Double-beta decay matrix elements and charge exchange reactions

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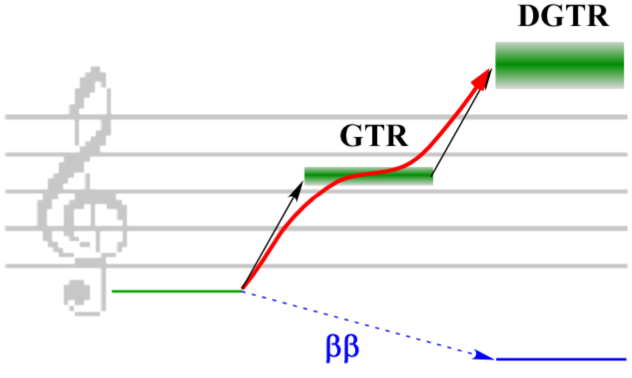


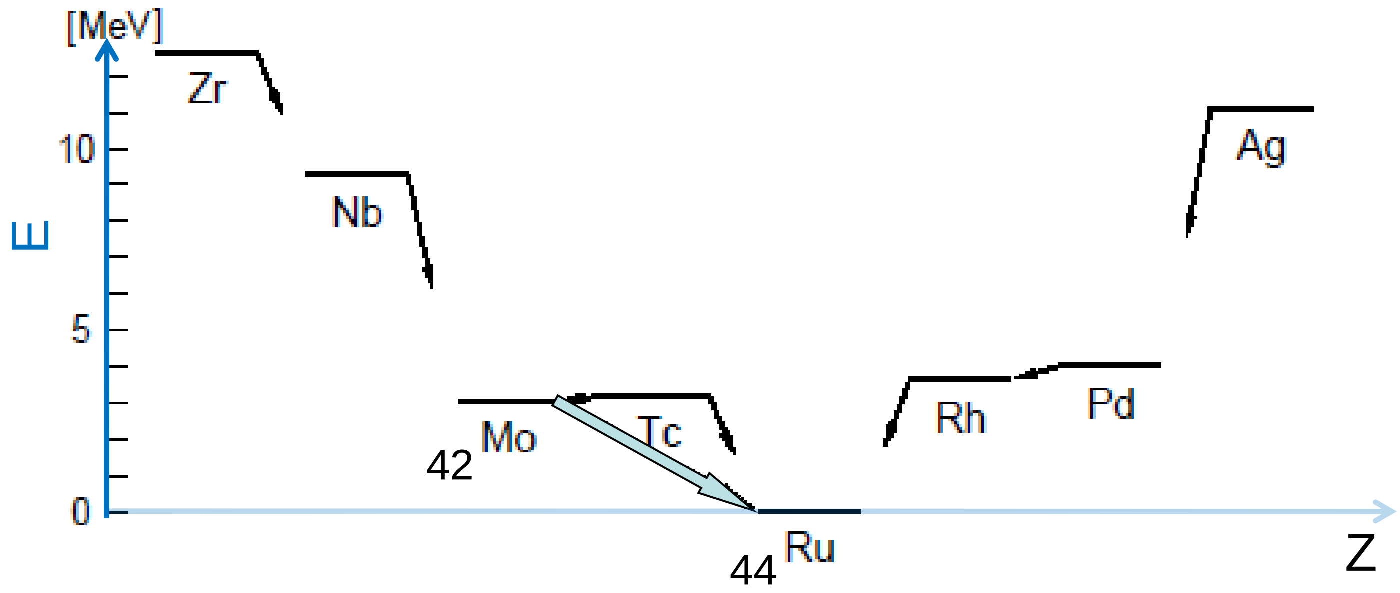
Double beta decay

Double beta decay (DBD):

decay process where a nucleus releases

two beta rays as a single process

example: A = 100 (^{100}Mo)



DBD nuclei (studied so far):

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

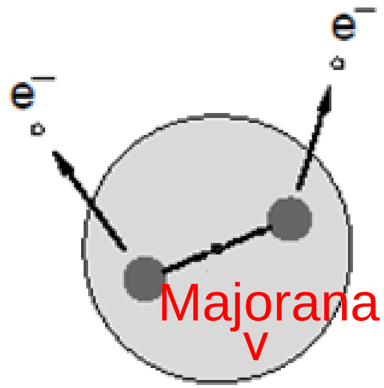
Two modes

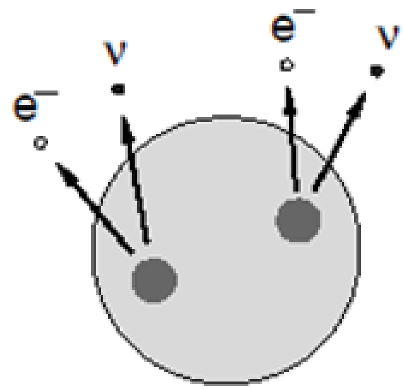
forbidden in
"standard" model

DBD

- 0ν mode $(A,Z) \rightarrow (A,Z+2) + 2e^-$
- 2ν mode $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu_e}$

0ν mode 2ν mode





0ν event …

→ ν is Majorana particle.

→ absolute mass is deduced from the half life. …mass hierarchy

→ origin of matter / antimatter imbalance?

→ …

Nuclear Matrix Elements

…0ν DBD occurs in nucleus

- second order process
- intermediate states:
  - g.s.
  - other states of various J^{π}.

0ν life time and ν mass

Phase space / weak coupling

"nuclear matrix element" (NME)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \langle m_\nu \rangle^2 \left| M_{\mathrm{DGT}}^{0\nu} - M_{\mathrm{DF}}^{0\nu} \right|^2 + \ldots$$

nuclear structure calculation

Shell model, RPA,…

NME is important!

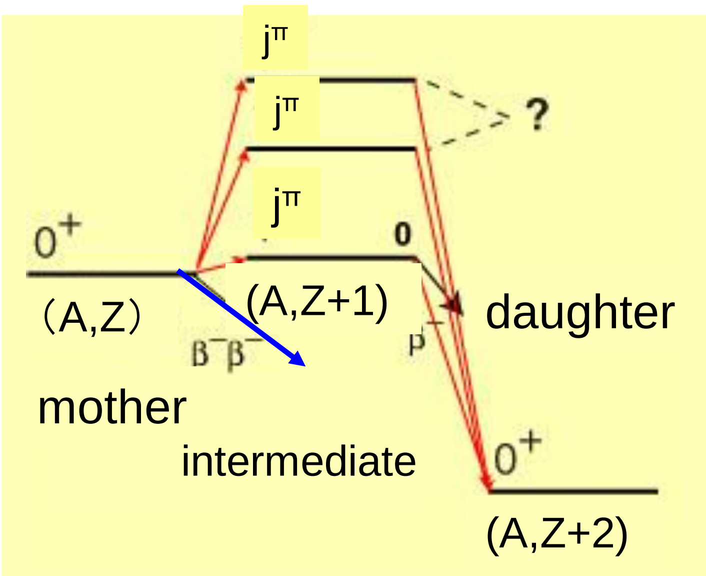
- analysis … absolute mass / mass limit of ν
- search planning … which nucleus is the best candidate?

