Study of nuclear matrix elements of two-neutrino double-beta decay by (p,n) and (n,p) reactions

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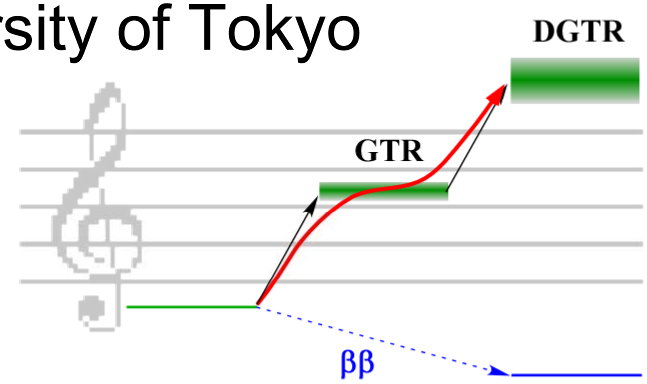

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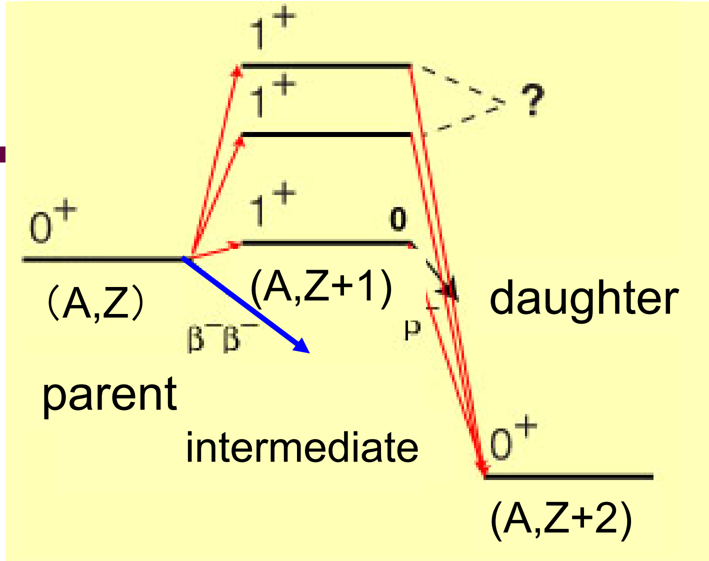
Two-neutrino double beta decay



2vββ decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\overline{\nu}_e$$

- second order weak process
- rarest process confirmed so far
- if thoroughly understood,
  it helps analysis of 0vββ decay rate.

Half-life and matrix element:

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu}\left|M_{\mathrm{DGT}}^{2\nu}\right|^2$$

$$M_{\mathrm{DGT}}^{2\nu} = \sum_m \frac{\langle f \| O_{\mathrm{GT}-} \| m \rangle \langle m \| O_{\mathrm{GT}-} \| i \rangle}{E_m - (M_i + M_f)/2}$$

GT operator: $O_{\mathrm{GT}\pm} = \sum_j \sigma_j t_{\pm}$

GT strength: $B(\mathrm{GT}^{\pm}) = \left|\langle j \| O_{\mathrm{GT}\pm} \| i \rangle\right|^2$

Half lives … not understood well

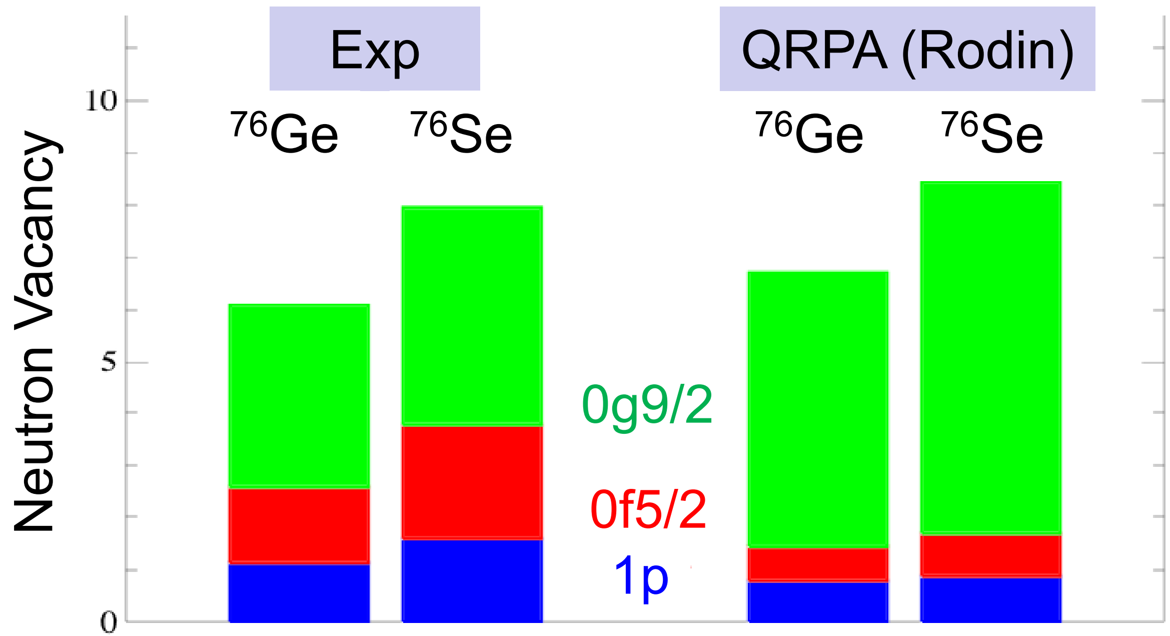
Suhonen et al., PR300(1998)123

Nucleus	Exp $T_{1/2}$ (y)	Calc $T_{1/2}$ (y)
^{48}Ca	~ 4.3 x 10^{19}	(1.3 – 6.0) x 10^{19}
^{76}Ge	~ 1.4 x 10^{21}	(0.8 – 1.4) x 10^{21}
^{82}Se	~ 0.9 x 10^{20}	(0.1 – 1.1) x 10^{20}
^{96}Zr	~ 2.1 x 10^{19}	(3.0 – 11) x 10^{19}
^{100}Mo	~ 8.0 x 10^{18}	(1.7 – 32) x 10^{18}
^{116}Cd	~ 3.3 x 10^{19}	(5.1 – 10) x 10^{19}
^{128}Te	~ 2.5 x 10^{24}	(0.6 – 37) x 10^{24}
^{130}Te	~ 0.9 x 10^{21}	(0.3 – 2.7) x 10^{21}
^{150}Nd	~ 7.0 x 10^{18}	(6.7 – 27) x 10^{18}

Model adjustments

Effective interaction is adjusted so that the model reproduces…

- $M^{2\nu}$
- Single β^- & β^+ rates



Kay, Schiffer et al., 2009

Further constrants…

- Occupation numbers of "valence" nucleons:

  (d,p), (p,d),

  (α,^{3}He), (^{3}He,α)

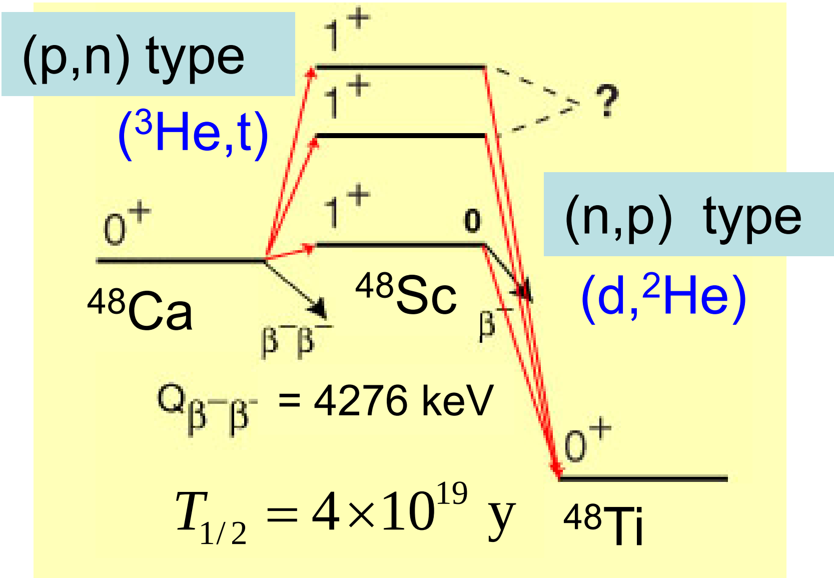
  extra ground-state correlation is necessary.

- Distribution of GT(1^+) transition strengths:

  → charge exchange reactions

B(GT) in low-lying states

GT strengths:



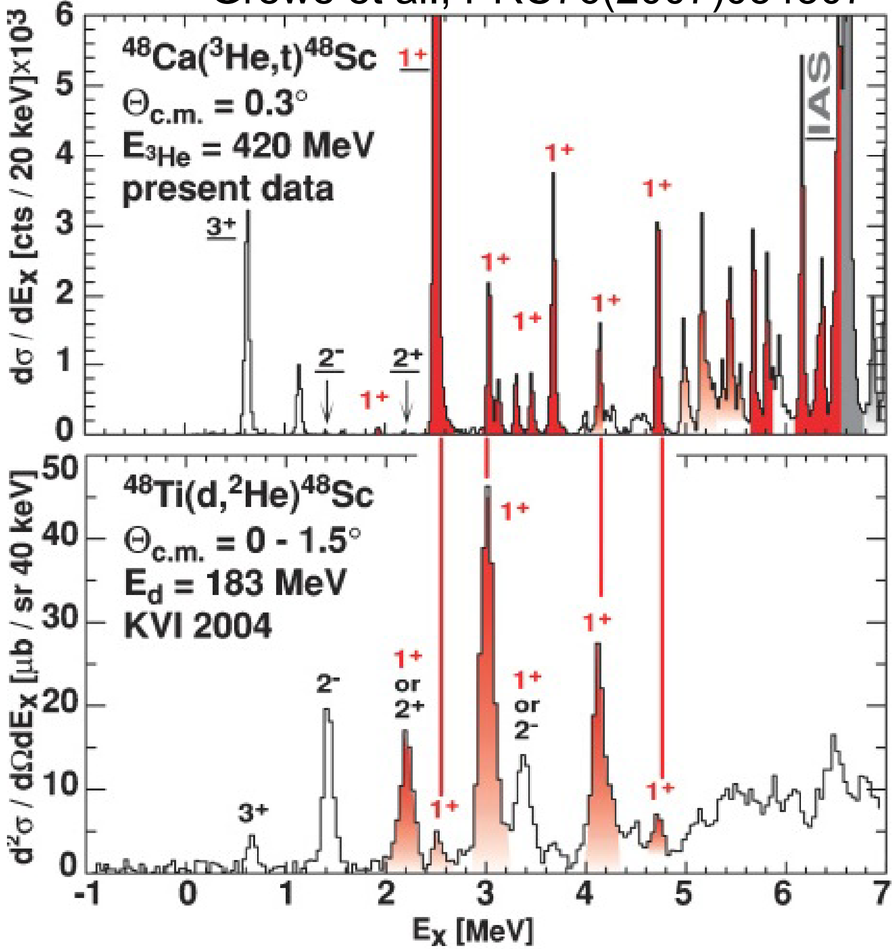
Low lying states

… high resolution measurements

^{48}Ca(^{3}He,t) @ 140A MeV (RCNP)

^{48}Ti(d,^{2}He) @ 90A MeV (KVI)

