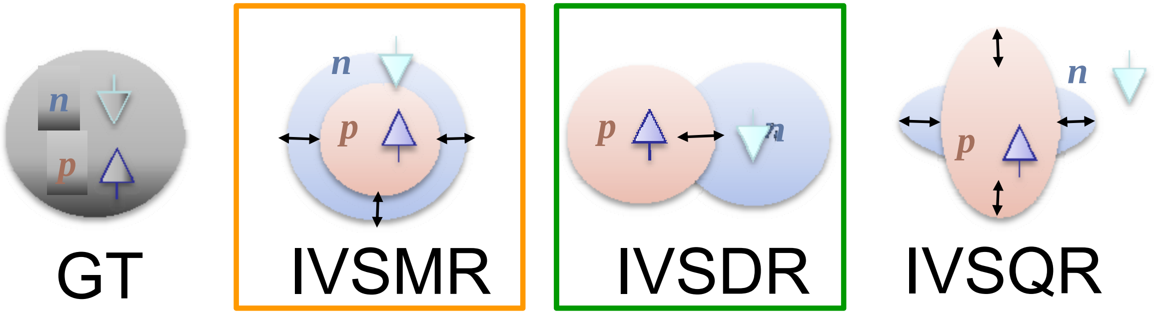
- Gross feature of nuclear matter at $\rho \approx \rho_0$
- Constraints on effective interaction: (f.g. Skyrme type)

  Excitation energy, Width, …

  N.B.) comparison through structure model

Isovector spin modes

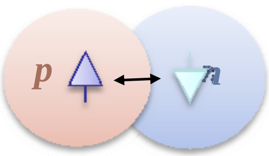
isovector spin giant resonances ($\Delta T=1, \Delta S=1$)



GT	IVSMR	IVSDR	IVSQR
$\Delta L=0$	$\Delta L=0$	$\Delta L=1$	$\Delta L=2$
$0\hbar\omega$	$2\hbar\omega$	$0\hbar\omega$	$0\hbar\omega$

Contents

1. Deduction of less model-dependent quantity



IVSDR

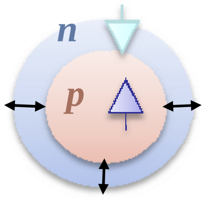
$\Delta L=1$

$0\hbar\omega$

→ Neutron skin thickness

^{90}Zr(p,n) and ^{90}Zr(n,p) work
@RCNP

2. Search / establishment of new collective modes



IVSMR

$\Delta L=0$

$2\hbar\omega$

^{90}Zr, ^{208}Pb(t,^{3}He) work
@BigRIPS + SHARAQ

Neutron skin thickness

proton and neutron distributions : fundamental properties of nuclei

$\sqrt{\langle r^2 \rangle_p}$: well known … $\delta\left(\sqrt{\langle r^2 \rangle_p}\right) < 0.01\,\mathrm{fm}$

$\sqrt{\langle r^2 \rangle_n}$: poorly known … $\delta\left(\sqrt{\langle r^2 \rangle_n}\right) \approx 0.1\,\mathrm{fm}$

Neutron skin thickness:

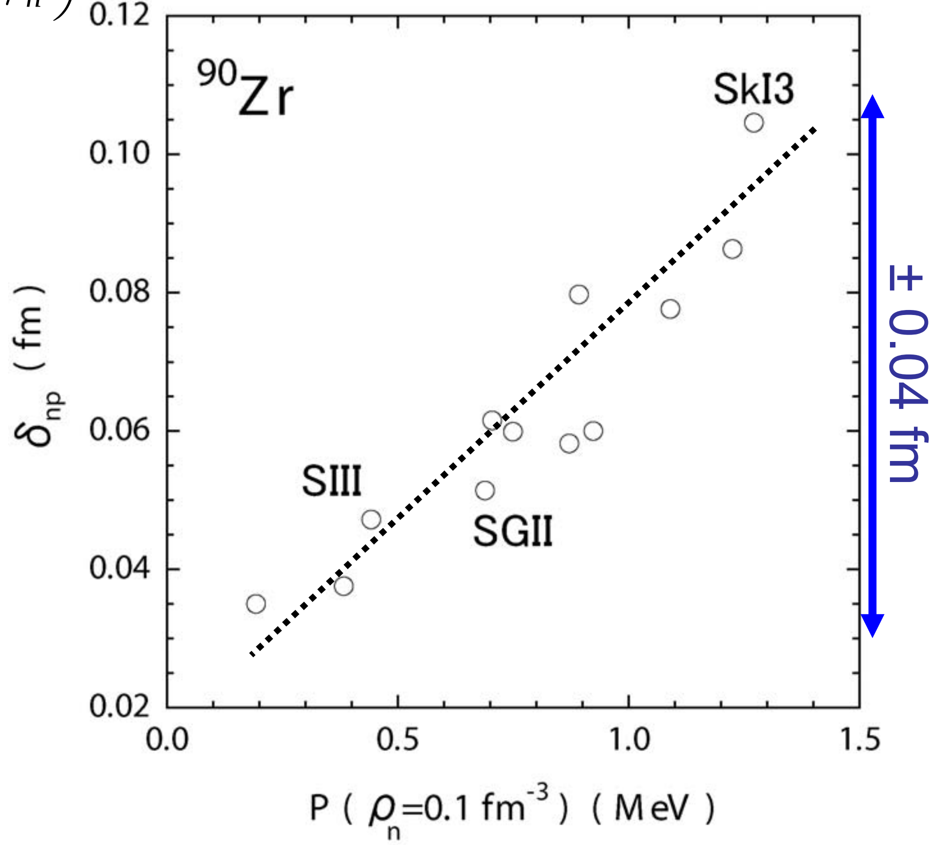
$$\delta_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p}$$

related to physics
on nuclear matter.

δ_{np} has
strong correlations with
- symmetry energy
- EOS of neutron matter

accuracy of better than
± 0.04 fm is needed.

Sagawa et al.



Method of obtaining δ_{np}

$\sqrt{\langle r^2\rangle_p}$

- electron elastic scattering

$\sqrt{\langle r^2\rangle_n}$

- proton elastic scattering
- isovector GDR excitation by α scattering
- antiprotonic x-ray

$\Big\}$ model dependent

- parity-violation electron scattering
- isovector spin-dipole sum rule

Charge exchange spin dipole operator: $\hat{O}_{\mathrm{SD}\pm} = \sum_{im\mu} t^i_\pm \sigma^i_m r_i Y_1^\mu(\hat{r}_i)$

$J^\pi = 0^-, 1^-, 2^-$

Model independent sum rule:

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

↑ ↑ (p,n) (n,p)

↑ e scattering

extract total SD strengths from

^{90}Zr(p,n) [Wakasa et al.] and ^{90}Zr(n,p) data taken at RCNP

(p,n) & (n,p) work

(p,n) & (n,p) at 300 MeV

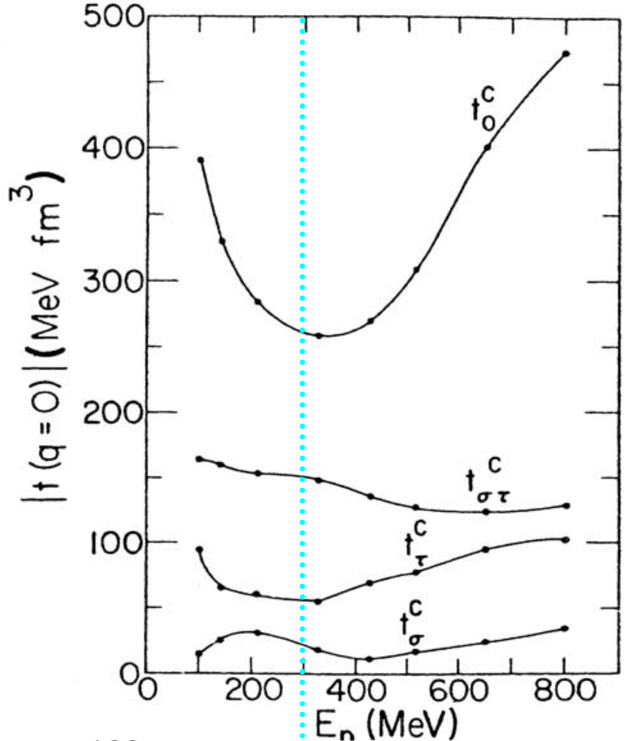
- Simple reaction mechanism
- 300 MeV:
  - Distortion effects are smallest (t_0).

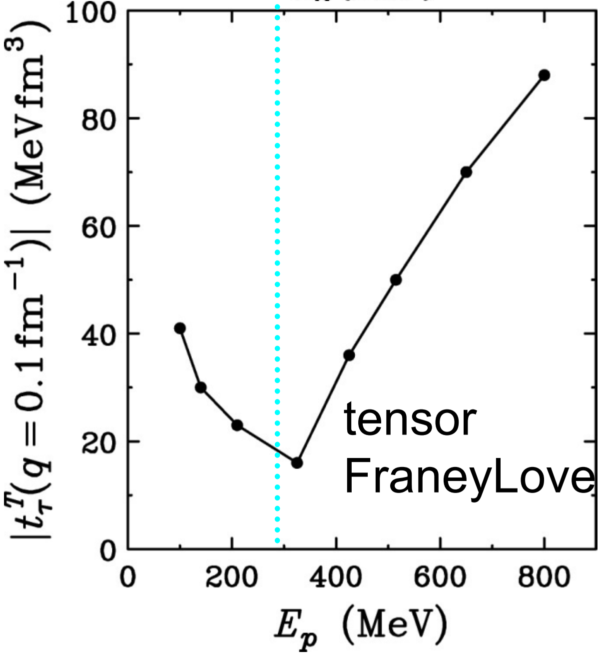
    ⇒ analysis with DWIA is reliable.
  - Tensor interaction is smallest (t_τ^T).