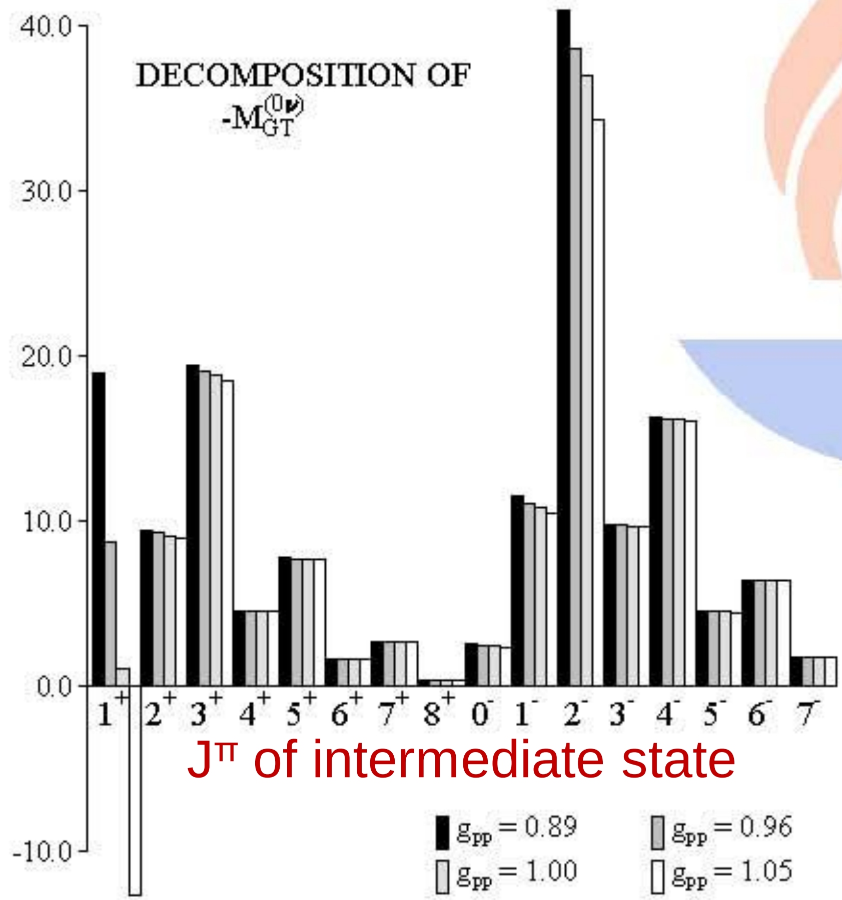
$0\nu\beta\beta$ Matrix Element: Decomposition in the pnQRPA

Suhonen, 2005

$$M_{\rm GT}^{(0\nu)} = \sum_{J^\pi} M_{\rm GT}^{(0\nu)}(J^\pi)\,,$$

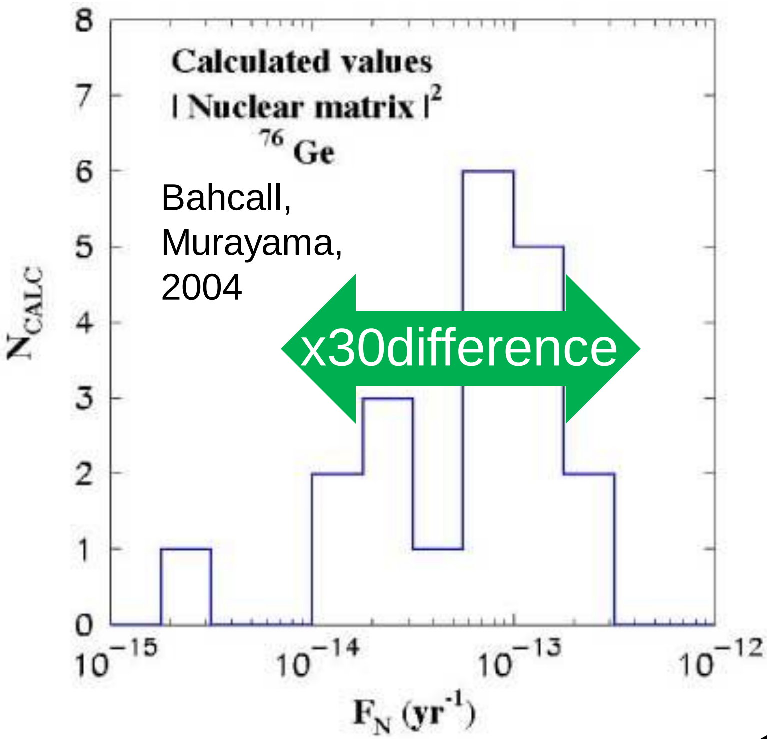
$$M_{\rm GT}^{(0\nu)}(J^\pi) = \sum_{n\lambda} (0_f^+ \| \sum_j \left[\sigma_j F_\lambda(\mathbf{r}_j)\right]_J t_j^- \| J^\pi n)$$
$$\times\, (J^\pi n \| \sum_j \left[\sigma_j F_\lambda(\mathbf{r}_j)\right]_J t_j^- \| 0_i^+)$$





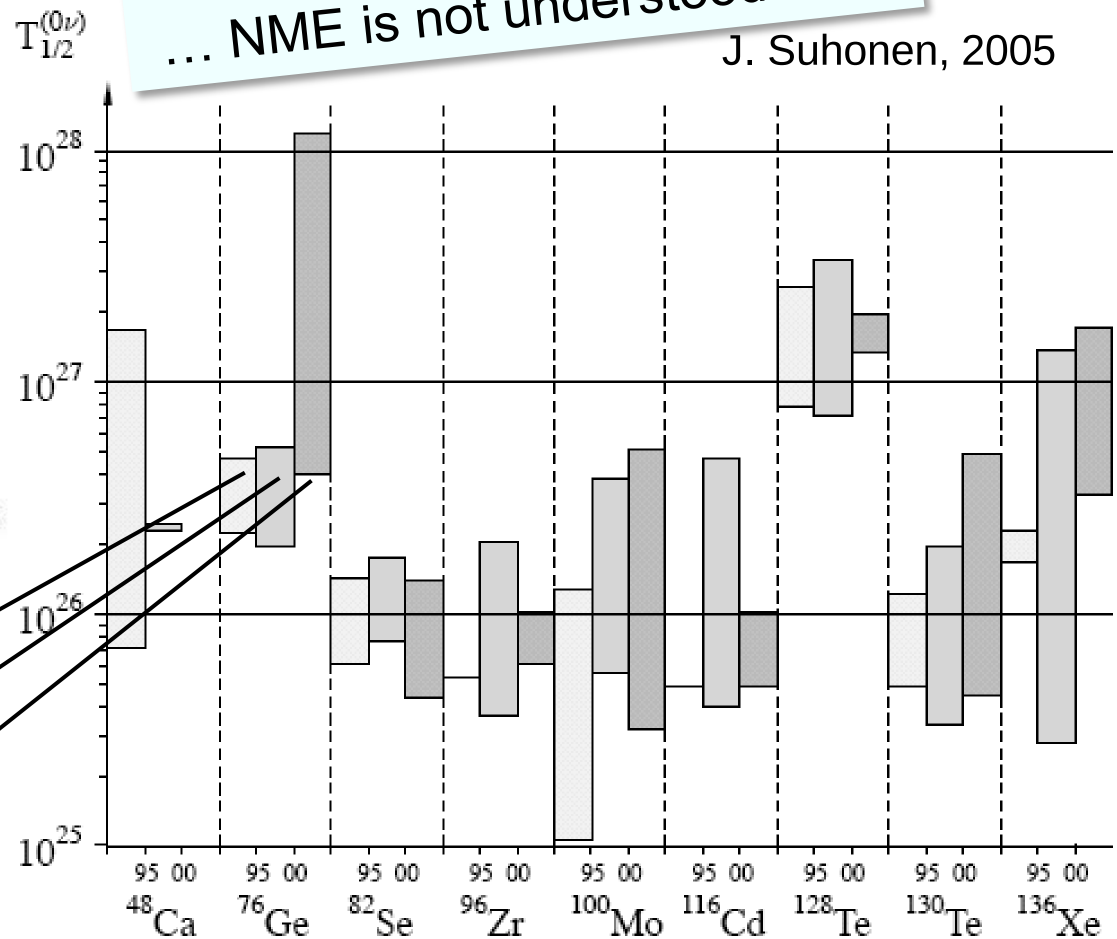
Reliability of NME (2005)

Ex) ^{76}Ge



No sign of "convergence"
… NME is not understood well.