Grewe et al., PRC76(2007)054307



"Contribution" of low-lying states

Grewe et al., PRC76(2007)054307

"upperlimit" matrix element: $M_{+}^{2\nu}$

$$M^{2\nu} = \sum_m \frac{\langle f \| O_{\mathrm{GT}-} \| m \rangle \langle m \| O_{\mathrm{GT}-} \| i \rangle}{E_m - (M_i + M_f)/2}$$

$$M_{+}^{2\nu} = \sum_m \frac{\sqrt{B(\mathrm{GT}^{+})}\sqrt{B(\mathrm{GT}^{-})}}{E_m - (M_i + M_f)/2}$$

No sign info & additive sum
→ upper limit

Decay measurement :

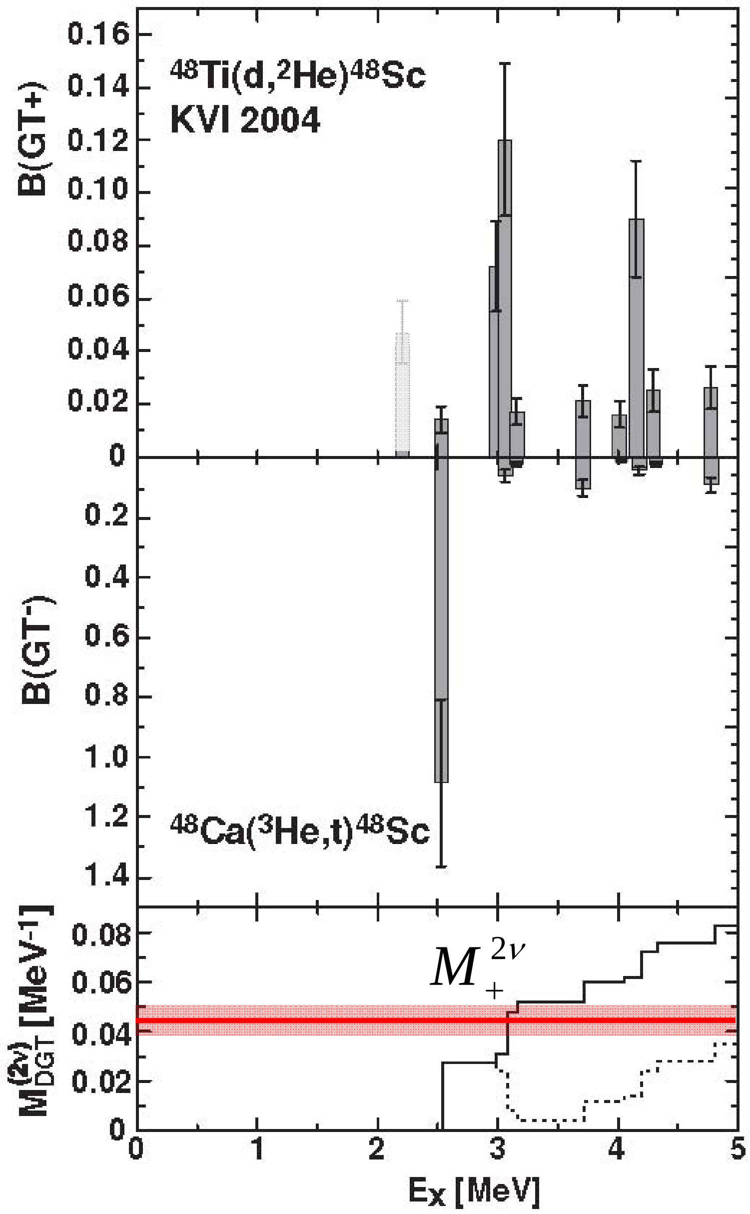
Balysh et al., PRL77(1996)5186

$(4.3\ ^{+2.4}_{-1.1}\ (\mathrm{stat}) \pm 1.4(\mathrm{sys})) \times 10^{19}$ y

NEMO3 (Vala et al., NPB188(2009)62)

$(4.4\ ^{+0.5}_{-0.4}\ \pm 0.4) \times 10^{19}$ y

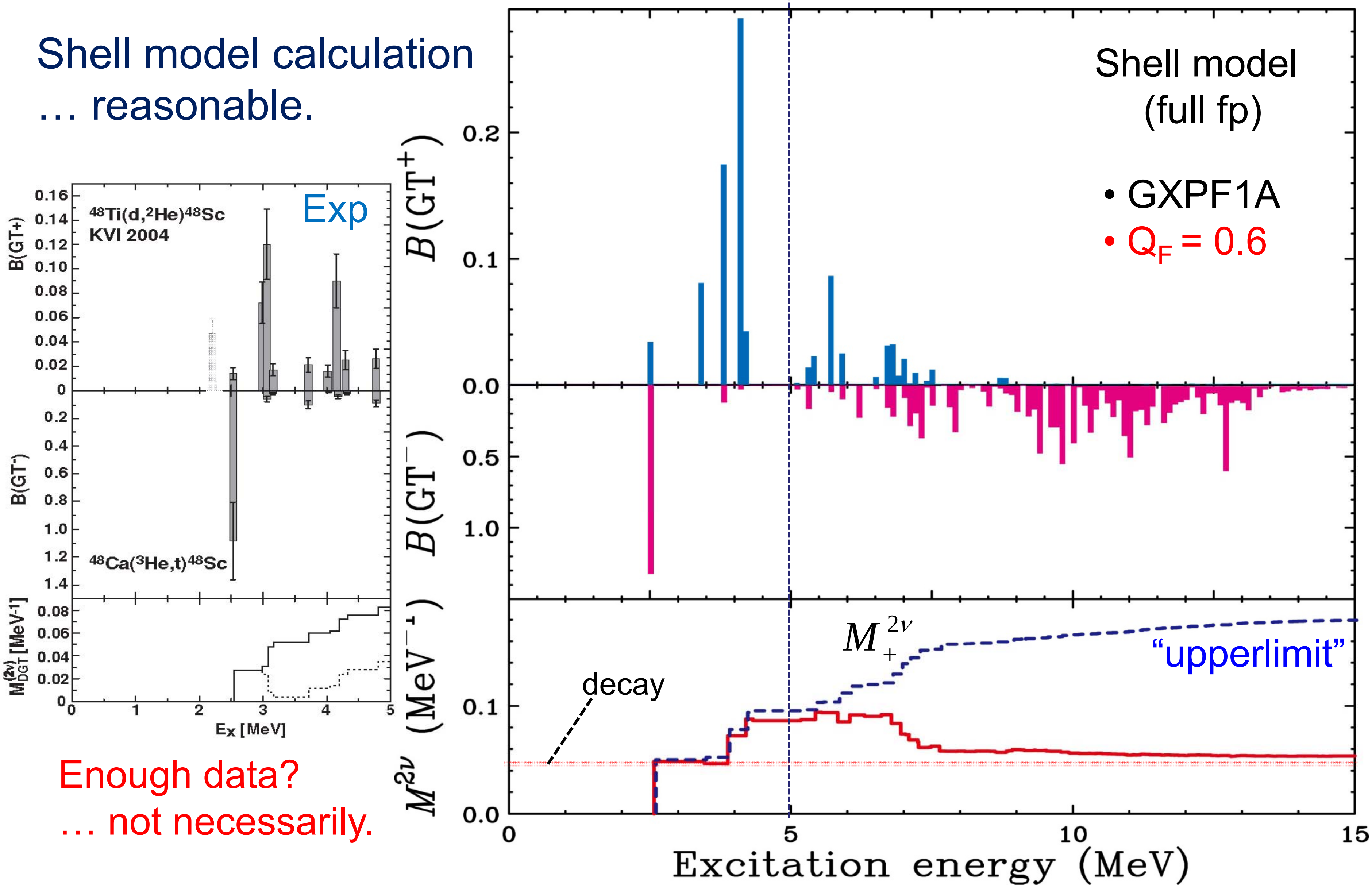
$M^{2\nu} \rightarrow 0.045\ \mathrm{MeV}^{-1}$



Current understanding by shell model

Same as Horoi et al. PRC75(2007)034303

Shell model calculation
… reasonable.

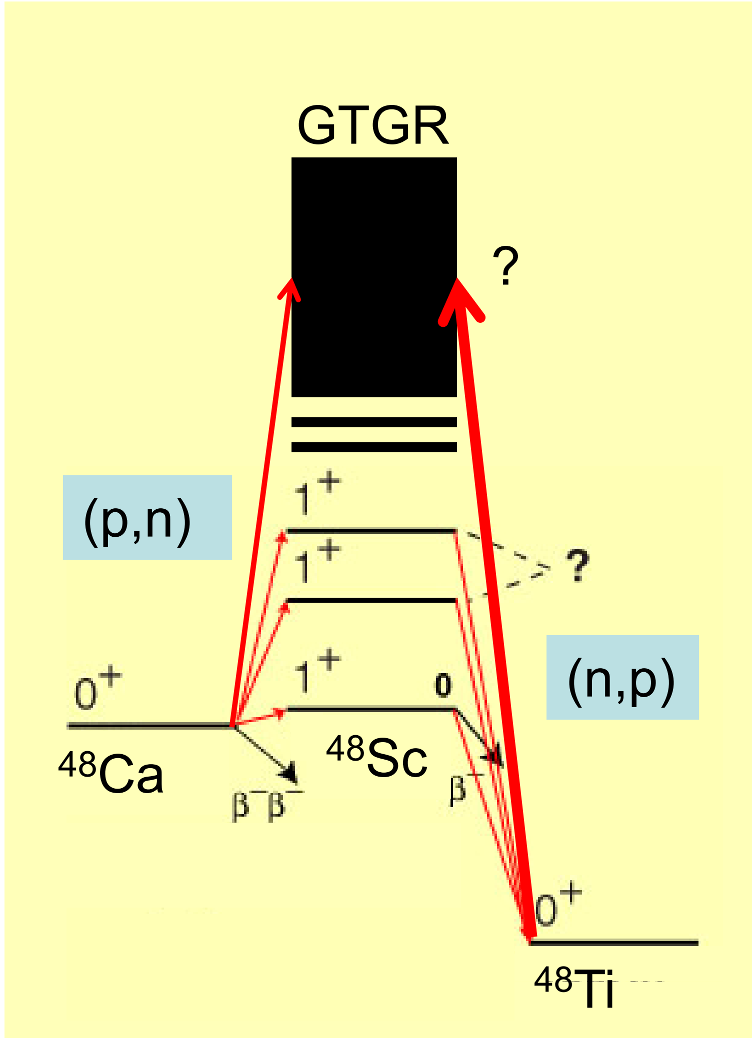


Enough data?
… not necessarily.

Aim

- If your strategy is to check or constrain the theoretical calculations, you need the full snapshots of the B(GT) distribution.
- B($GT^{+/-}$) distributions were studied up to the continuum, in the intermediate nuclei,

  ^{48}Sc, ^{116}In.
- Measurement
  - E_{beam}= 300 MeV
  - θ = 0° ~12°



^{48}Ca(p,n)^{48}Sc
^{48}Ti(n,p)^{48}Sc

^{116}Cd(p,n)^{116}In
^{116}Sn(n,p)^{116}In

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

Advatages

- Simple reaction mechanism
- 300 MeV:

  1. Effective interaction favors Spin-flip transitions over Non-Spin-flip ones ($t_{\sigma\tau} / t_{\tau}$)

  ⇒ GT transitions are most clearly seen.