    ⇒ Proportionality relation is reliable.

    cross section ⇔ strength

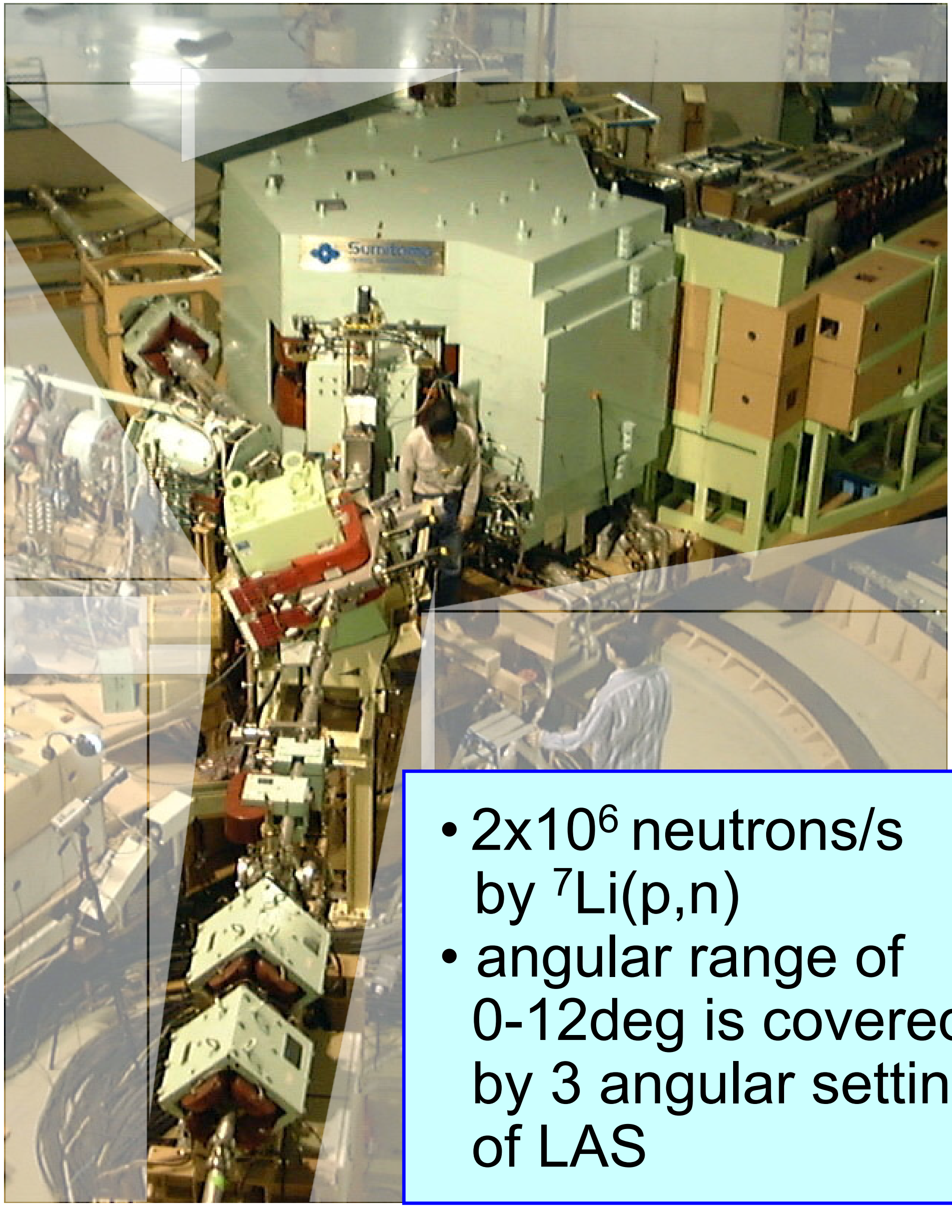
… Multipole decomposition analysis works best.





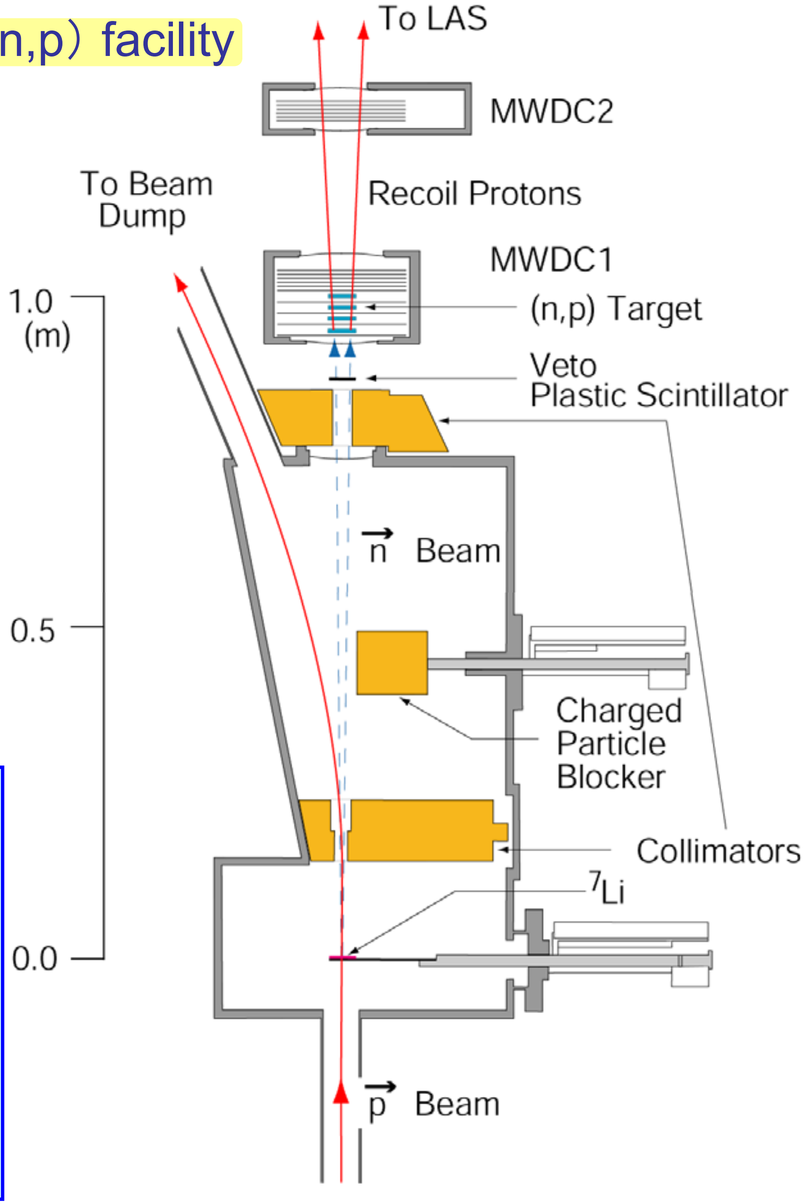
tensor
FraneyLove

(n,p) experiment at RCNP



- 2×10^6 neutrons/s by ^{7}Li(p,n)
- angular range of 0-12deg is covered by 3 angular setting of LAS