J. Suhonen, 2005

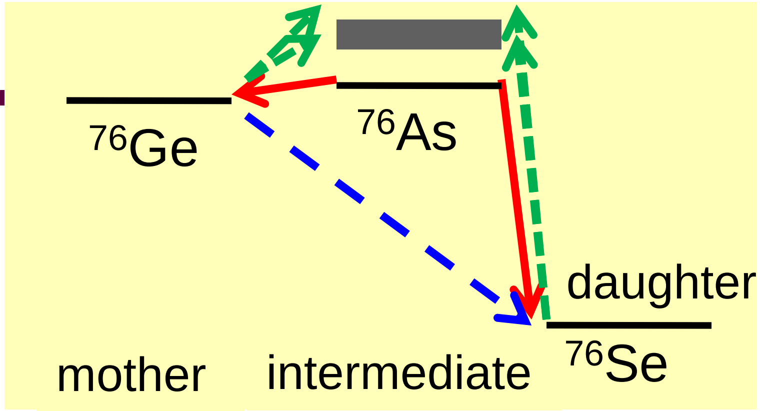


before 1995

1995 - 2000

2000 - 2005

Constraints on the calculations



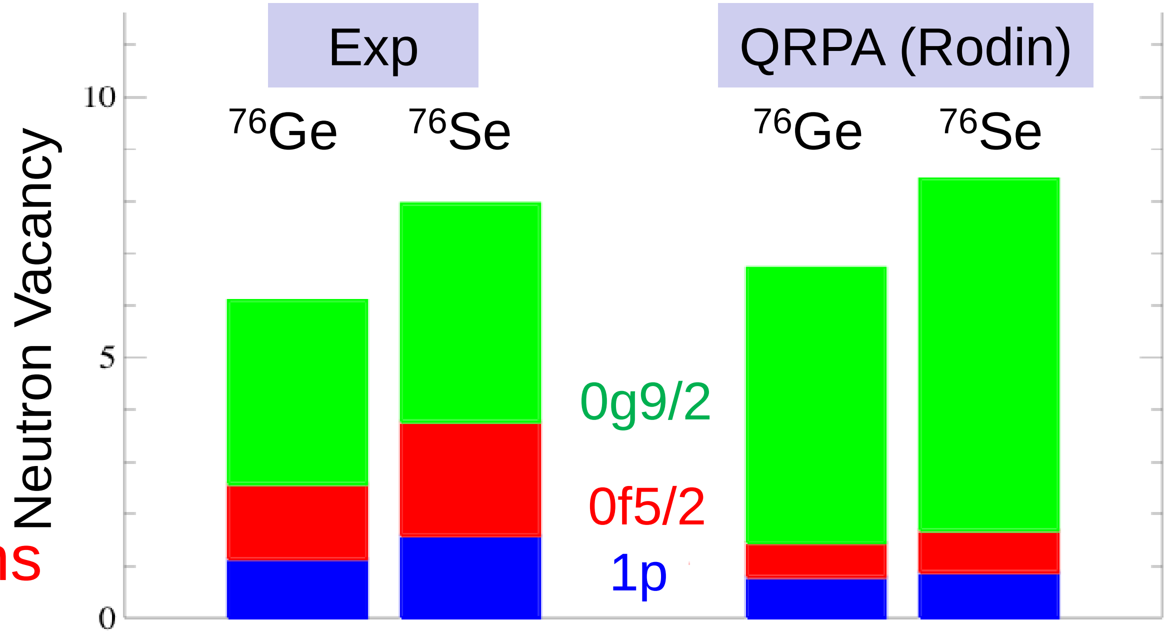
step1 first order transitions

- Single β^- & β^+ rates
- 2v-DBD rate

step2 ground states

- Occupation numbers
  of "valence" nucleons:
  (d,p), (p,d),
  (α,^{3}He), (^{3}He,α)

Extra g.s. correlation is necessary.



Kay, Schiffer et al., 2009

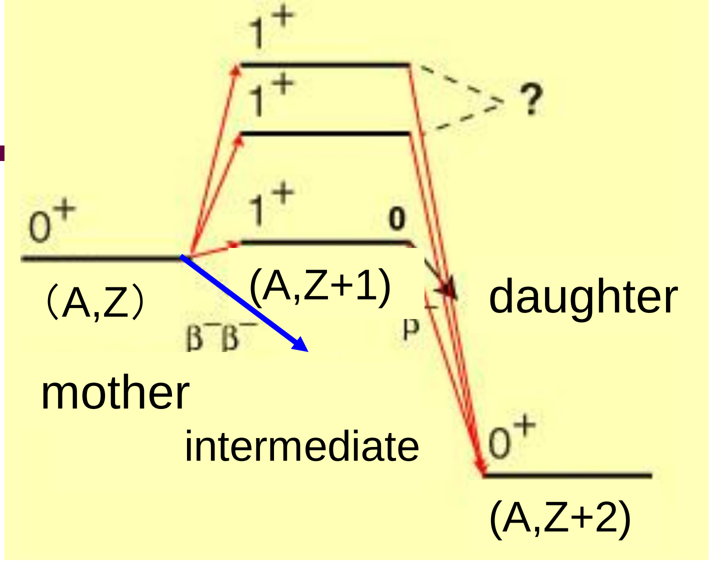
step3 relevant transitions

- β-type transitions:
  energy, strength, …

mother → intermediate → daughter

Our work:
Gamow-Teller (1^+)
($\Delta L=0$, $\Delta S= \Delta T=1$)

GT transitions and 2ν-DBD



2νββ 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 0νββ decay rate.

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}

Half-life and matrix element:

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

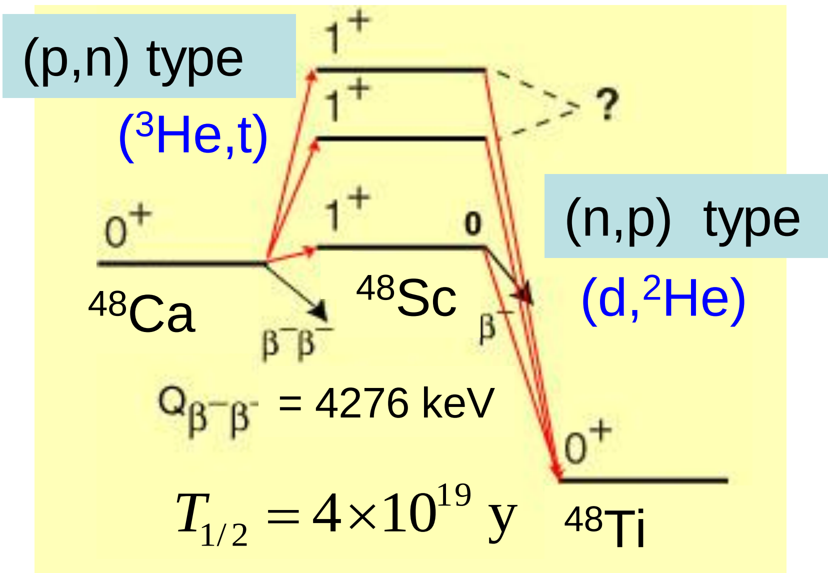
$$\boxed{M_{\mathrm{DGT}}^{2\nu} = \sum_m \frac{\langle f\|O_{\mathrm{GT}-}\|m\rangle\langle m\|O_{\mathrm{GT}-}\|i\rangle}{E_m - (M_i + M_f)/2}}$$

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

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

B(GT) in low-lying states

GT strengths:



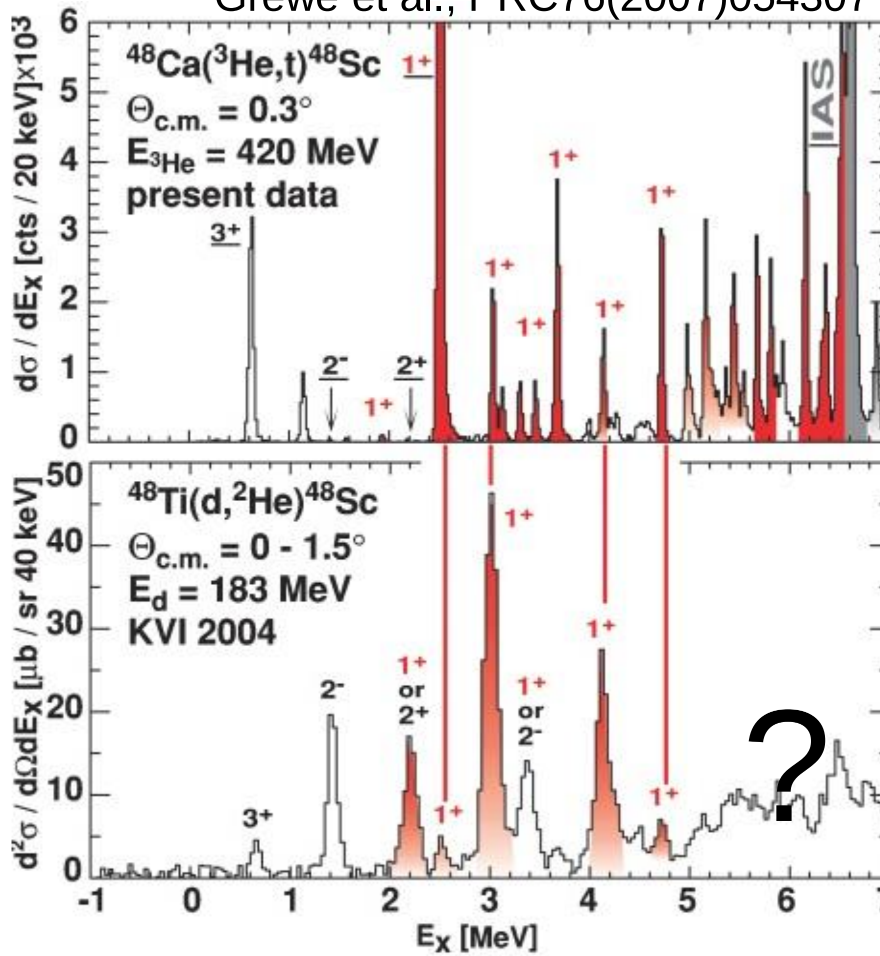
Low lying states

… high resolution measurements

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

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

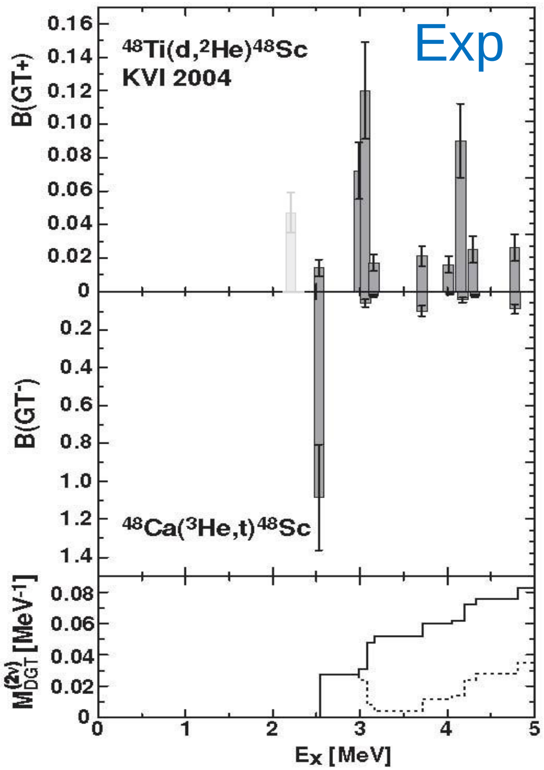
Grewe et al., PRC76(2007)054307

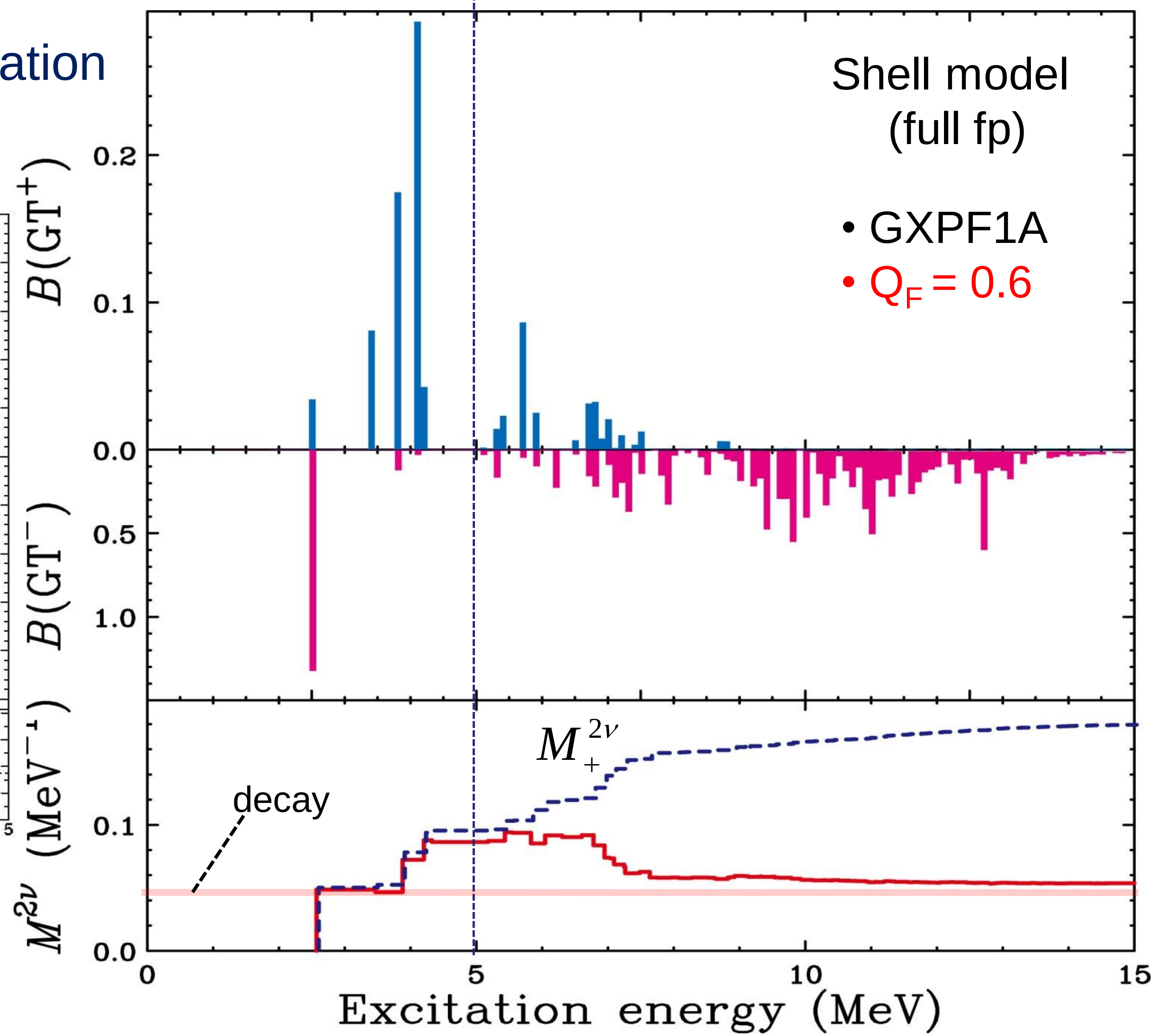


Current understanding by shell model

Same as Horoi et al. PRC75(2007)034303

Shell model calculation
… reasonable.