  2. Distortion effects are smallest (t_0).

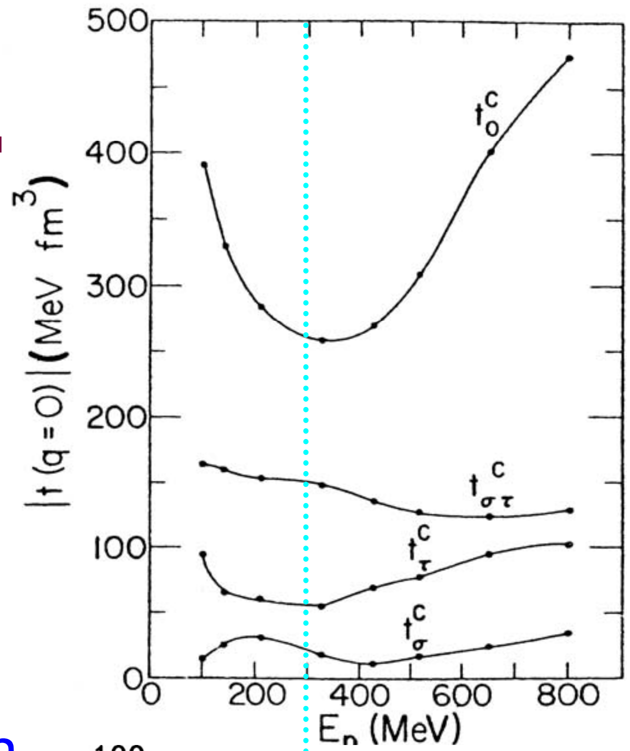
  ⇒ analysis with DWIA is reliable.

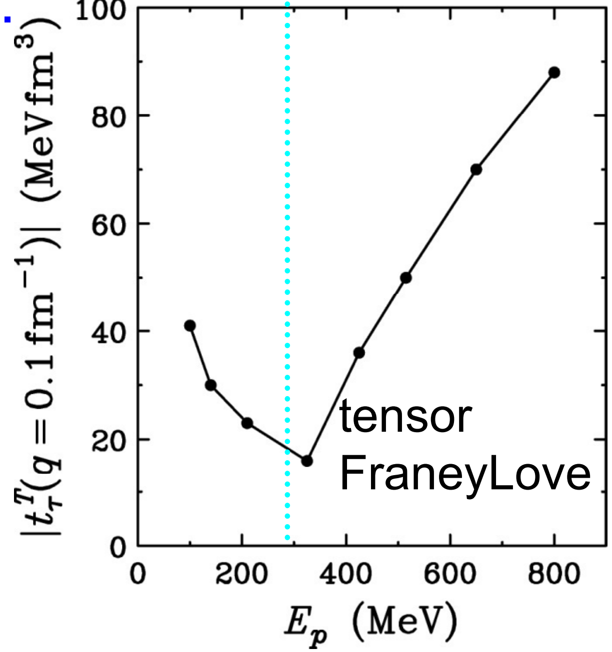
  3. Tensor interaction is smallest (t_{τ}^{T}).

  ⇒ Proportionality relation is reliable.

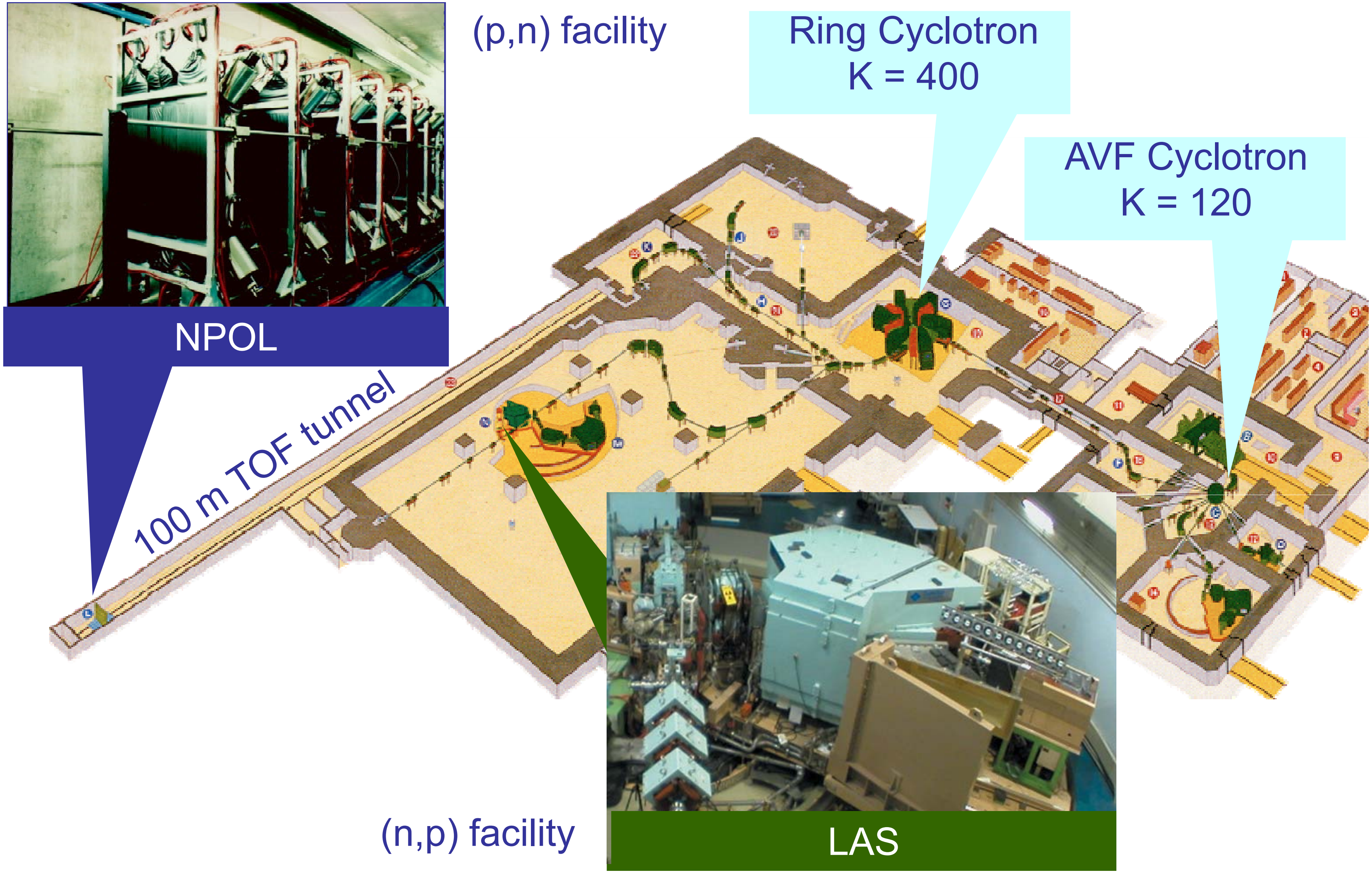
  cross section ⇔ strength

… Multipole decomposition analysis works best.