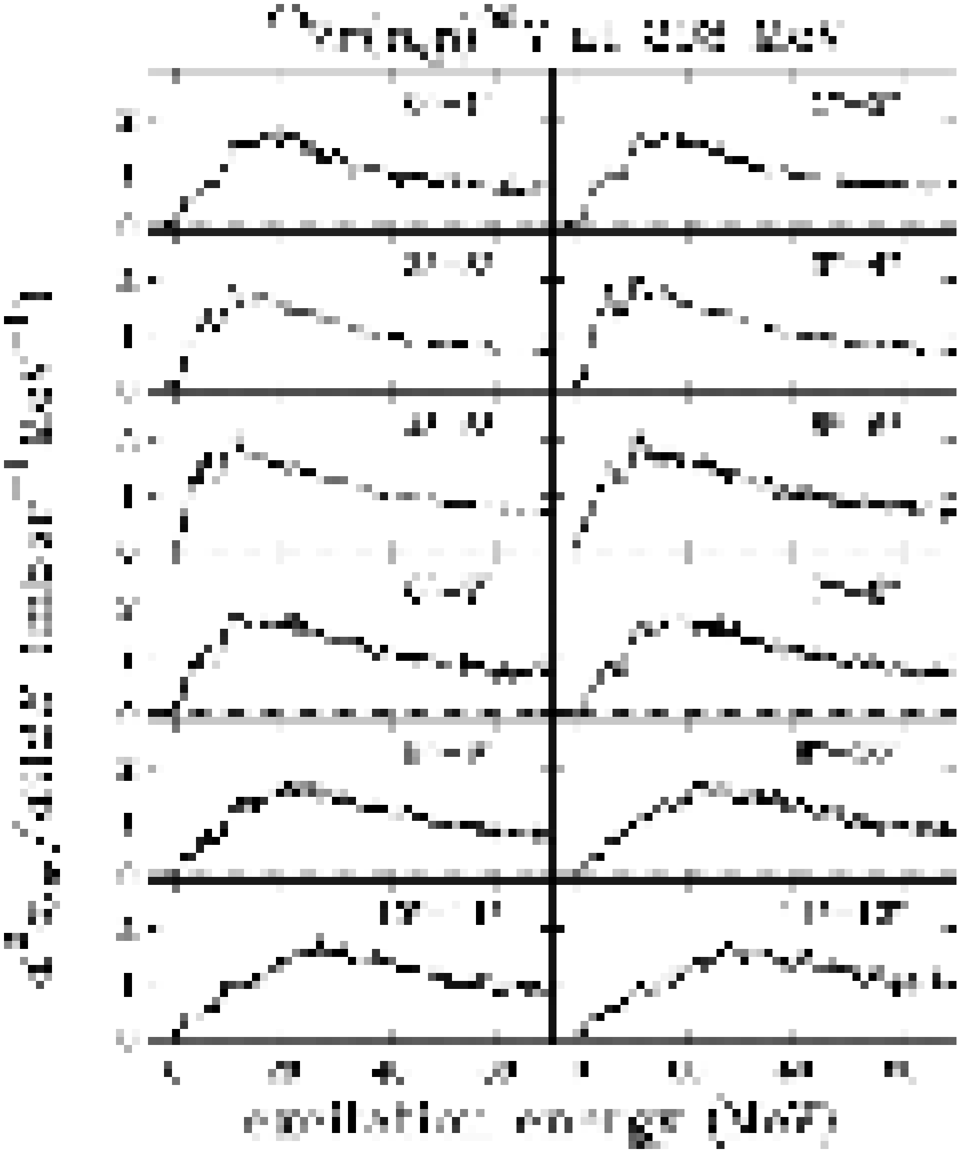
（n,p）facility



Cross section spectra

Double differential
cross sections

- statistical accuracy
  ~4% / 0.5 MeV bin
  ~2% / 2 MeV bin
- energy resolution
  1.5 MeV



Small dipole (?) peaks
are observed at
3 MeV
6 MeV
10 MeV

SD strengths?

Multipole decomposition analysis

MDA

$$\sigma^{\mathrm{exp}}(\theta_{\mathrm{cm}},E_x) \approx \sum_{J^\pi} a_{J^\pi}\,\sigma^{\mathrm{calc}}_{ph;J^\pi}(\theta_{\mathrm{cm}},E_x)$$

DWIA

$$J^\pi = 1^+, 0^-, 1^-, 2^-, 3^+, 4^- \quad (\Delta L = 0, 1, 2, 3)$$

DWIA inputs

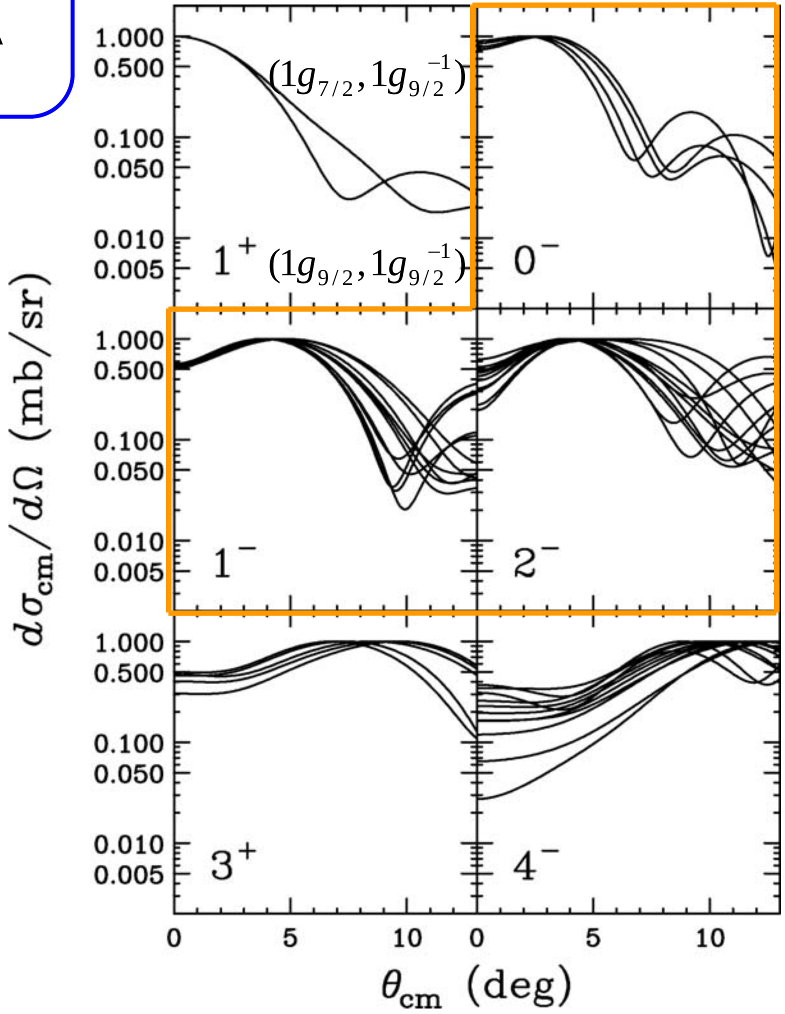
- NN interaction:
  t-matrix by Franey & Love @325 MeV
- optical model parameters:
  Global optical potential
  (Cooper et al.)
- one-body transition density:
  pure 1p-1h configurations
  - n-particle
    $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $1h_{11/2}$, $3s_{1/2}$
  - p-hole
    $2p_{1/2}$, $2p_{3/2}$, $1f_{5/2}$, $1f_{7/2}$

  radial wave functions … W.S. / H.O.

^{90}Zr(n,p) angular dist.

ω = 20 MeV

0^-, 1^-, 2^-: inseparable



DWIA … reliable

K.Y. , PRL 103, 012503 (2009)