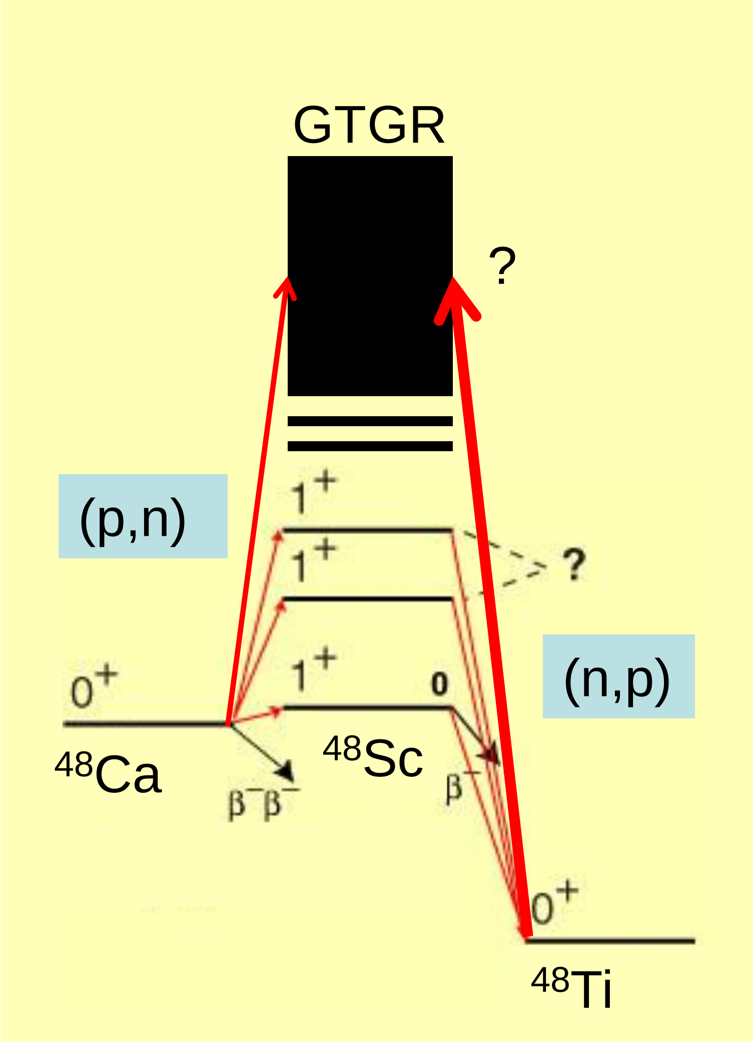
Aim

- 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

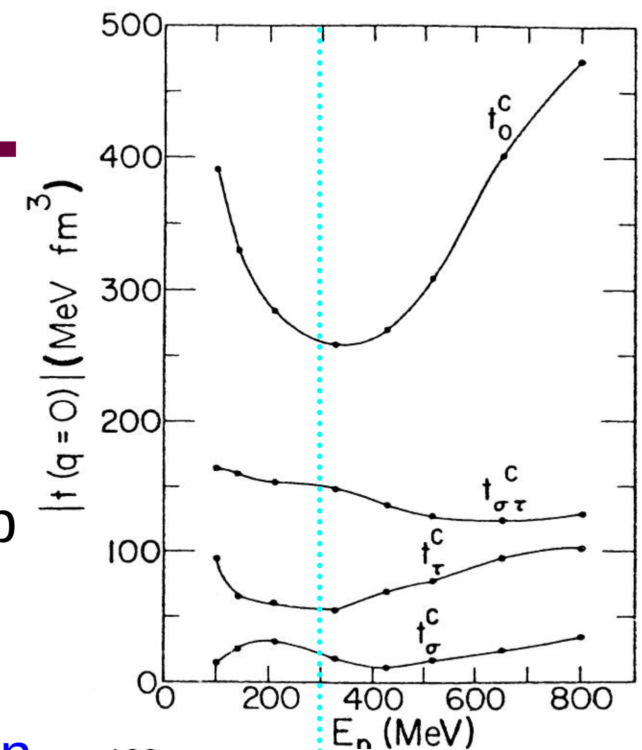


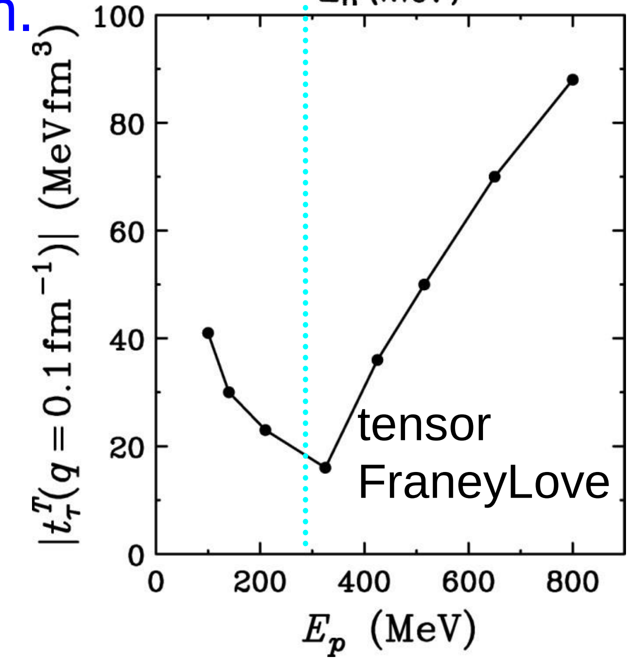
(p,n) & (n,p) at 300 MeV

Advatages

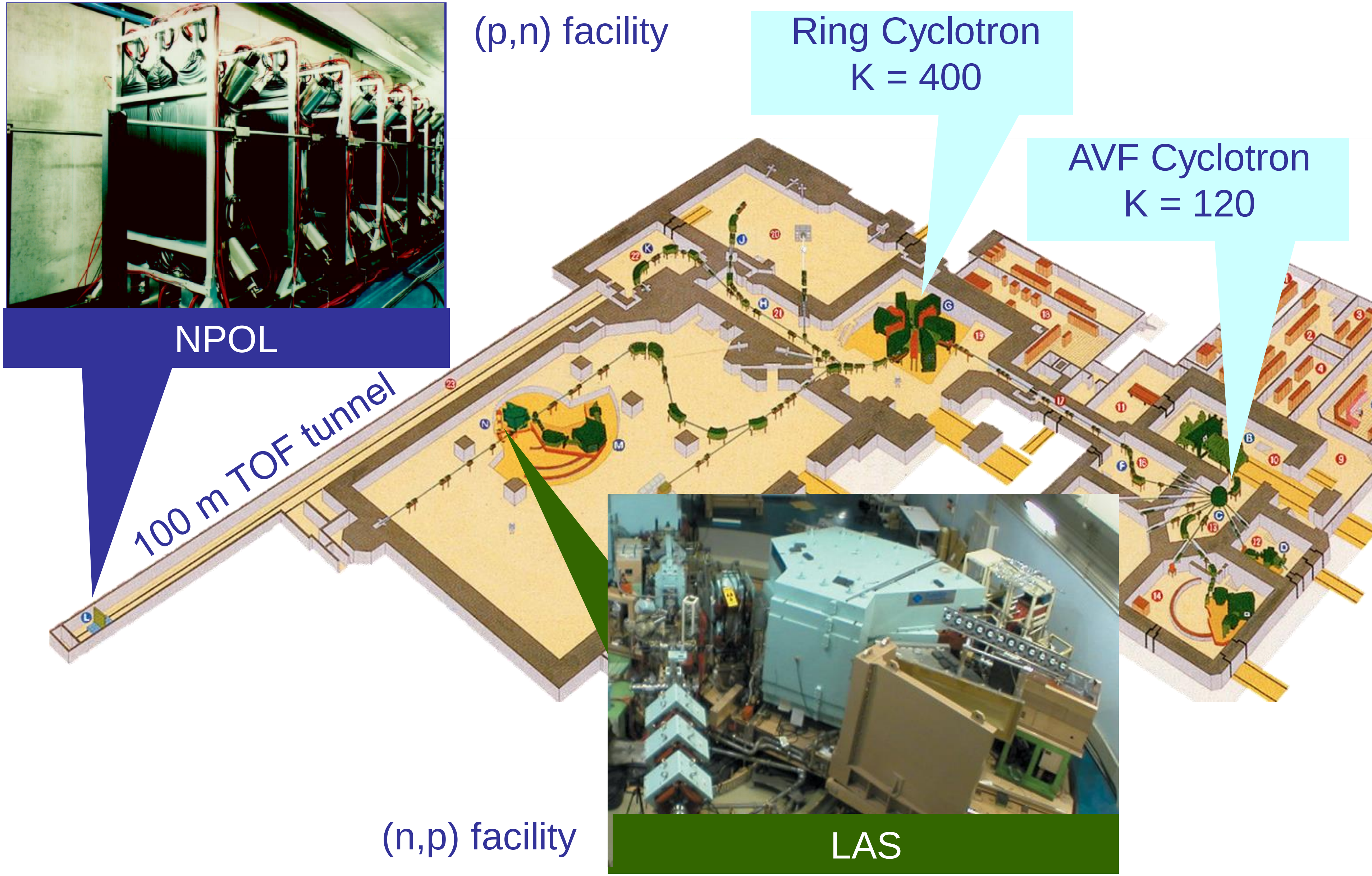
- Simple reaction mechanism
- 300 MeV:
  1. Effective interaction favors Spin-flip transitions over Non-Spin-flip ones
     $(t_{\sigma\tau}/t_{\tau})$
     ⇒ GT transitions are most clearly seen.
  2. Distortion effects are smallest (t_0).
     ⇒ analysis with DWIA is reliable.
  3. Tensor interaction is smallest (t_τ^T).
     ⇒ Proportionality relation is reliable.
     cross section ⇔ strength

… Multipole decomposition analysis works best.