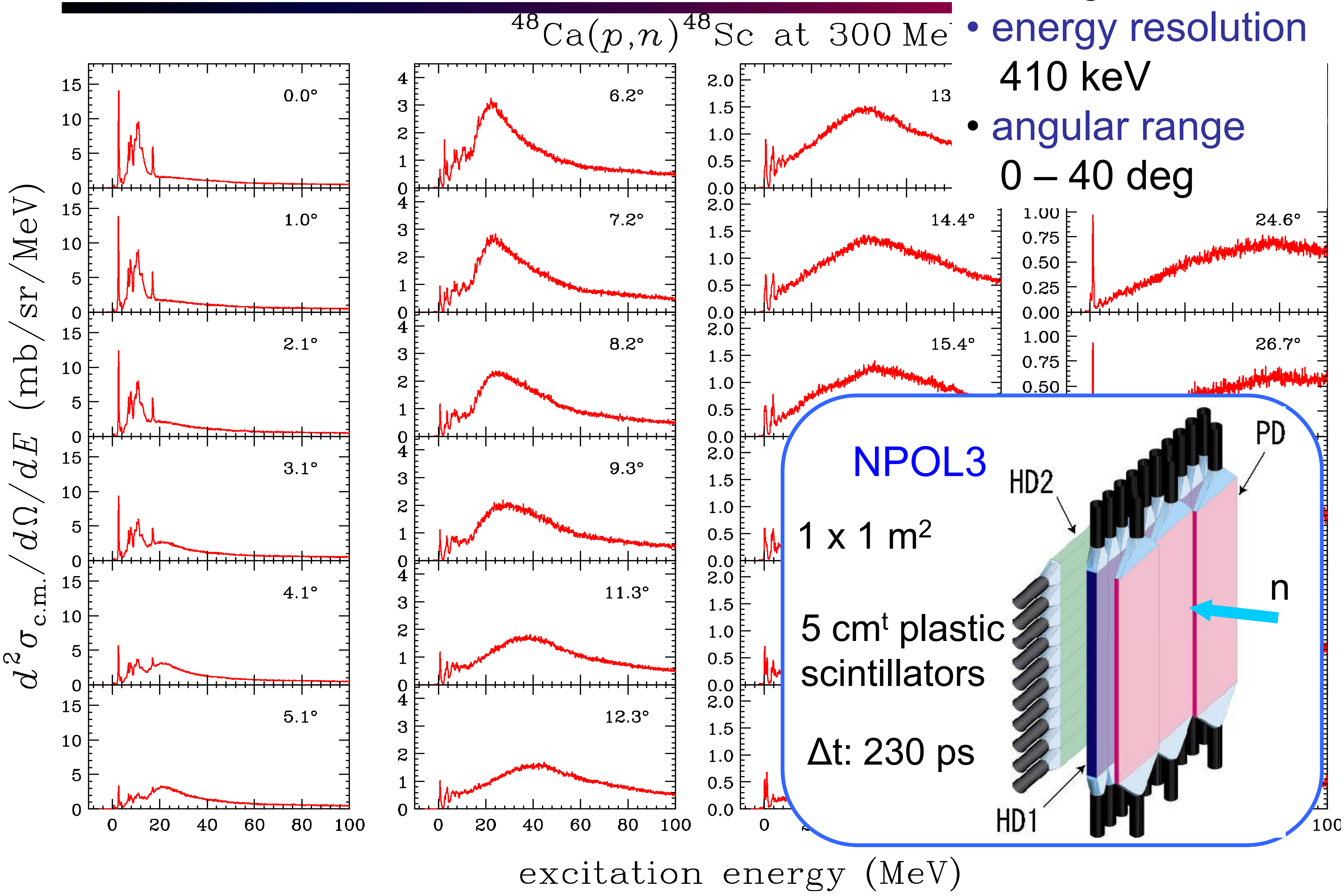


(p,n) & (n,p) facilities at RCNP



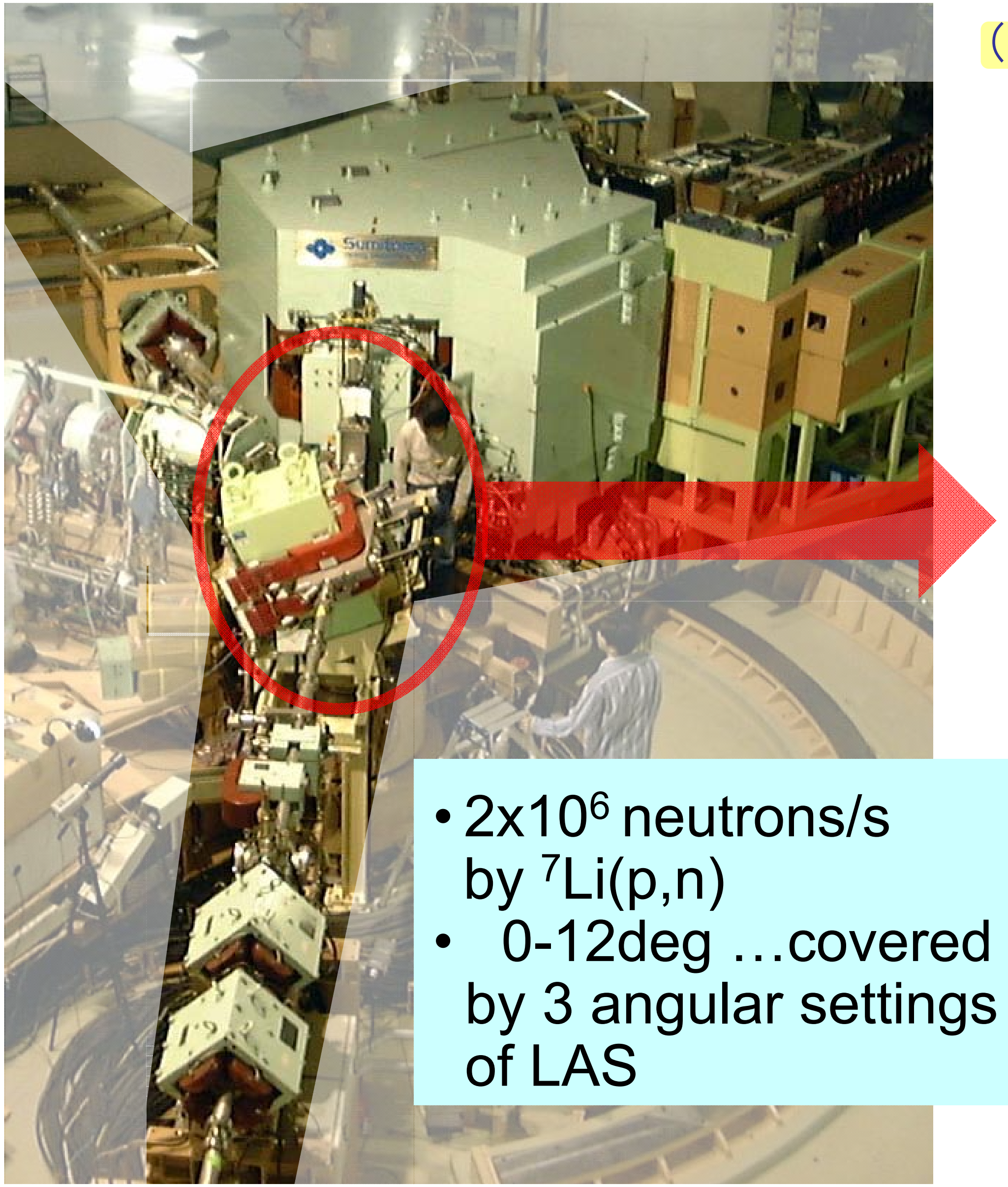
^{48}Ca(p,n) measurement

- ^{48}Ca target
  17 mg/cm^2, 98%
- energy resolution
  410 keV
- angular range
  0 – 40 deg

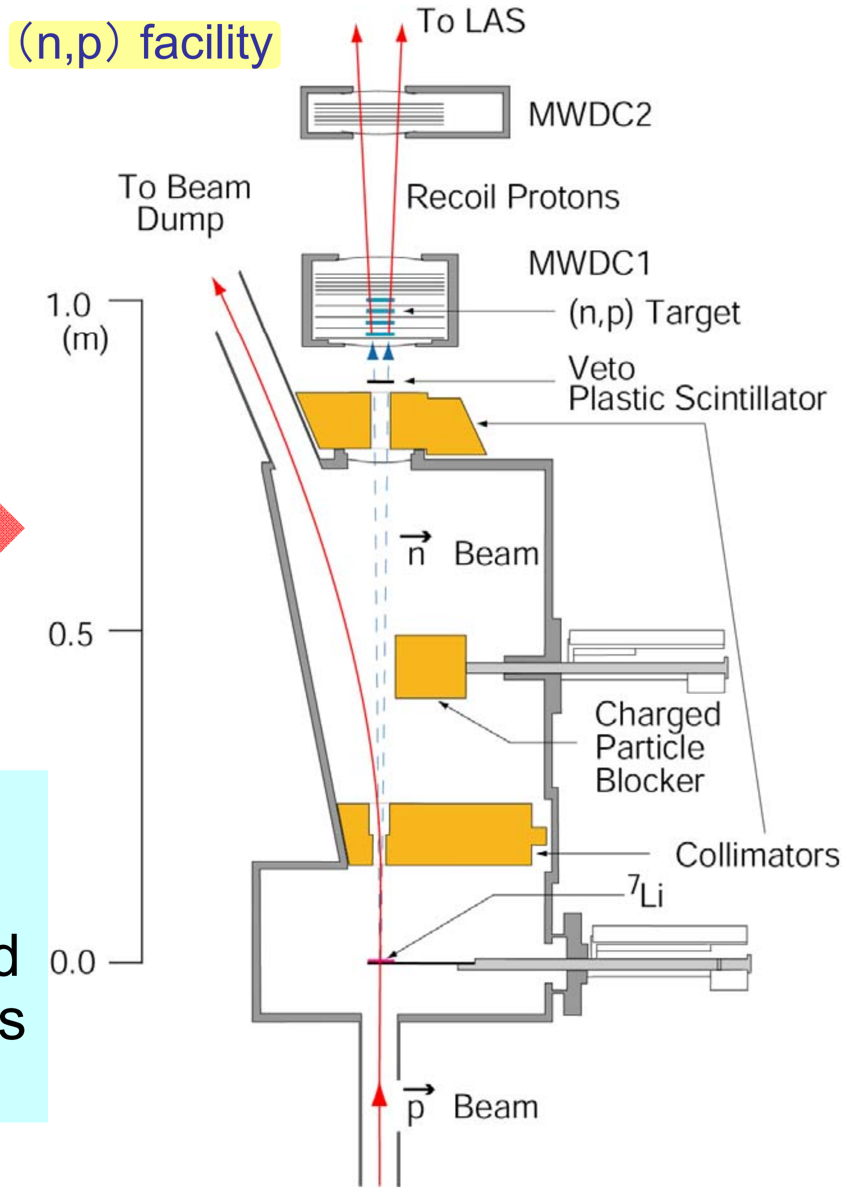


(n,p) measurement

K.Y. et al., NIMA592(2008)88



- $2x10^6$ neutrons/s by $^7Li(p,n)$
- 0-12deg …covered by 3 angular settings of LAS



^{48}Ti target

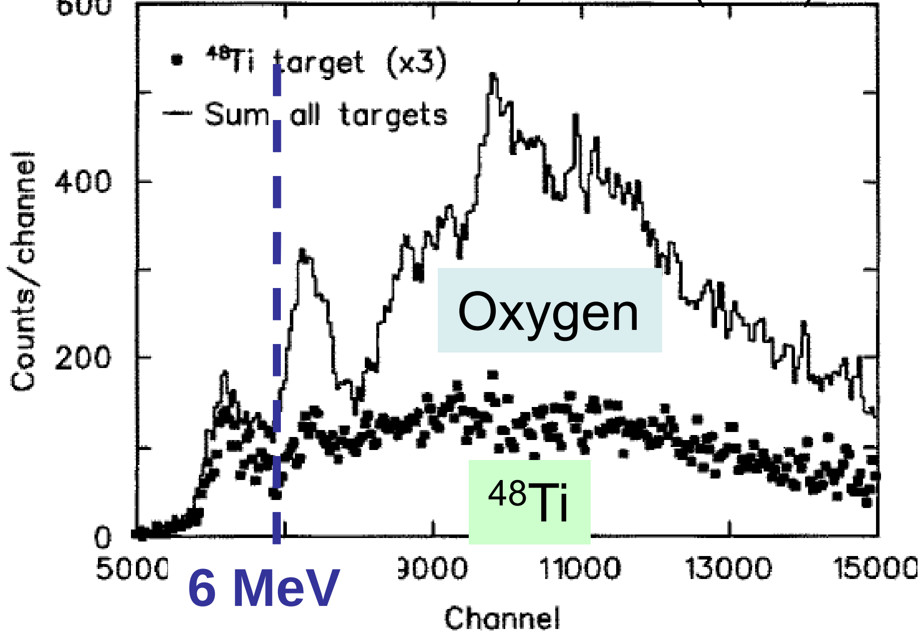
^{48}Ti(n,p) at TRIUMF (1990, Alford et al.)

- metal ^{48}Ti: thin … low statistics
  - Data at 3 angles

    … not ideal for MD analysis
- $^{48}TiO_2$: contribution of oxygen

  at E_x > 6 MeV

Alford et al., NPA514(1990)49



1. metallothermic reduction

   （IIS UT, Okabe Gr.）

   $TiO_2 + 2Ca = Ti + 2CaO$

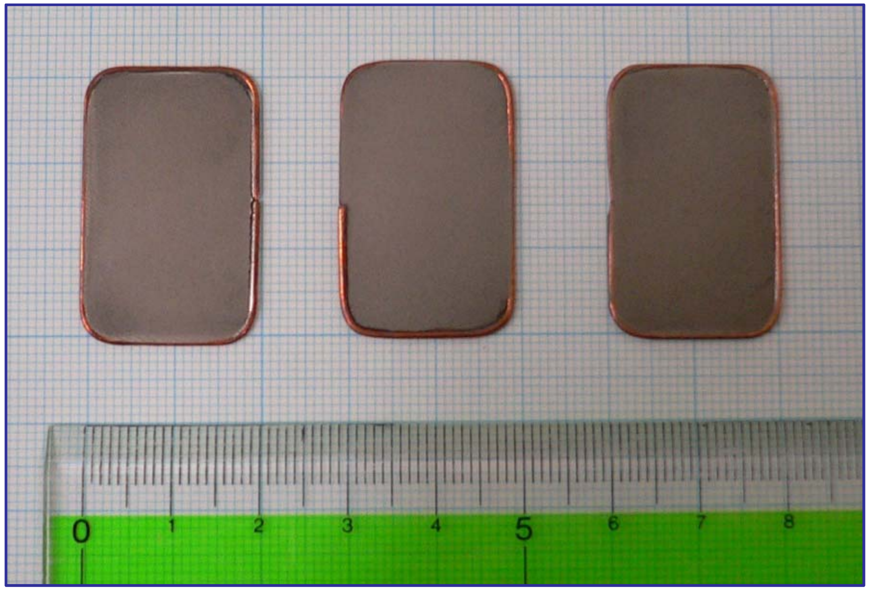
   $^{48}TiO_2$ 13g → ^{48}Ti 5g (70%)