Low Ex region

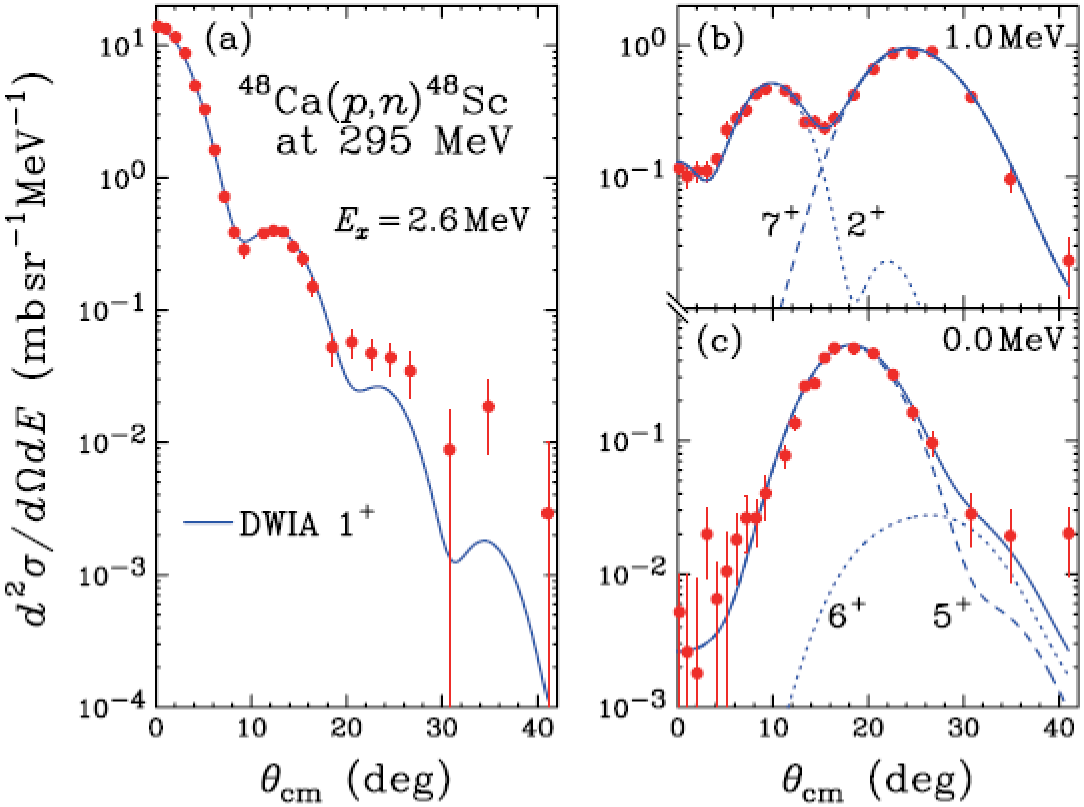


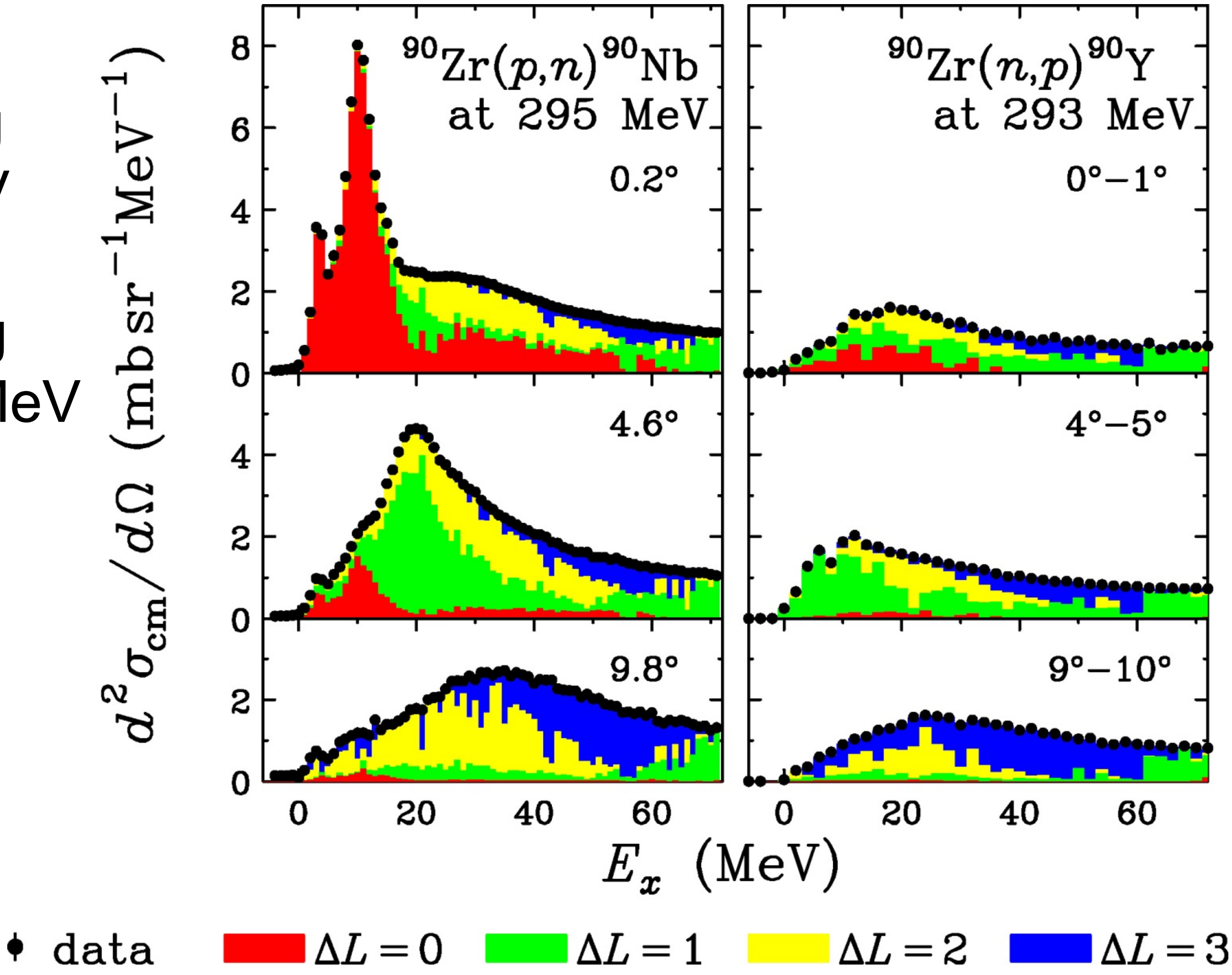
FIG. 2 (color online). Angular distributions of the double-differential cross section for the ^{48}Ca$(p, n)^{48}$Sc reaction at (a) $E_x = 2.6$ MeV, (b) 1.0 MeV, and (c) 0.0 MeV. The curves represent DWIA calculations with appropriate normalizations.

Decomposed spectra

PLB615(2005)193

- (p,n) at 4.6 deg
  SDR at 20 MeV

- (n,p) at 4-5 deg
  c.s. below 10 MeV
  … due to ΔL=1

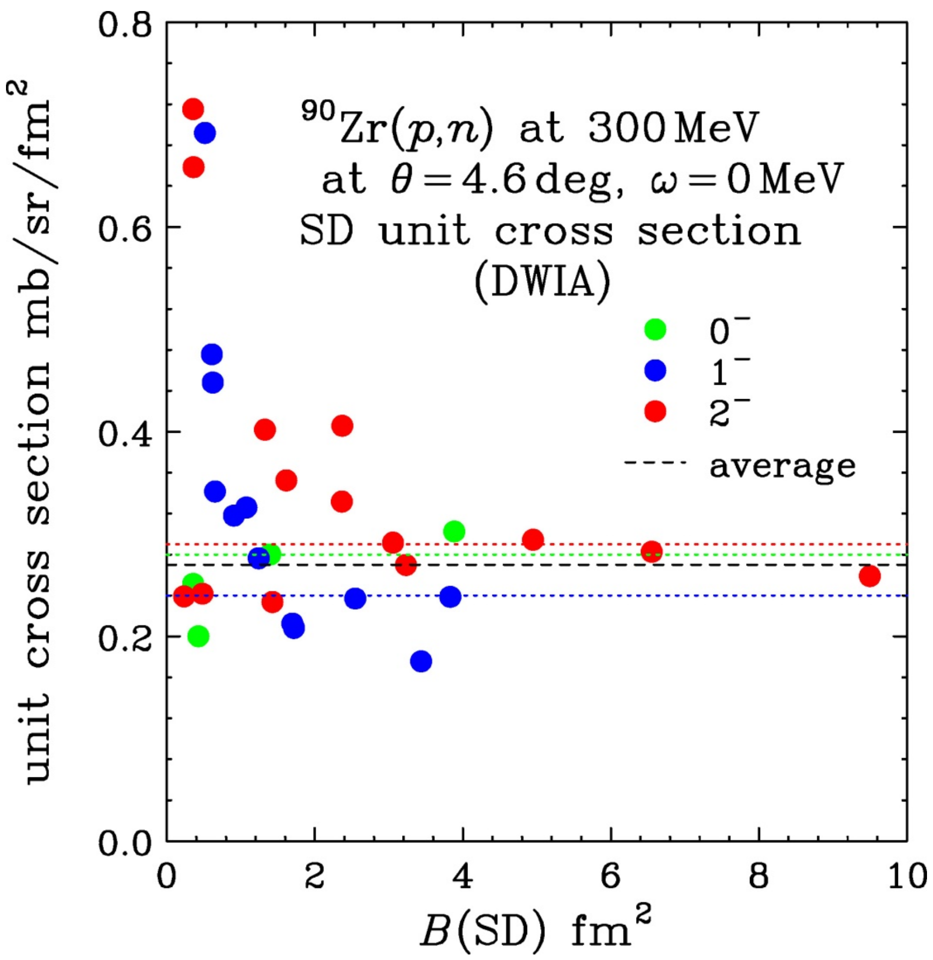


Proportionality relation & unit cross section

$$\sigma_{\Delta L=1,\pm}(q,\omega) = \hat{\sigma}_{\mathrm{SD}\pm}(q,\omega)\, B(\mathrm{SD}_{\pm})$$

data “unit cross section” ← DWIA

(p,n) … $\sigma_{\Delta L=1,-}(q,\omega)$ at 4.6 deg



- The averaged value works if you discuss the sum rule value rather than state-by-state strengths.
- Uncertainty of calculated $\hat{\sigma}_{\mathrm{SD}\pm}(q,\omega$

  … ±14%. ↰

  optical potential, radial wave function

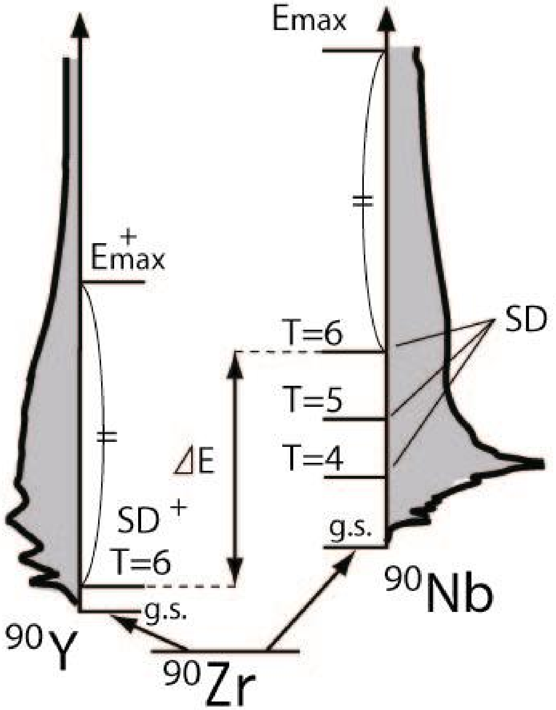
Differences are due to:

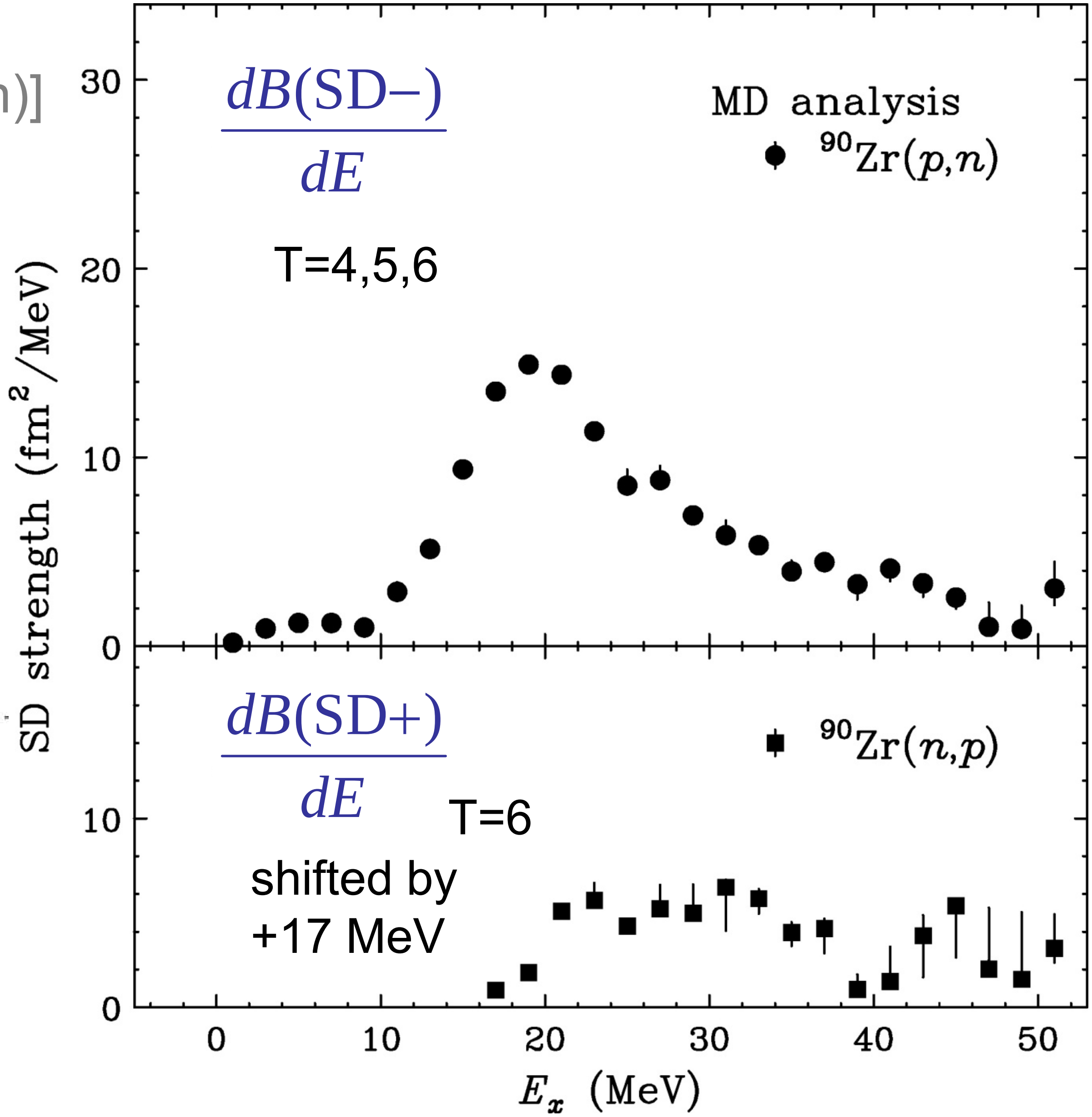
- tensor interaction
- ph combinations of…
  - different radial quantum numbers
  - “ $j_< j_<$ ”

SD strength distributions

MD analysis

- single SDR bump [(p,n)]
- asymmetric shape … strength extends to ∼50 MeV
- unstable analysis above 40 MeV [(n,p)]





$$\frac{dB(SD-)}{dE}$$

T=4,5,6

$$\frac{dB(SD+)}{dE}$$

T=6

shifted by
+17 MeV

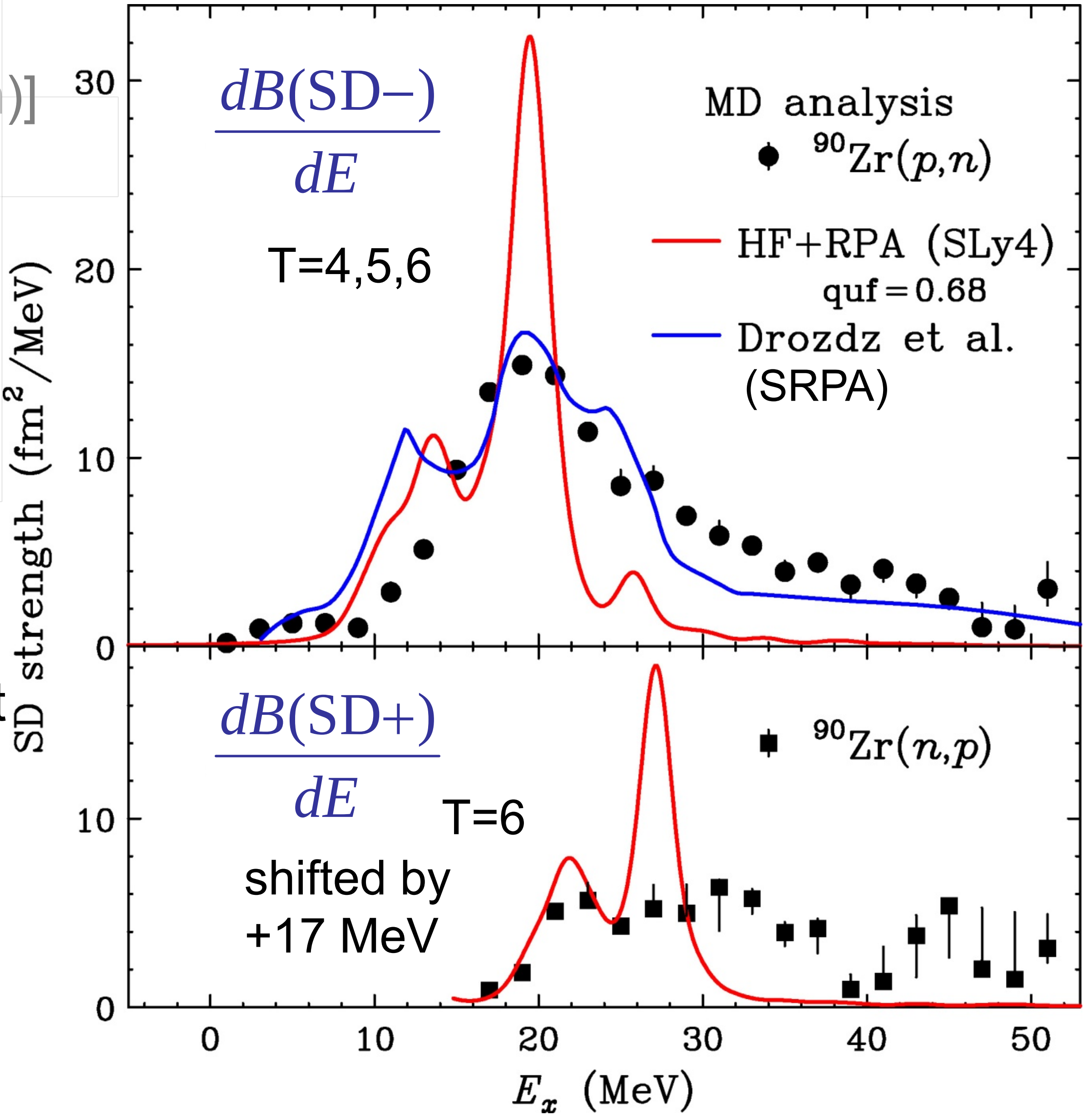
SD strength distributions

MD analysis

- single SDR bump [(p,n)]
- asymmetric shape … strength extends to ∼50 MeV
- unstable analysis above 40 MeV [(n,p)]

HF+RPA

- two or more bumps
- reasonable agreement below 25 MeV with quf = 0.68
- 2p-2h is necessary above 25 MeV