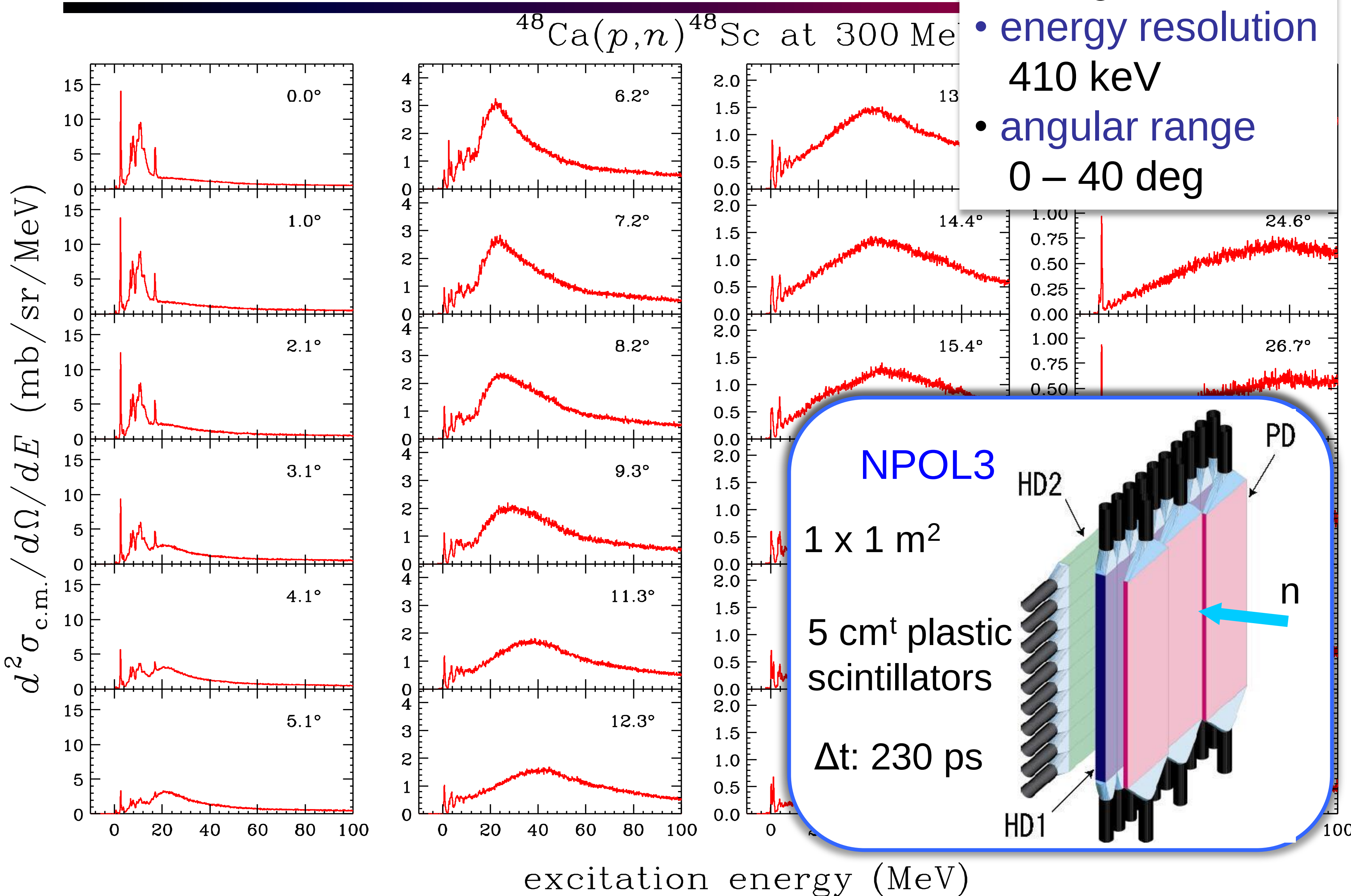


(p,n) & (n,p) facilities at RCNP



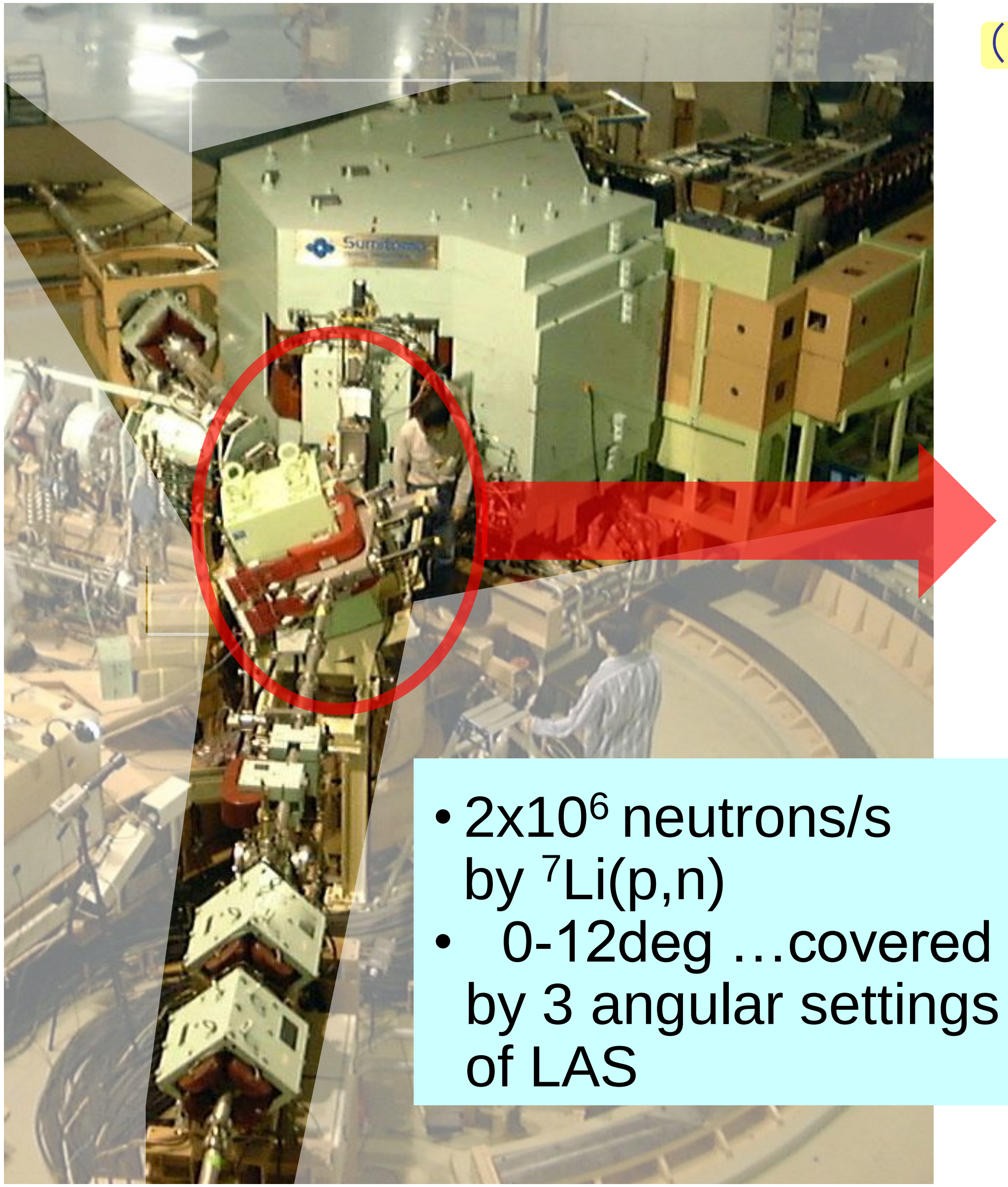
^{48}Ca(p,n) measurement

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

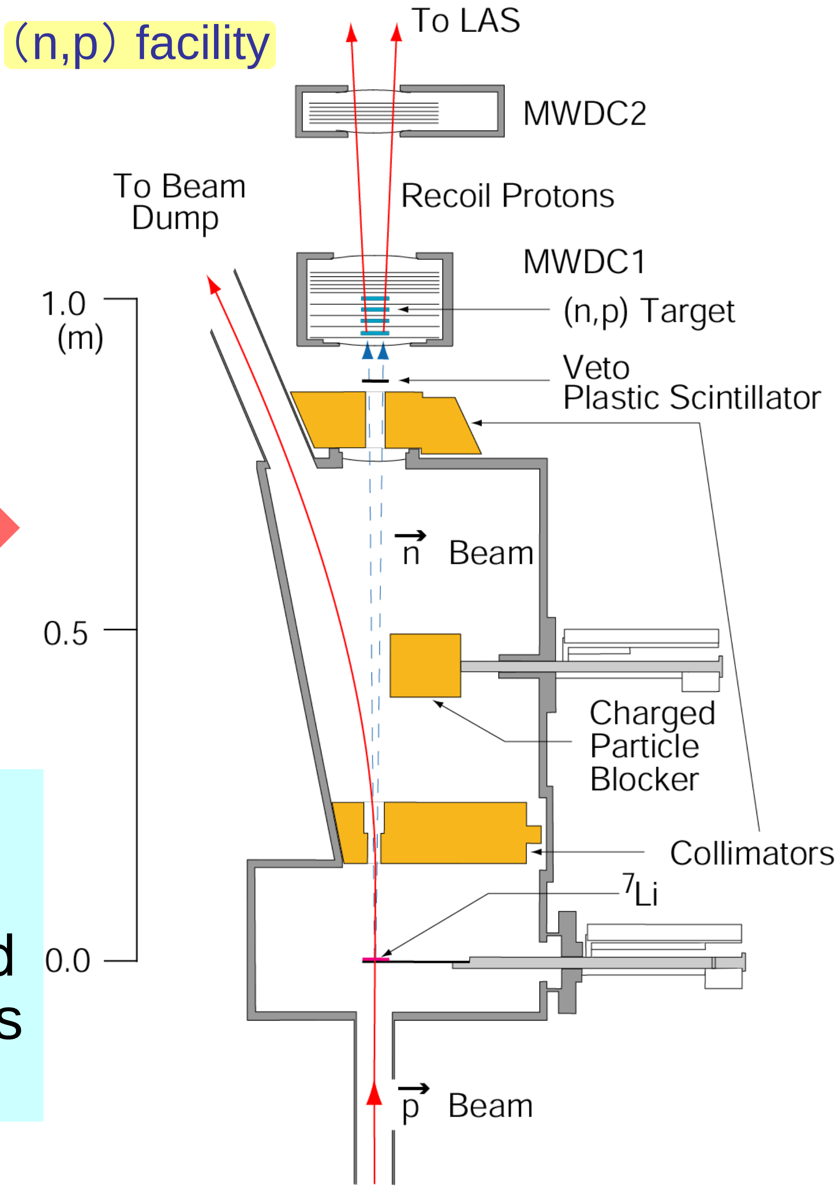


(n,p) measurement

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