   purity: 98.7%

2. solidification by pressure

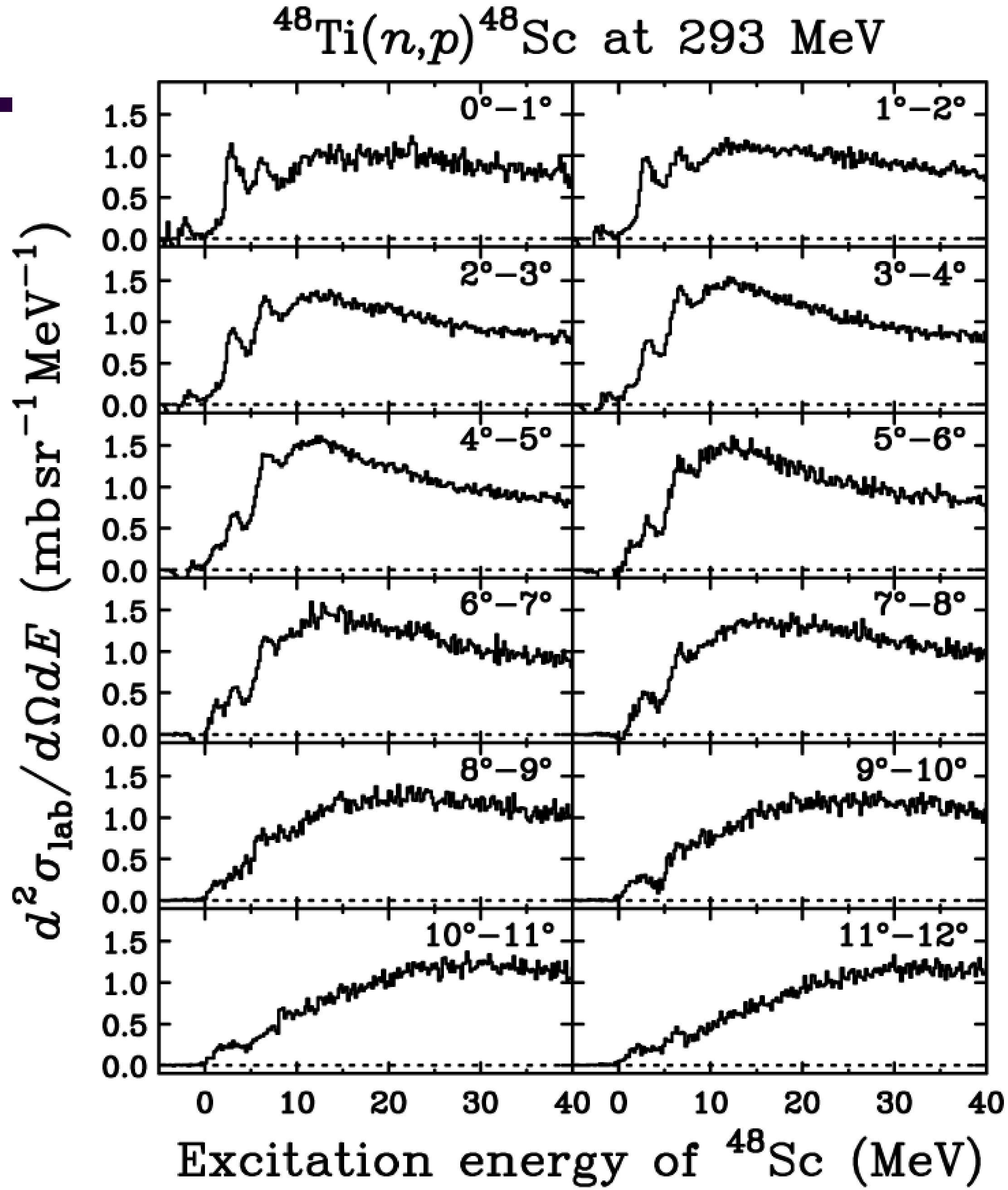
   3 x 300 mg/cm^2, 2 x 3 cm^2

   （c.f. Alford et al.: 130mg/cm^2）



^{48}Ti(n,p) spectra

- angular range
  0 -12 deg
- energy resolution
  1.2 MeV
- statistical accuracy
  1--3% / 2MeV･1deg
- systematic uncertainty
  4%



Multipole decomposition analysis

MDA

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

← DWIA

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

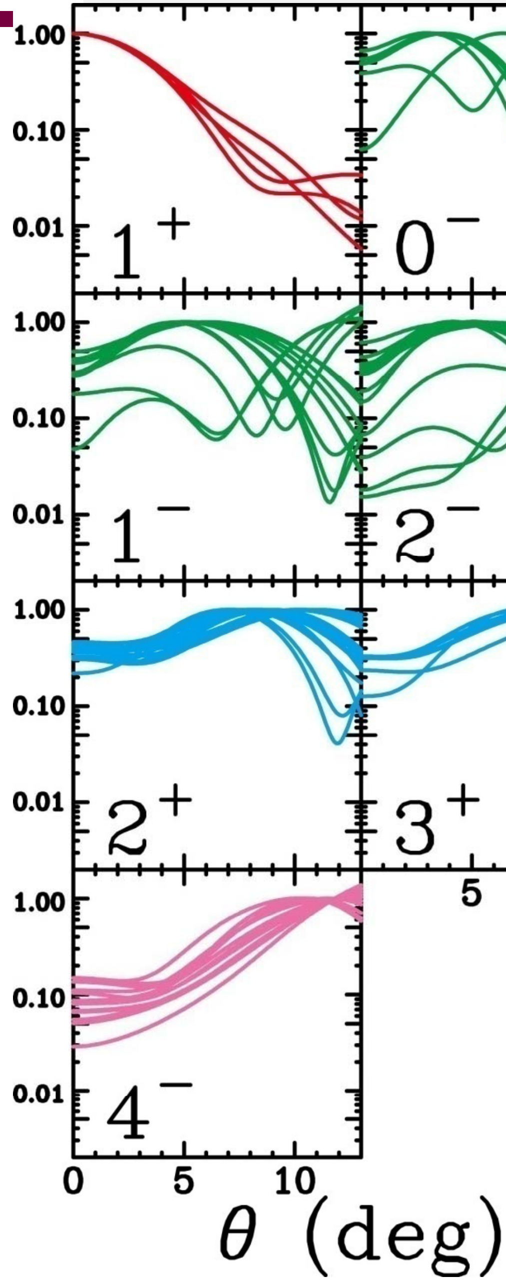
DWIA inputs (DW81)

- NN interaction:
  t-matrix by Franey & Love @325 MeV
- optical model parameters:
  Global optical potential
  (phenomenological, Cooper et al.)
- one-body transition density:
  pure 1p-1h configurations

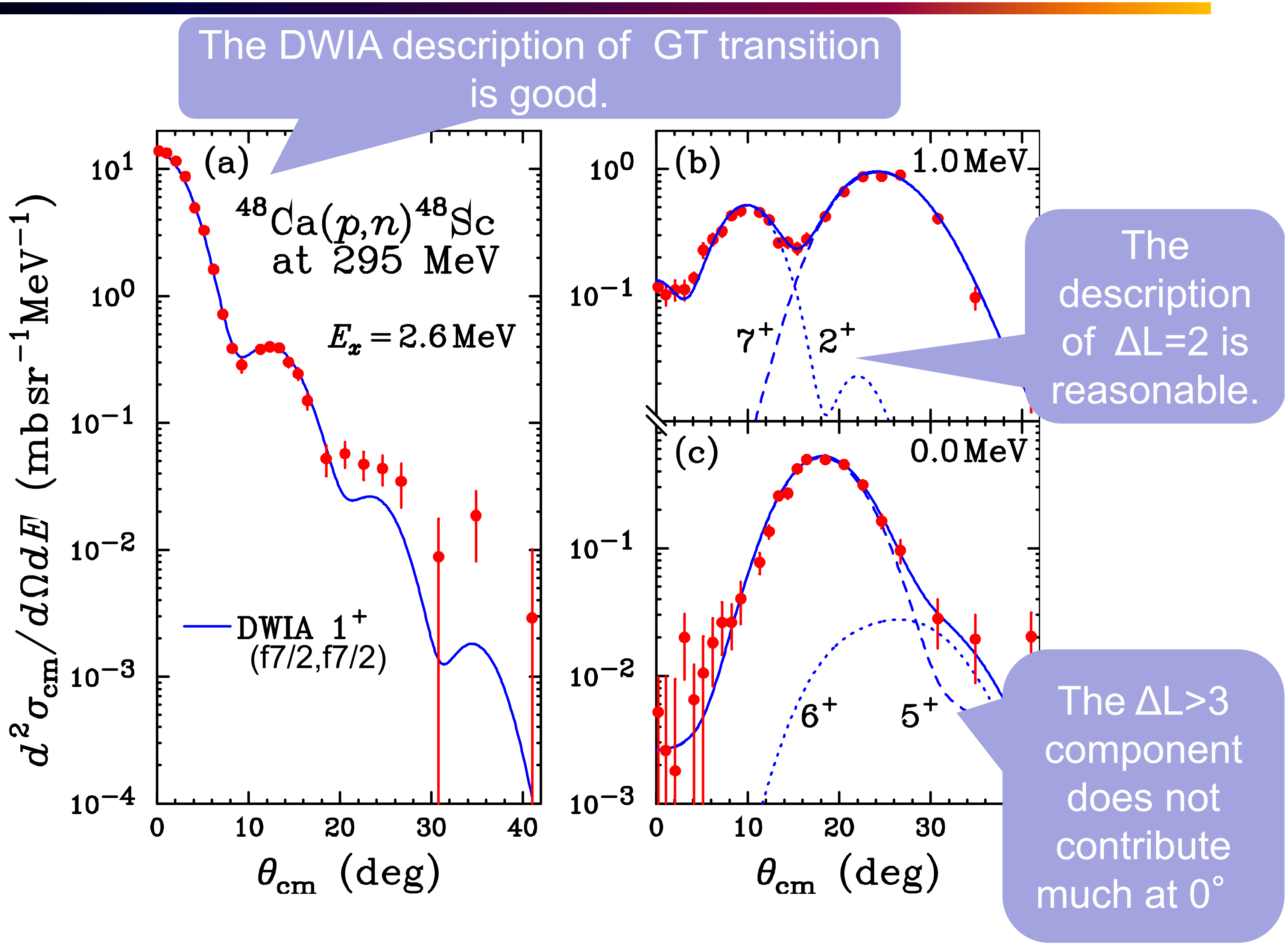
Particle:	1f, 2p, 1g, 2d, 3s, or 1h11/2
Hole:	1p, 1d, 2s, or 1f

radial wave functions … W.S. / H.O.

^{48}Ti(n,p) angular dist.
E_x = 15 MeV



Examples of angular distribution



Reliability of σ(θ) in the continuum

- Transitions with
  "stretched" configurations

… studied experimentally.
DW81 (shallow binding) gives excellent description.

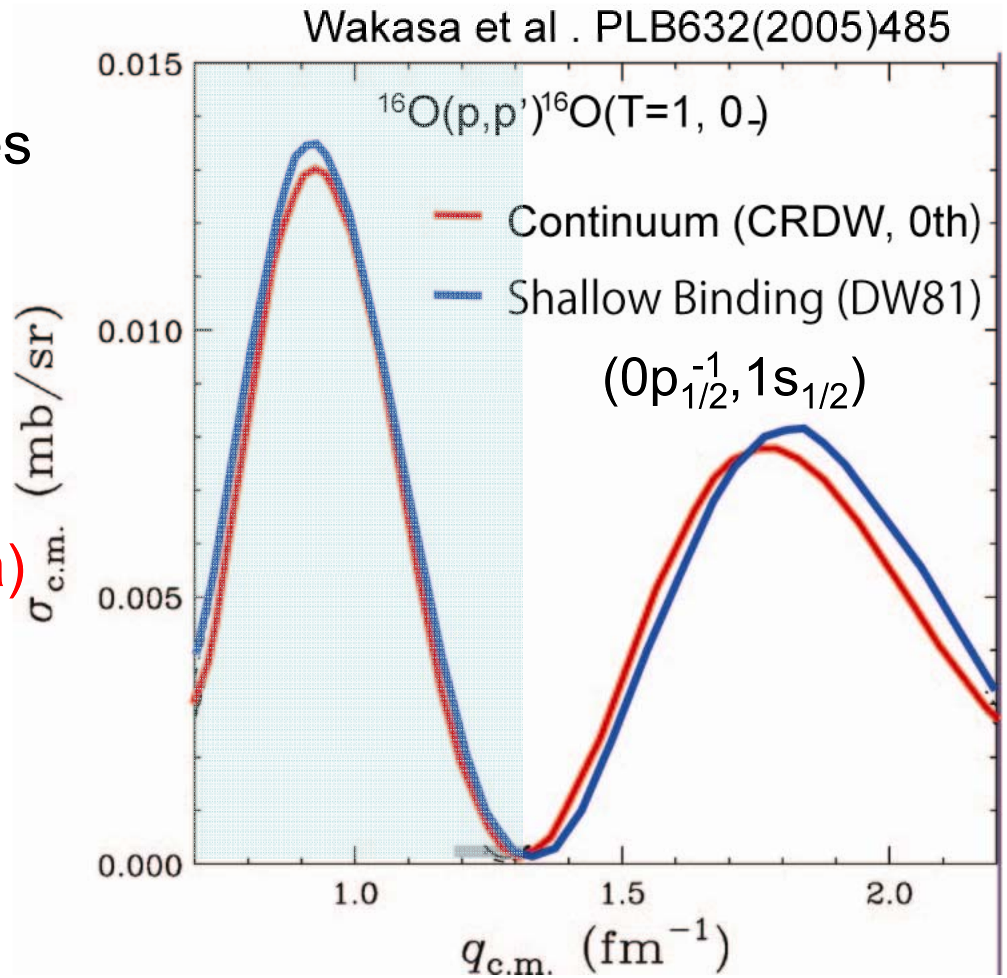
- Others

… DW81 (shallow binding)