$$\frac{dB(SD-)}{dE}$$

T=4,5,6

$$\frac{dB(SD+)}{dE}$$

T=6

shifted by +17 MeV

Sum rule value

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

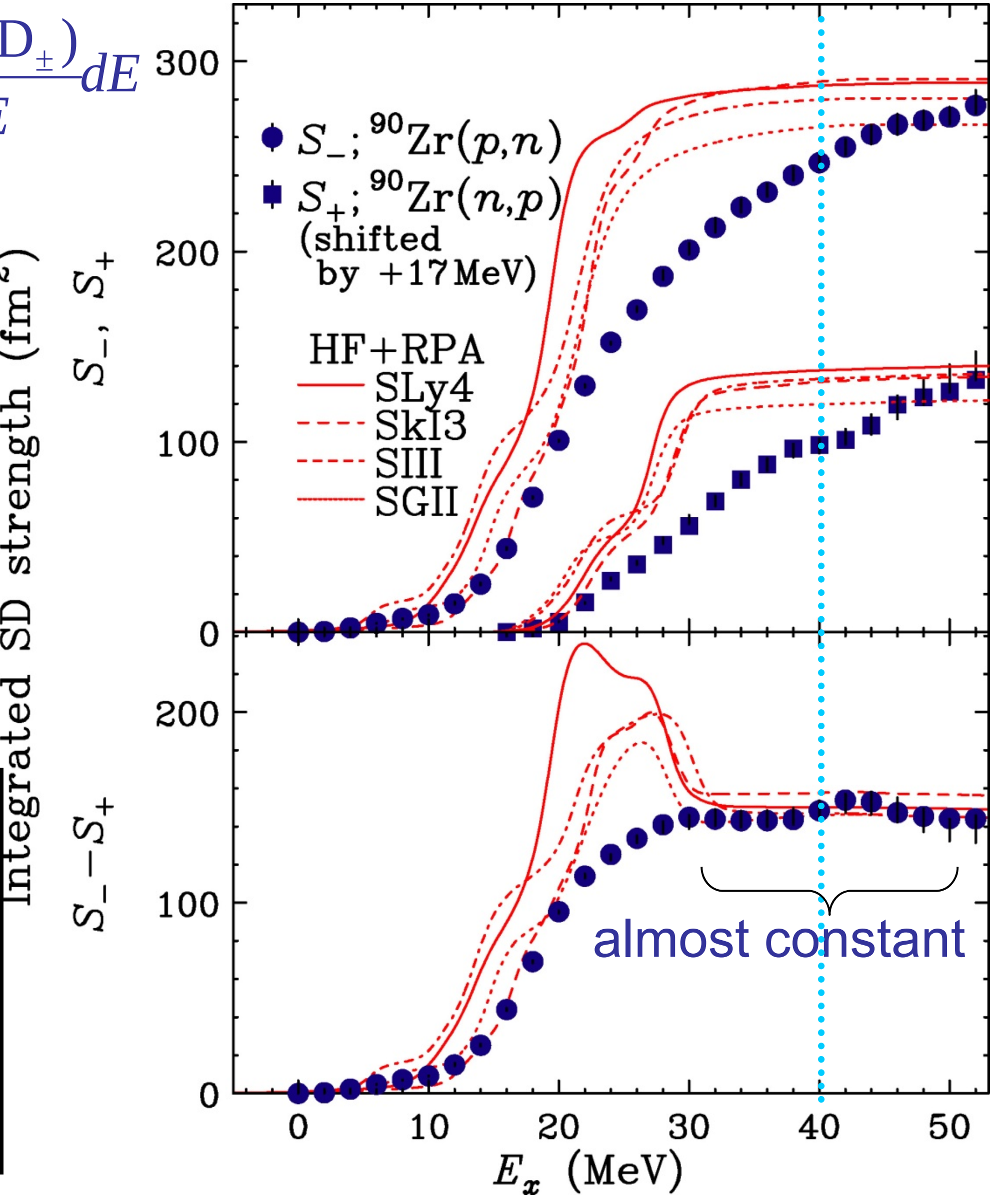
Exp values approach
HF+RPA values at
50 MeV excitation.

Sum rule value $S_{-} - S_{+}$

stable at 30 < E_x < 50 MeV

Strengths (fm^2) below 40 MeV

S_-	S_+	$S_- - S_+$
247 ±4(stat.) ±12(MD)	98 ± 4(stat.) ± 5(MD)	148 ± 6(stat.) ± 7(MD) ± 7(syst.)



Neutron skin thickness

Neutron skin thickness

$$\left.\begin{array}{l} S_{-} - S_{+} = 148 \pm 13\ \mathrm{fm}^2 \\ \sqrt{\langle r^2 \rangle_p} = 4.19\ \mathrm{fm} \end{array}\right\} \quad \delta_{np} = 0.07 \pm 0.04\ \mathrm{fm}$$

method	nucleus	δ_{np} (fm)	Ref.
p elastic scatt.	^{90}Zr	0.09 ± 0.07	Ray, PRC18(1978)1756
antiprotonic x-ray	^{90}Zr	0.09 ± 0.02	Trzcinska, PRL87(2001)082501
IVGDR by α scatt.	^{116,124}Sn	… ± 0.12	Krasznahorkay, PRL66(1991)1287
SDR by (^{3}He,t)	$^{114\text{--}124}$Sn	… ± 0.07	Krasznahorkay, PRL82(1999)3216
SDR by (p,n) & (n,p)	^{90}Zr	0.07 ± 0.04	this work, PRC74(2006)51303R

goal of parity violation electron scattering: ± 0.04 (1%)

Summary … SDR → δ_{np}

- We studied SD excitations from ^{90}Zr by the (p,n) and (n,p) reactions by MD analysis.
- The strength distributions below 25 MeV excitation are well reproduced by HF+RPA calculations with quf=0.68.
- Integrated SD str. below 40 MeV (in fm^2):
  - S_- = 247±4(stat.)±12(MD)
  - S_+ = 98±4(stat.)±5(MD)
  - S_- - S_+ = 148±6(stat.)±7(MD) ±7(syst.)
- Neutron skin thickness: 0.07±0.04 fm

Collaborators:

Experiment:

K. Y., H. Sakai, and RCNP-E149 collaborators

Theory:

H. Sagawa, S. Yoshida

[E149 members]

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Measurement of the Isovector Spin Monopole Resonance via the ^{208}Pb,^{90}Zr(t,^{3}He) Reactions at 300MeV/u

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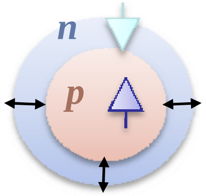
Isovector spin monopole resonance (IVSMR)



IVSMR

ΔL=0, ΔS=1

2ħω

operator : $O^{\pm}_{1\mu} = \sum_i \sigma_\mu t_\pm r^2$

sum rule : $S_- - S_+ = 3\left(N\langle r^4\rangle_n - Z\langle r^4\rangle_p\right)$

Significance

- Constrain Effective interaction (Skyrme int. etc.)
- "Compression" mode
  ⇒ nuclear compressibility involving spin-isospin vibration
- Very sensitive to skin thickness

Previous Exp.

IVSMR(β^-) – a few signatures
(^{3}He,t)@KVI, (p,n)@LANL

IVSMR(β^+) – no clear signature
(n,p)@TRIUMF

Our Measurement : **^{208}Pb, ^{90}Zr(t,^{3}He) @ 300A MeV**

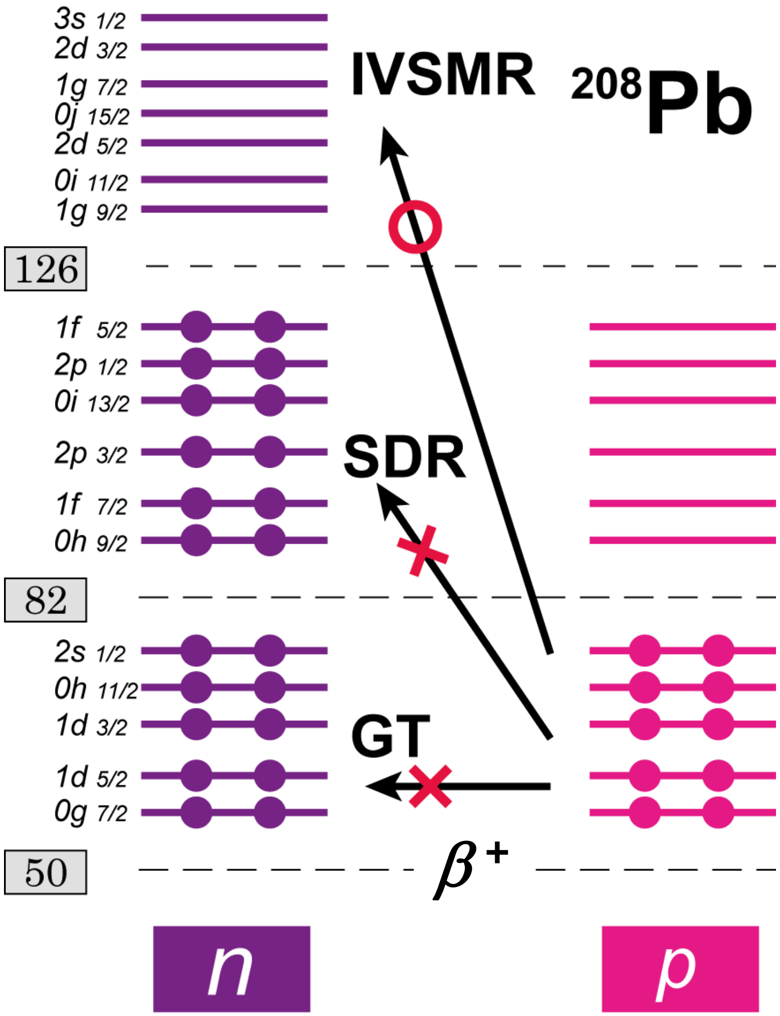
Target : Pauli-blocking emphasizes IVSMR(β^+)

^{208}Pb & ^{90}Zr

In β^+ channel …

- **GT** → blocked
- **SDR** → blocked for ^{208}Pb
  [except for ($\nu 0i_{11/2}, \pi\, 0h_{11/2}^{-1}$)]

⇒ **IVSMR** will be a major component.