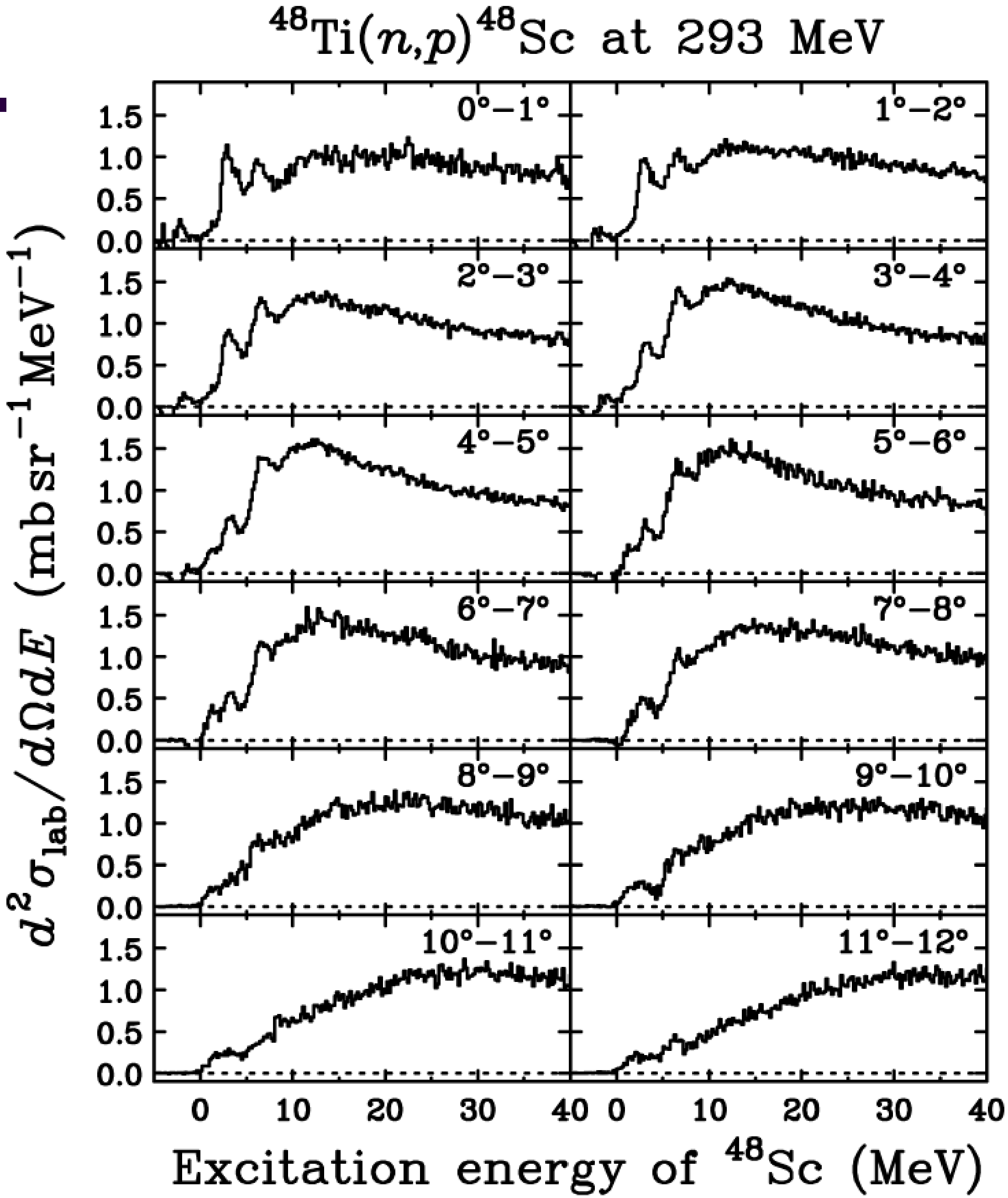


- 2×10^6 neutrons/s by $^7Li(p,n)$
- 0-12deg …covered by 3 angular settings of LAS



^{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)

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

DWIA

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

DWIA inputs (DW81)