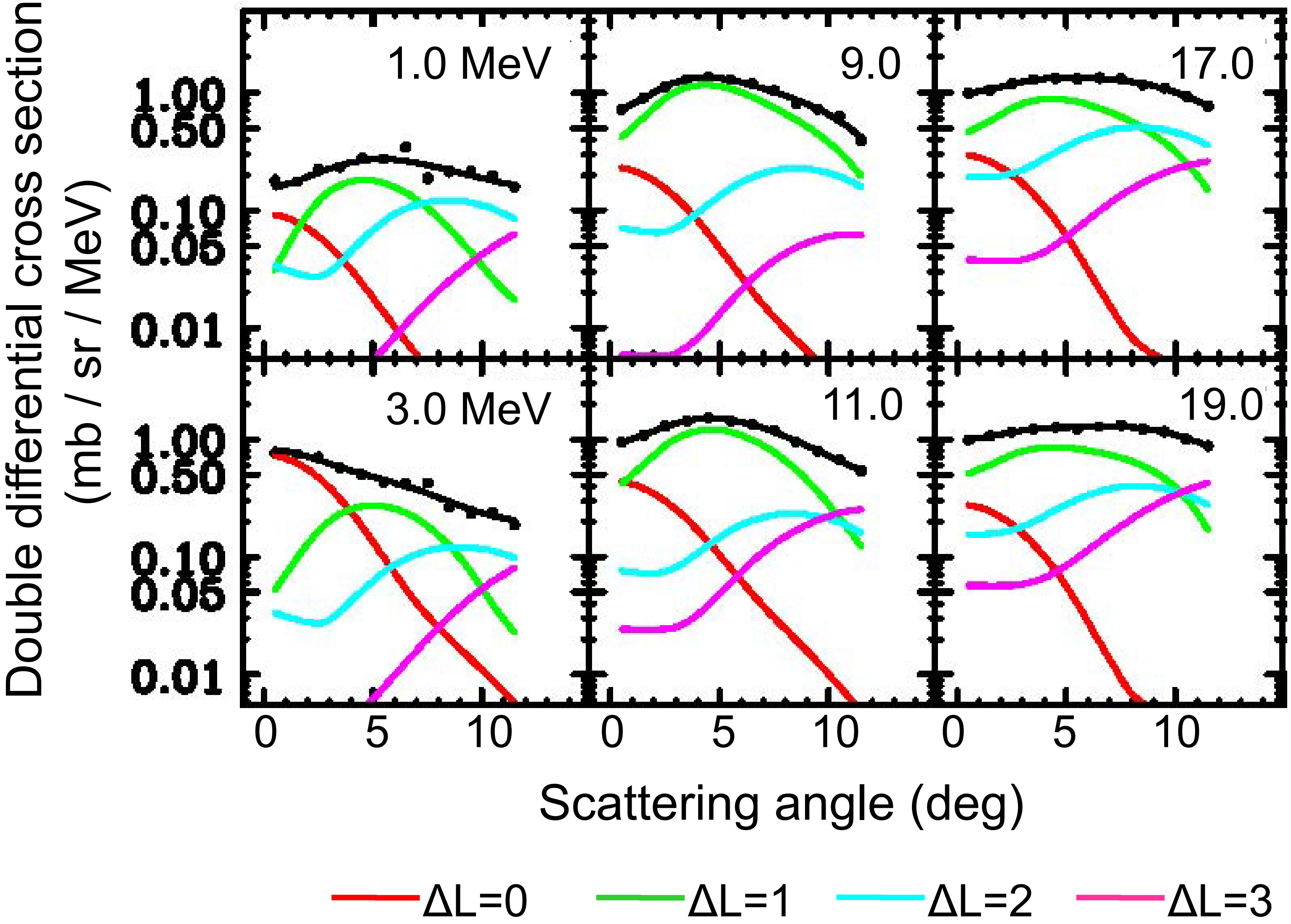
⬍

CRDW (continuum, Ichimura)

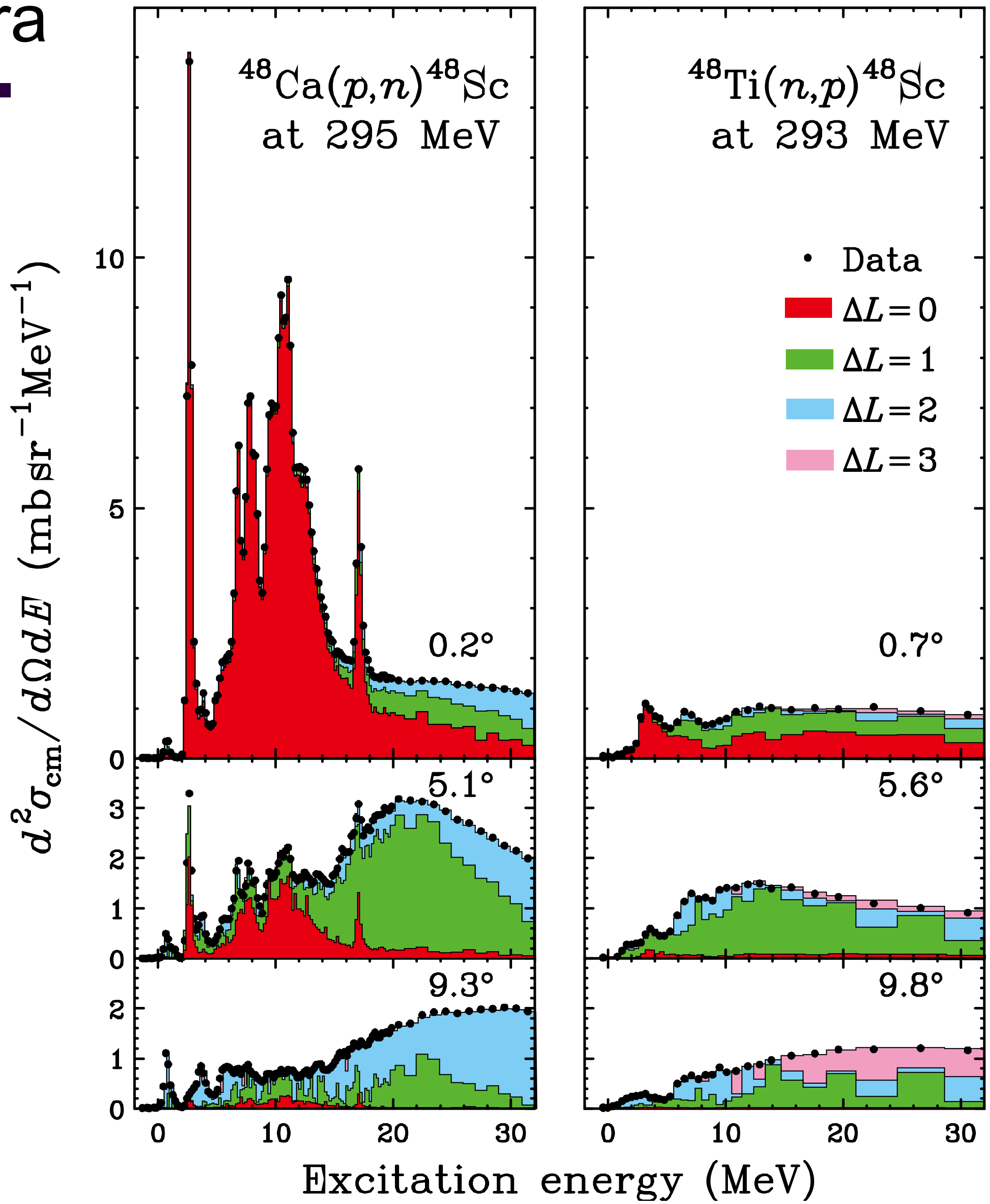
- $^{16}O(p,p')^{16}O$
  ($T=1$, 0^-; 12.8 MeV)
  at 295 MeV



Decomposed angular distributions [$^{48}Ti(n,p)$] Miki



Decomposed spectra



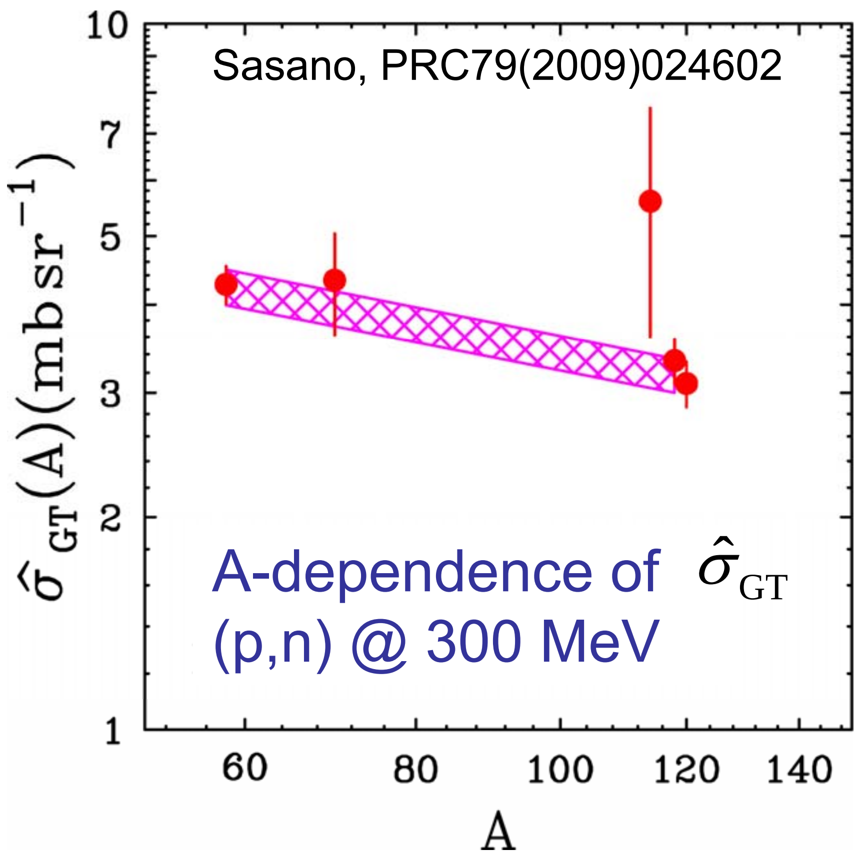
Proportionality relation

$$\frac{d\sigma}{d\Omega}(0^\circ)_{\Delta L=0} = \hat{\sigma}_{\rm GT} F(q,\omega) B({\rm GT})$$

GT unit cross section

kinematical
correction
by DWIA

$\hat{\sigma}_{\rm GT}$ = 4.69±0.35 mb/sr



Is $\hat{\sigma}_{\rm GT}$ a good quantity?

…depends on transition density.