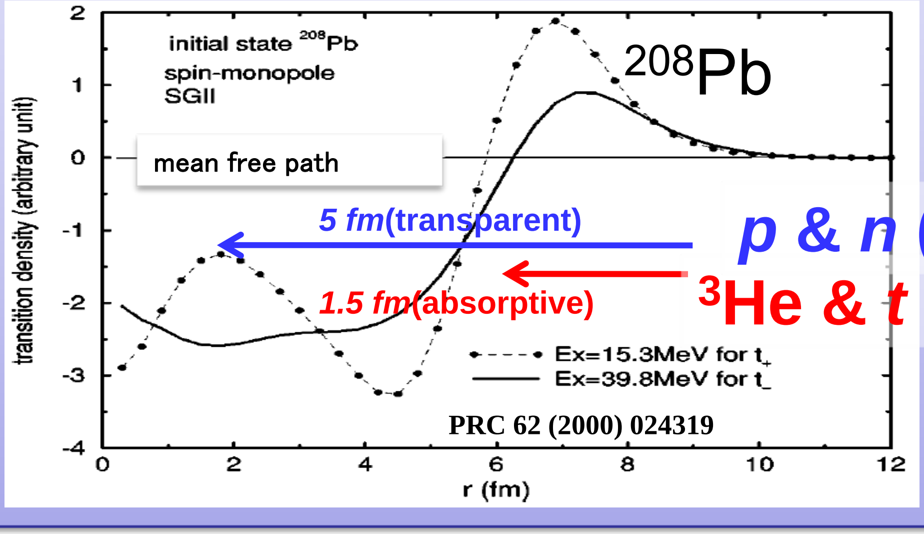
Probe : Clean & Surface-sensitive

(t,^{3}He) @ 300A MeV

1. **300A MeV** → -- spin-isospin response is favored
   -- one-step contribution is dominant
   quantitative analysis (e.g. MDA) is applicable.
2. **(t,^{3}He) reaction** → -- large absorption effect

Transition density has a radial node.

$$4\pi\int\rho_{\mathrm{tr}}(r)\,r^2\,dr = 0$$



PRC 62 (2000) 024319

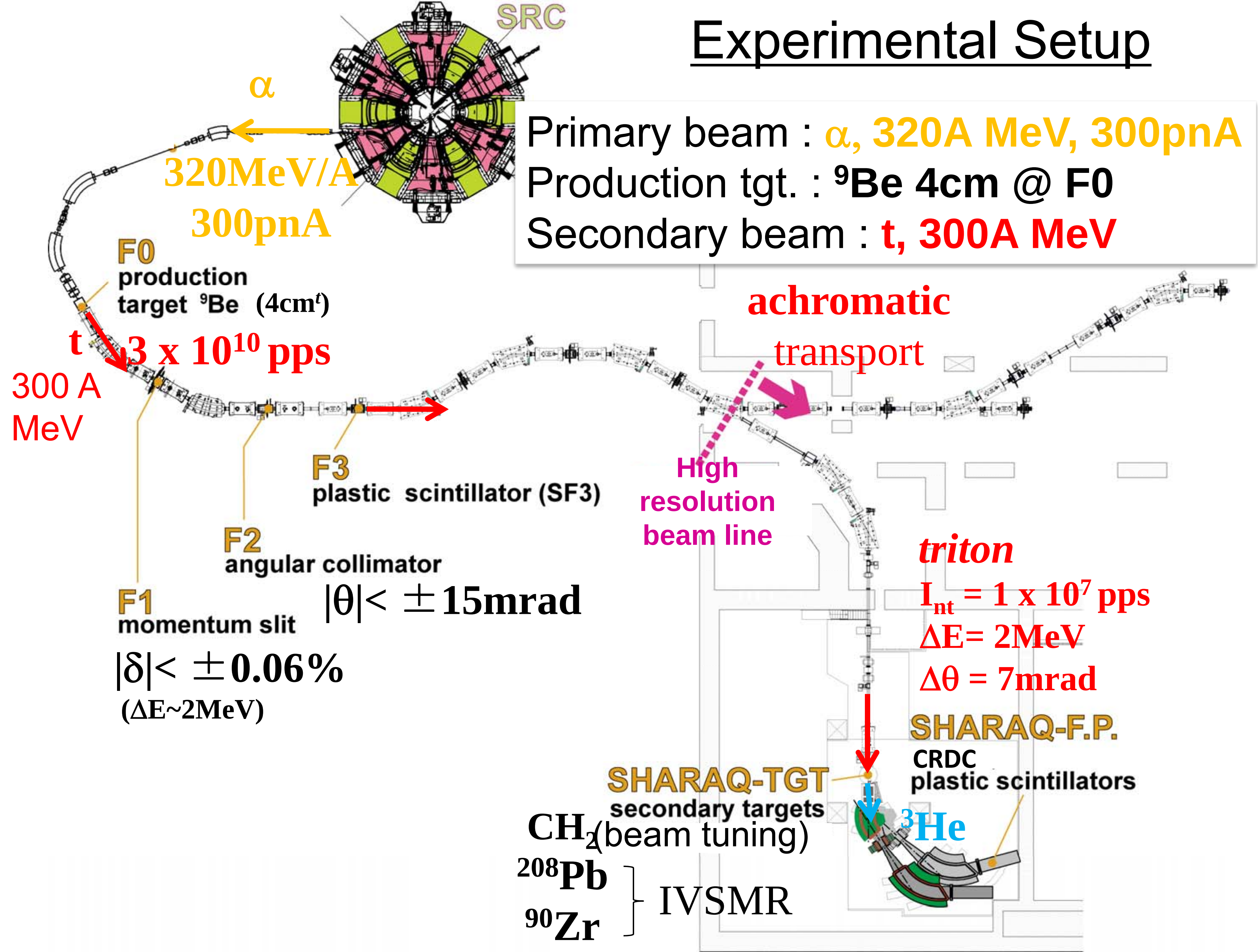
Cross section

p** & **n **(σ_{IVSM}~small)**

^{3}He & *t* (σ_{IVSM}~large)

Experimental Setup

Primary beam : α, 320A MeV, 300pnA
Production tgt. : ^{9}Be 4cm @ F0
Secondary beam : t, 300A MeV



SRC

α

320MeV/A
300pnA

F0
production
target ^{9}Be (4cm^t)

t
3 x 10^{10} pps

300 A
MeV

achromatic
transport

F3
plastic scintillator (SF3)

F2
angular collimator
|θ|< ±15mrad

F1
momentum slit
|δ|< ±0.06%
(ΔE~2MeV)

High resolution beam line

triton
I_{nt} = 1 x 10^7 pps
ΔE= 2MeV
Δθ = 7mrad

SHARAQ-F.P.
CRDC
plastic scintillators

SHARAQ-TGT
secondary targets

^{3}He

CH$_2$(beam tuning)
^{208}Pb
^{90}Zr
} IVSMR

Experimental conditions

Beam

Primary : ^{4}He 320MeV/u 300pnA

Secondary : triton 300MeV/u 1×10^7pps

Purity > **99%**

Obtained spectra

^{208}Pb(t,^{3}He) ^{208}Tl

^{90}Zr (t,^{3}He) ^{90}Y

@ $0 < E_x < 70$ MeV

$0 < \theta < 3$ deg

Resolution(FWHM)

$\Delta E \sim 2.5$MeV

- energy spread of 2nd beam – 1.9MeV
- energy loss in target – 1.4MeV

$\Delta\theta \sim 0.5$deg

- angular spread of 2nd beam – 7mrad
- multiple scattering in target – 6mrad

Angular distribution

- ^{208}Pb(t,^{3}He)@300A MeV

  DWIA calculation

  ΔL=0 IVSMR (N.M.)

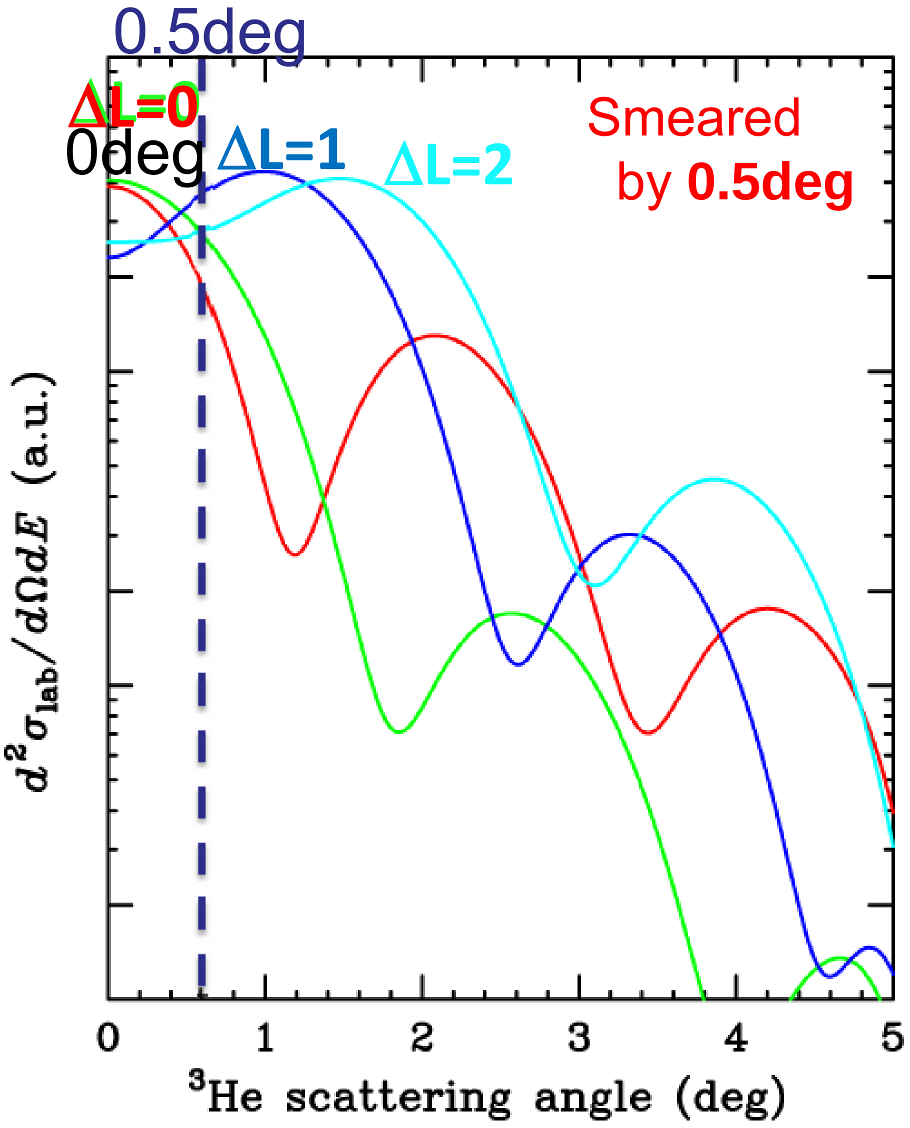
  ΔL=0 GT (N.M.)