Proportionality test by shell model

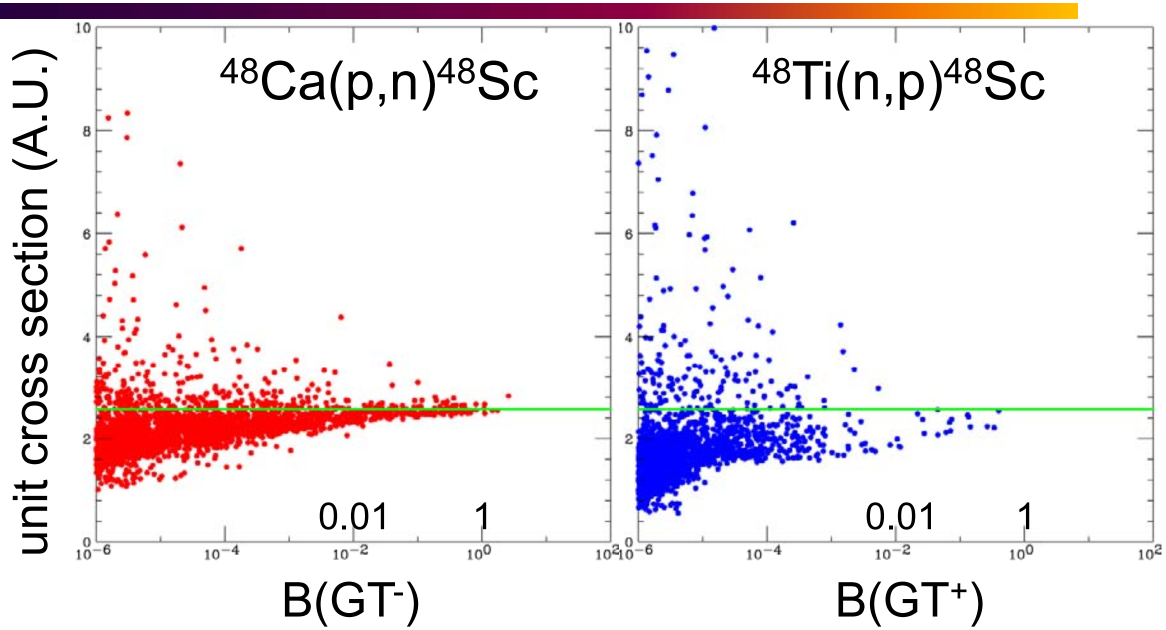
Sasano

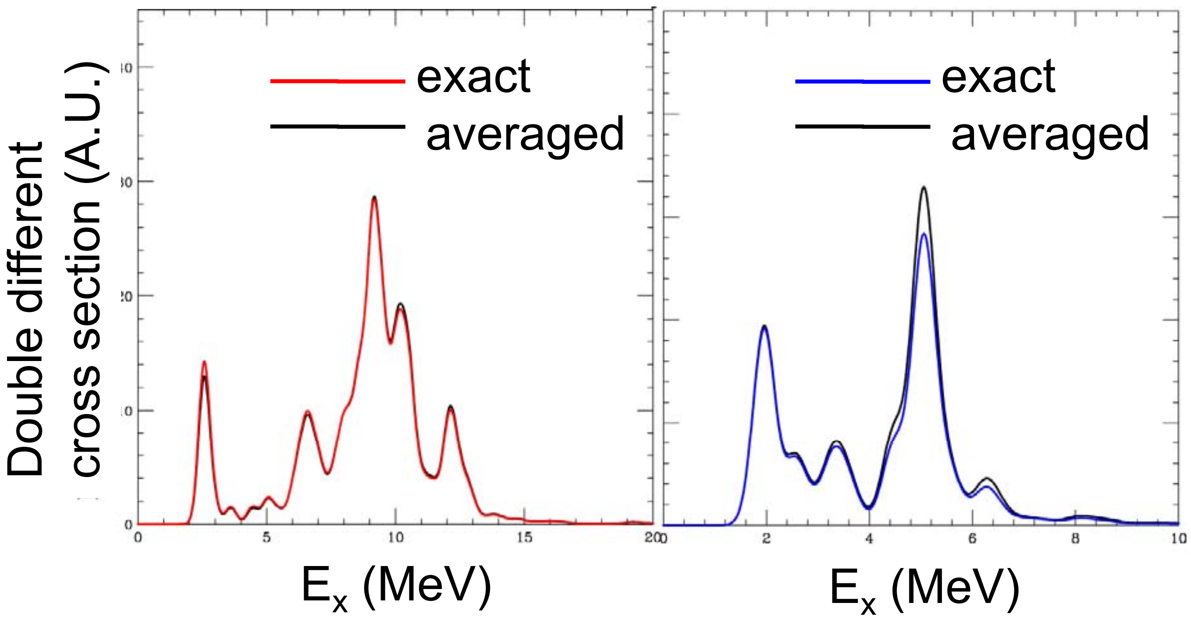
Exercise by using:
- ^{48}Ca--^{48}Ti system
- Shell model calc. ($n \leq 4$)
- Standard DWIA calc.

Deviations are small for large B(GT) for both sides.

Average $(\hat{\sigma}_{GT})$ could work.

$\hat{\sigma}_{GT}$ works in this case.





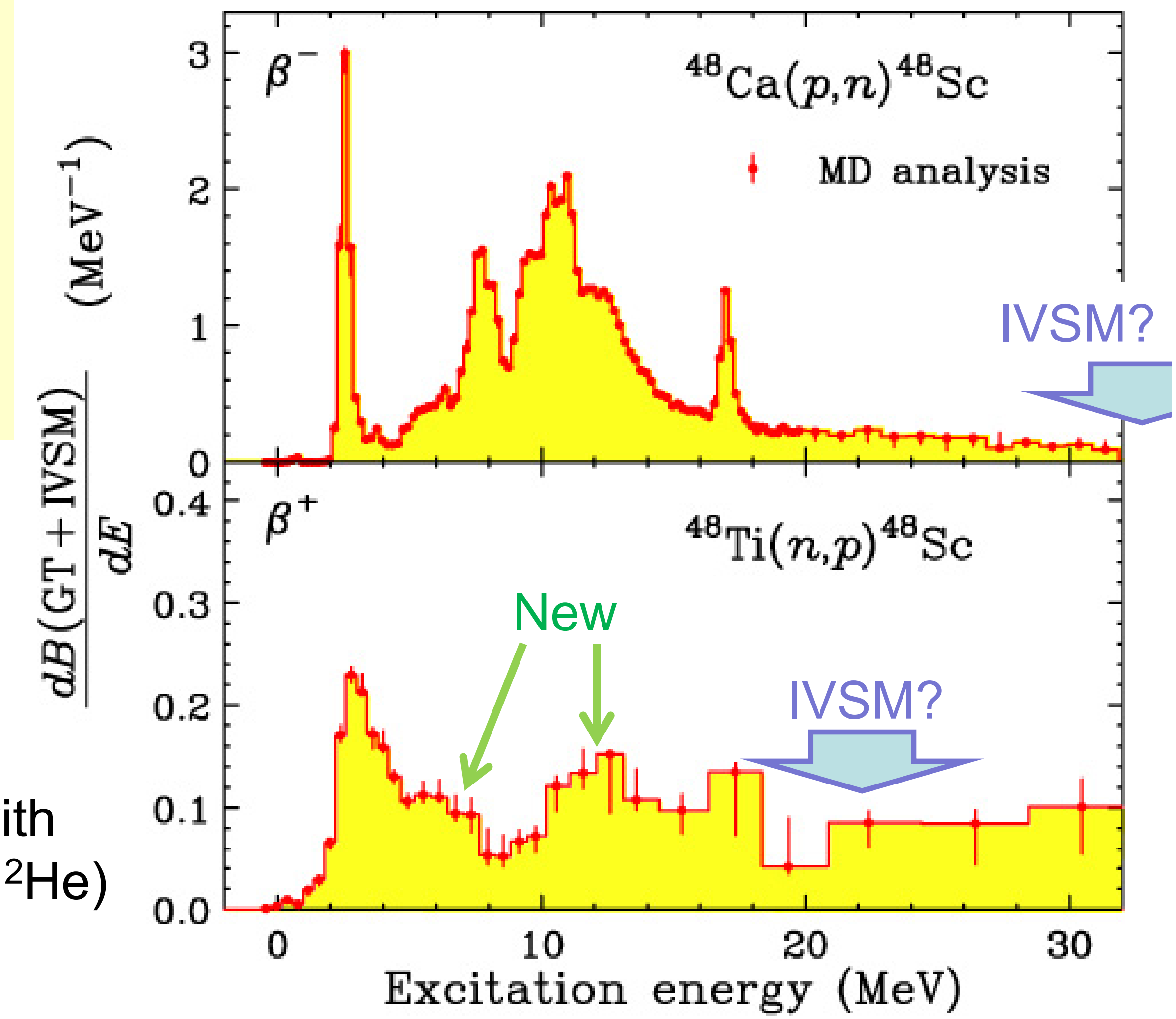
B($GT^{+/-}$) distribution

K.Y. et al., PRL103(2009)012503

MD analysis …

(p,n) : strengths exist beyond GTGR

(n,p) : peak at 3 MeV
shoulder at 6 MeV
bump(?) at 12 MeV



Integrated strengths (E_x < 30 MeV)

$\Sigma B(GT^-) = 15.3 \pm 2.2$
$\Sigma B(GT^+) = 2.8 \pm 0.3$

E_x < 5 MeV … consistent with (^3He,t) & (d,^2He)

Contamination of IVSM?

isovector spin monopole … $\Delta S=1$, $\Delta L = 0$, $2\hbar\omega$, $O = r^2\sigma\tau$

contribution estimated by DWIA: 0.9 ± 0.2 for (p,n), 0.9 ± 0.4 for (n,p)

B(GT$^{+/-}$) distribution … comparison with shell model

Shell model …

with quenched operator

Spectra agree qualitatively up to …

(p,n) : E_x = 15 MeV

(n,p) : 8 MeV

Strengths beyond … underestimated.

(n,p) channel :

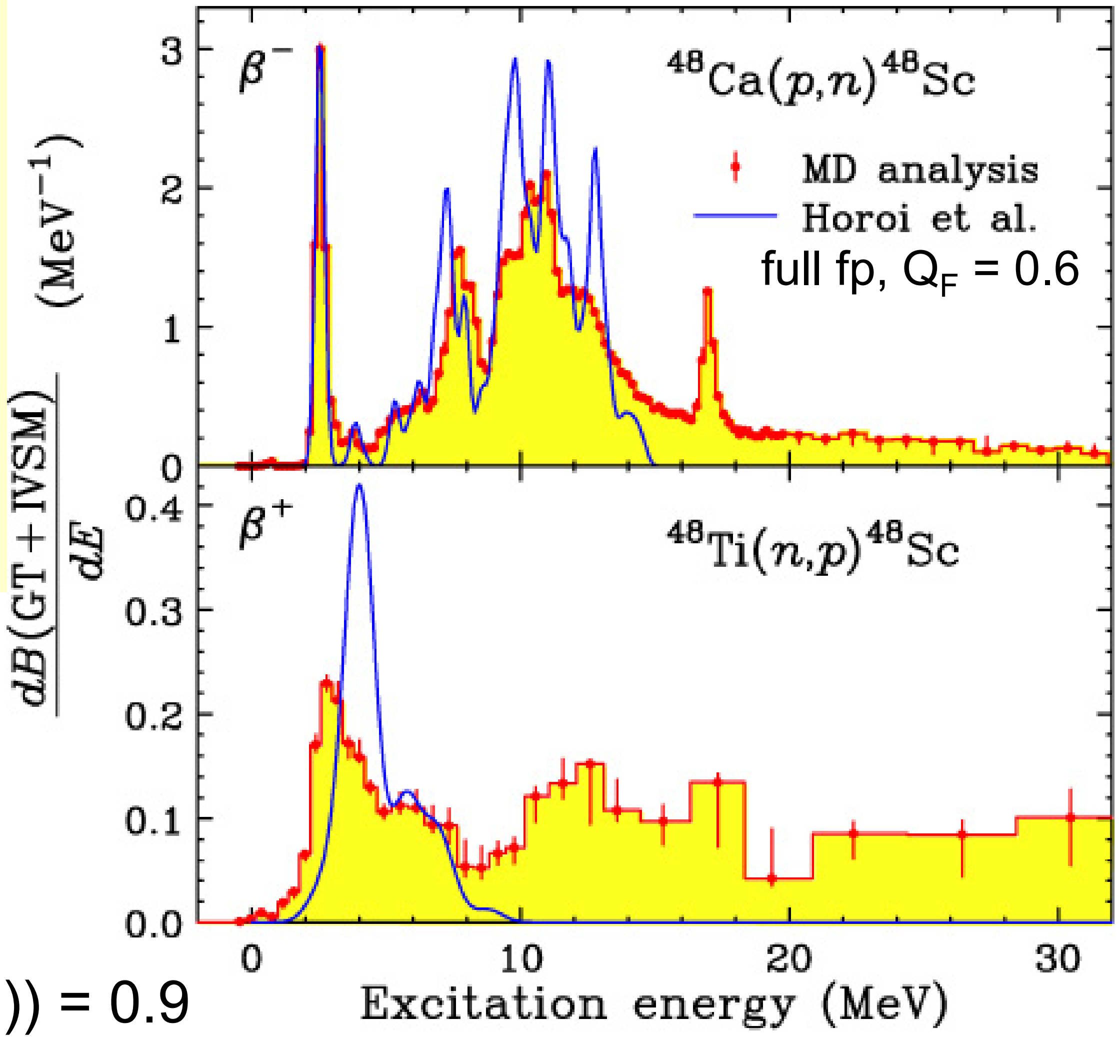
ΣB(GT$^+$;exp) = 1.9$\pm$0.3…

(w subtraction of IVSM)

⬍

ΣB(GT$^+$;ShellModel(Q_F=0.6)) = 0.9

larger model space?



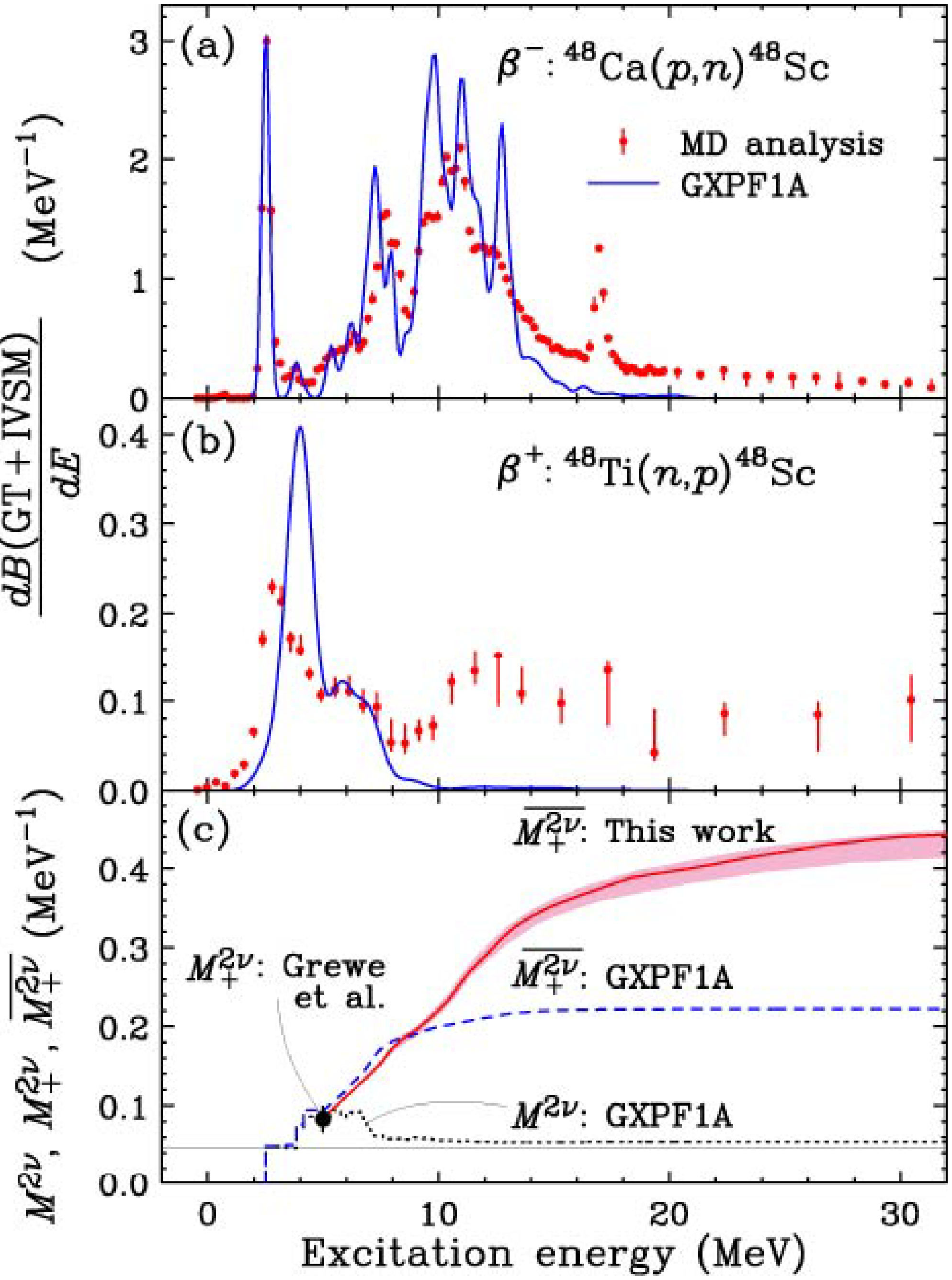
Contribution(?) to $M^{2\nu}$

At 8 MeV < E_x < 15 MeV
dB(GT$^-$)/dE : large
→ excess B(GT$^+$) might have significant contribution on $M^{2\nu}$.

"upperlimit" matrix element:

$$\overline{M}_{+}^{2\nu} = \int_E \frac{\sqrt{dB(\mathrm{GT}^+)/dE}\sqrt{dB(\mathrm{GT}^-)/dE}}{E-(M_i+M_f)/2}\,dE$$

The energy denominator alone does not diminish the importance of excess B(GT$^+$) .

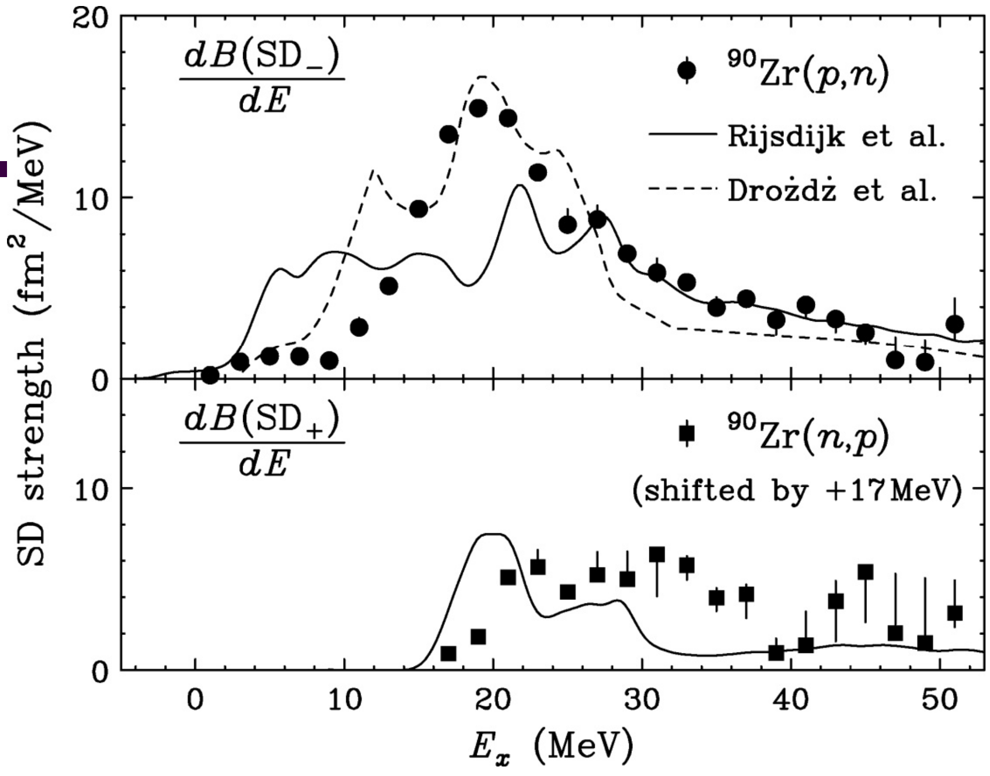


Future works

- Distribution of
  Spin Dipole strengths:

  …Important to $M^{0\nu}$

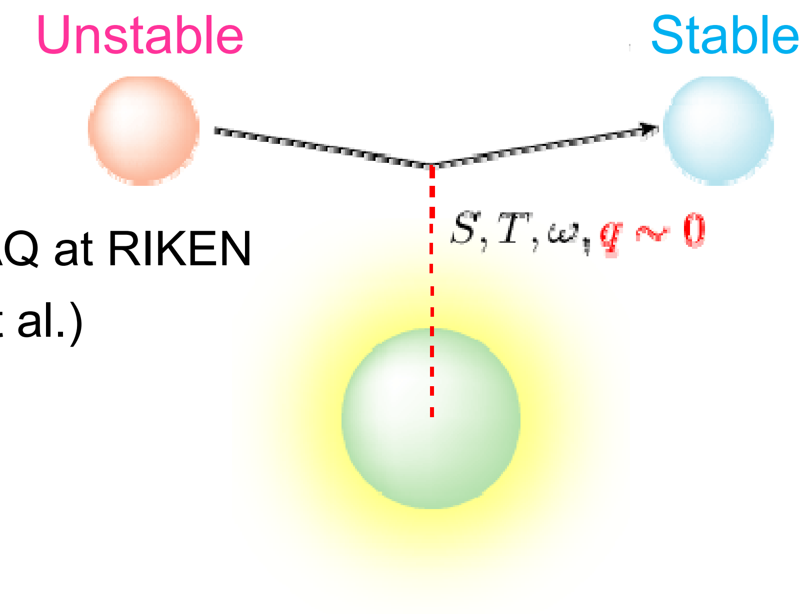
  ^{90}Zr: PRC74(2006)051303R



- Nature of
  high E_x region:

  ICHOR: Isospin-spin responses
  in CHarge-exchange
  exOthermic Reactions (SHARAQ at RIKEN
  Sakai et al.)

  – Surface sensitive
    Separation of
    0ħw and 2ħw components?



Summary

- The cross section spectra for
  the ^{48}Ca(p,n)^{48}Sc / ^{48}Ti(n,p)^{48}Sc reactions and
  the ^{116}Cd(p,n)^{116}In / ^{116}Sn(n,p)^{116}In reactions
  were measured at 300 MeV.
- MD analysis $\rightarrow$ B(GT$^{+/-}$) distribution (E_x < 30 MeV)

- ^{48}Ca $\rightarrow$ ^{48}Sc $\rightarrow$ ^{48}Ti [PRL103(2009)012503]
  - ΣB(GT$^-$) = 15.3$\pm$2.2
    ΣB(GT$^+$) = 2.8$\pm$0.3
  - shell model predictions :
    B(GT$^-$): good agreement up to GTGR (E_x < 15 MeV).
    B(GT$^+$): reasonable for E_x < 8 MeV,
    underestimation for E_x > 8 MeV
- ^{116}Cd $\rightarrow$ ^{116}In $\rightarrow$ ^{116}Sn
  B(GT$^+$): underestimation