  ΔL=1 SDR($\nu 2p_{3/2}, \pi 2s_{1/2}^{-1}$)

  ΔL=2 SQR($\nu 2d_{5/2}, \pi 2s_{1/2}^{-1}$)

- **Angular resolution**
  - crucial for the separation of ΔL=0 and ΔL≧1

Our resolution of Δθ ~ 0.5 deg is sufficient.



^{208}Pb(t,^{3}He)^{208}Tl @ 300A MeV

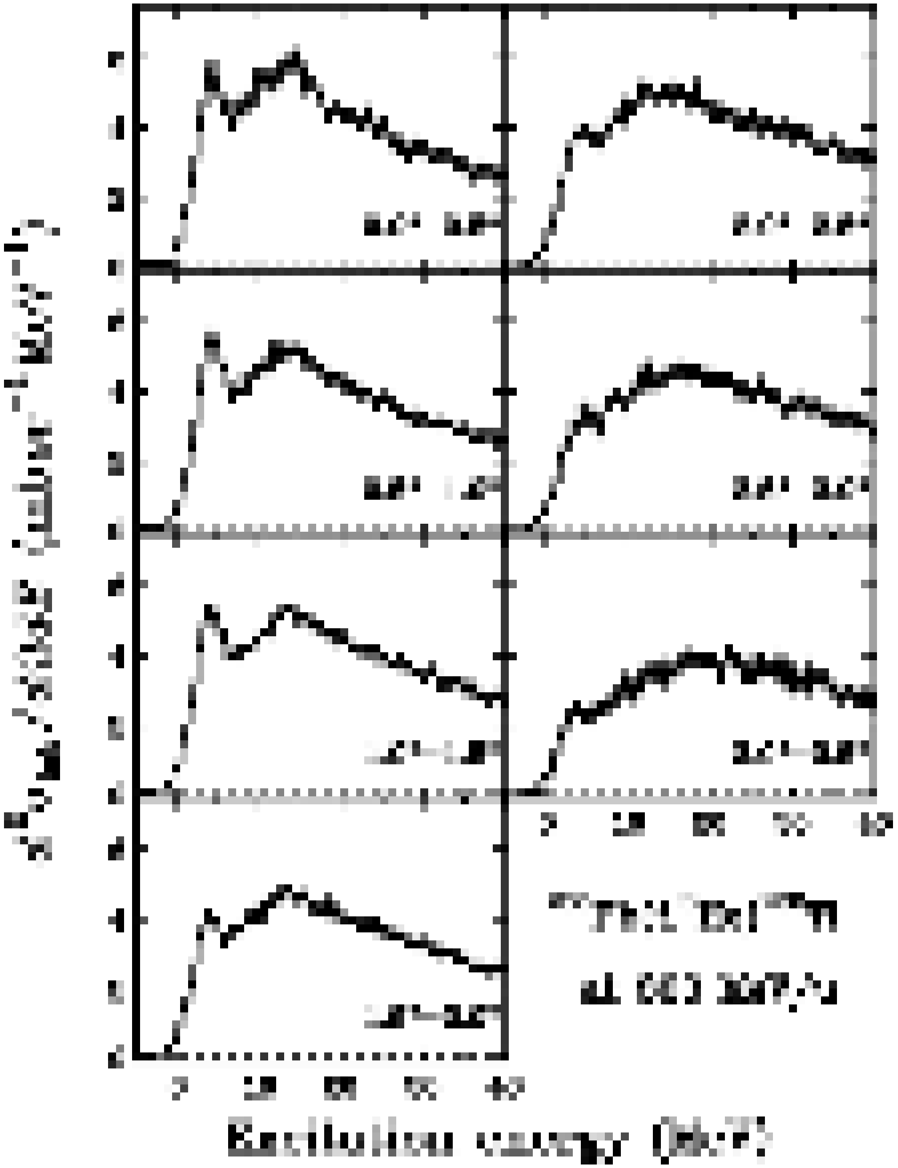
- Stat. accuracy (0deg)

  ~ 2% for 1msr ･1MeV –bin

- Bumps at 4MeV, 15MeV

  -- peak around the forward angle

  → ΔL=0 ?



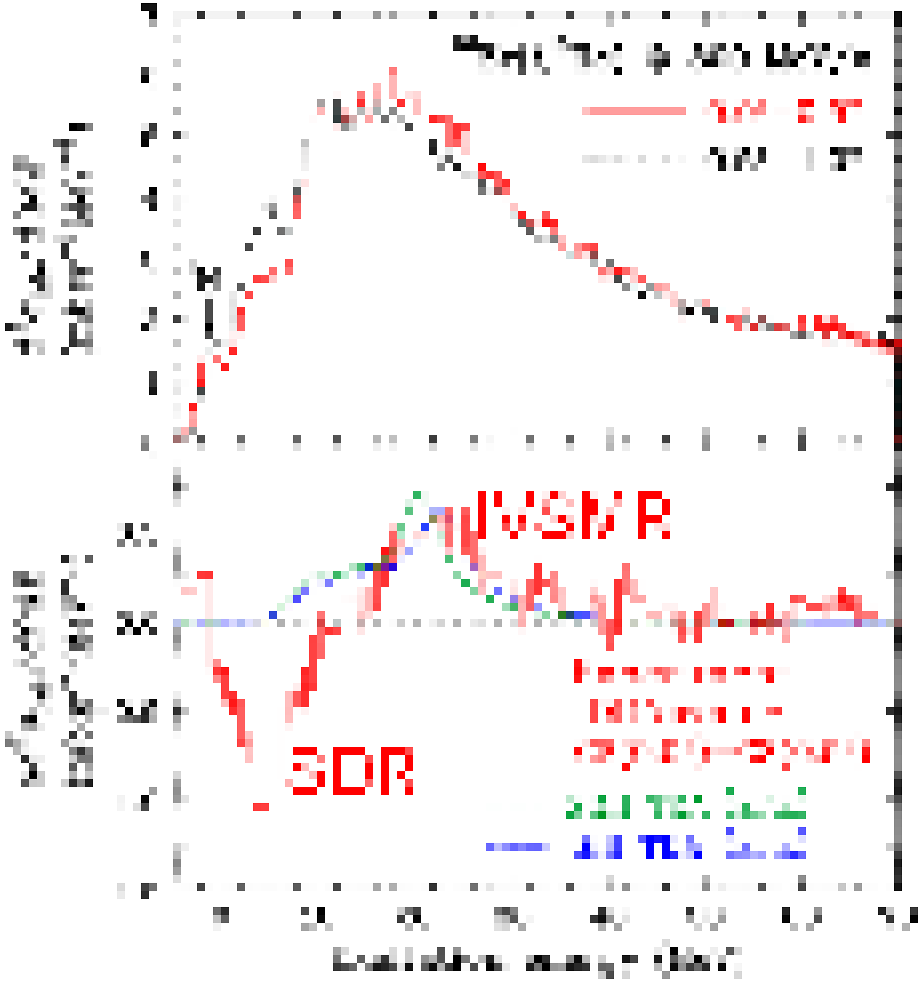
IVSMR(β^+) for ^{90}Zr

- IVSMR($\Delta L=0$) → Forward-peak
- Comparison between
  0.0-0.5 deg .vs. 0.5-1.0 deg
- Significant $\Delta L=0$ component
  around **20MeV**

- Theoretical predictions :
  TDA(SGII) , TDA(SIII)

Hamamoto, Sagawa :
Phys.Rev.C 62 (2000) 02431920

TDA(SIII) seems to be good.



Summary … IVSMR

- The ^{208}Pb, ^{90}Zr(t,^{3}He) reactions were measured
  at $0 < E_x < 70$ MeV and $0 < \theta < 3$ deg

- Evidences of IVSMR(β^+) were for the first time obtained.
  ^{90}Zr : ~ 20 MeV
  ^{208}Pb : ~ 12 MeV

- TDA(SIII) reproduces the distribution.

- Multipole Decomposition Analysis is in progress.
  Ex, Γ,
  collectivity / quenching (sum rule), …

Collaborators

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