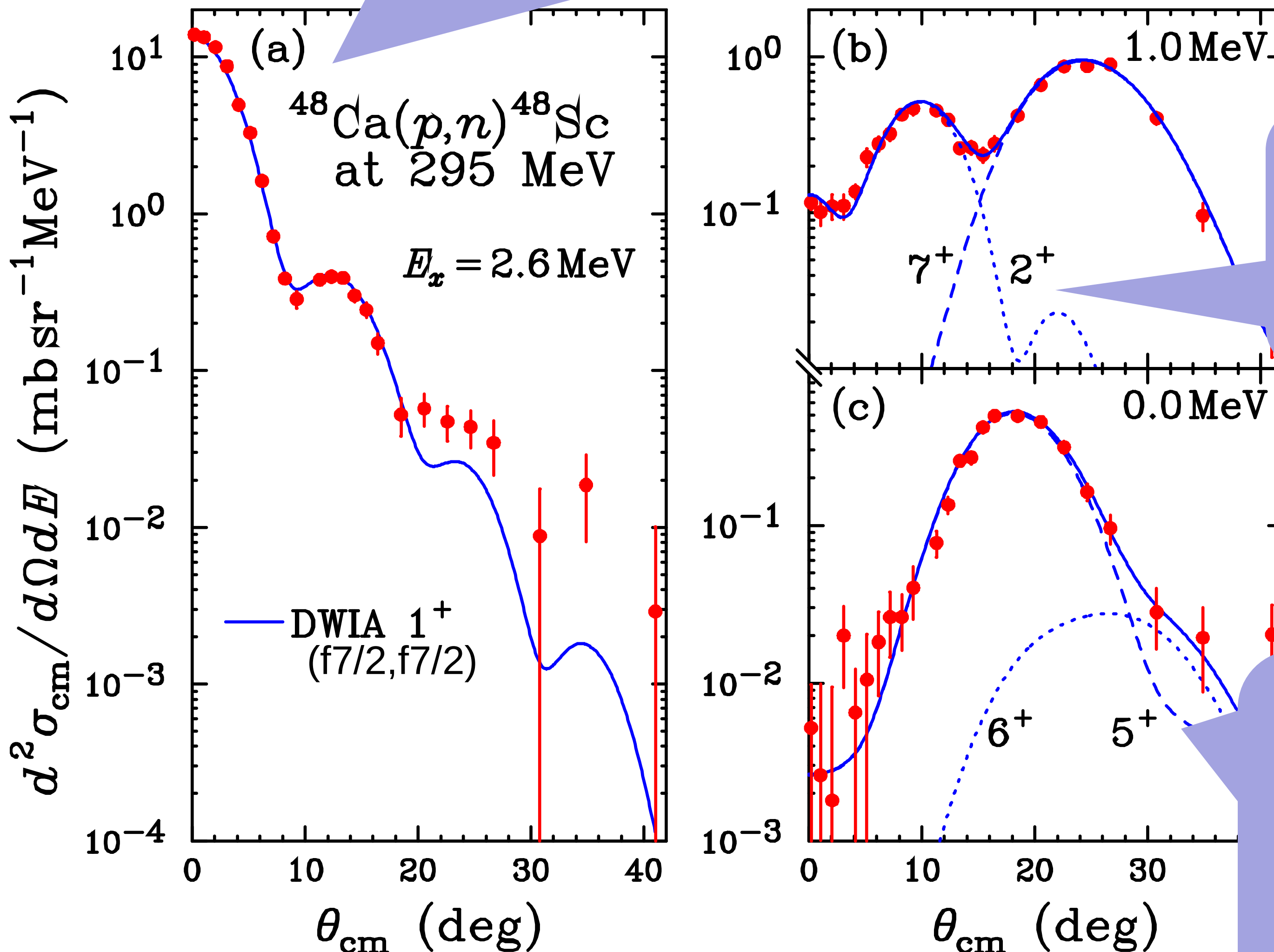
- NN interaction:
  t-matrix by Franey & Love @325 MeV
- optical model parameters:
  Global optical potential
  (phenomenological, Cooper et al.)
- one-body transition density:
  pure 1p-1h configurations

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

radial wave functions … W.S. / H.O.

Examples of angular distribution

The DWIA description of GT transition is good.



The description of ΔL=2 is reasonable.

The ΔL>3 component does not contribute much at 0°

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

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

MD analysis …

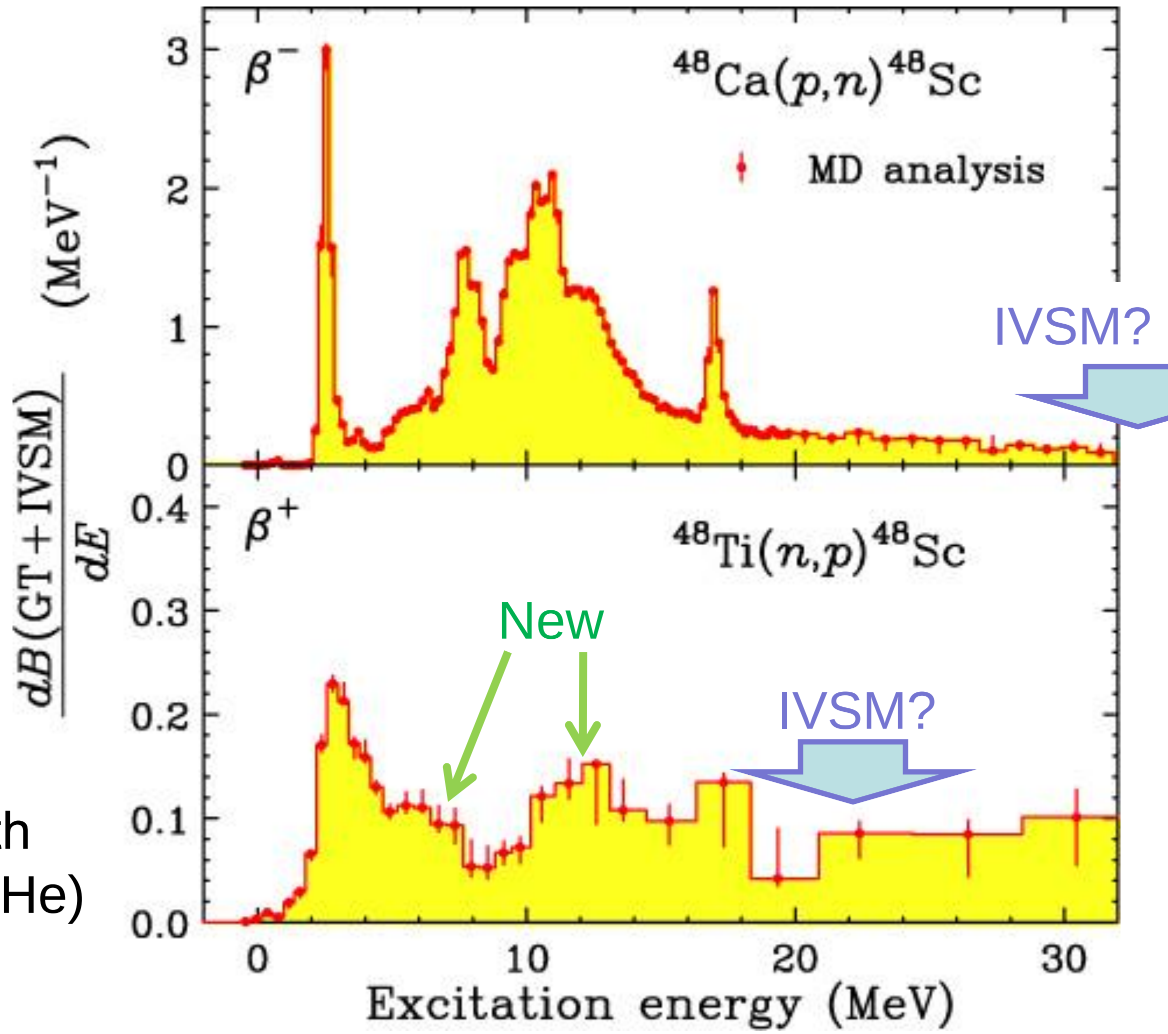
(p,n) : strengths exist
beyond GTGR

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

Integrated strengths
(E_x < 30 MeV)

$$\begin{cases} \Sigma B(GT^-) = 15.3 \pm 2.2 \\ \Sigma B(GT^+) = 2.8 \pm 0.3 \end{cases}$$

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



Contamination of IVSM?

isovector spin monopole … ΔS=1, Δ L = 0, 2ħω, 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 …

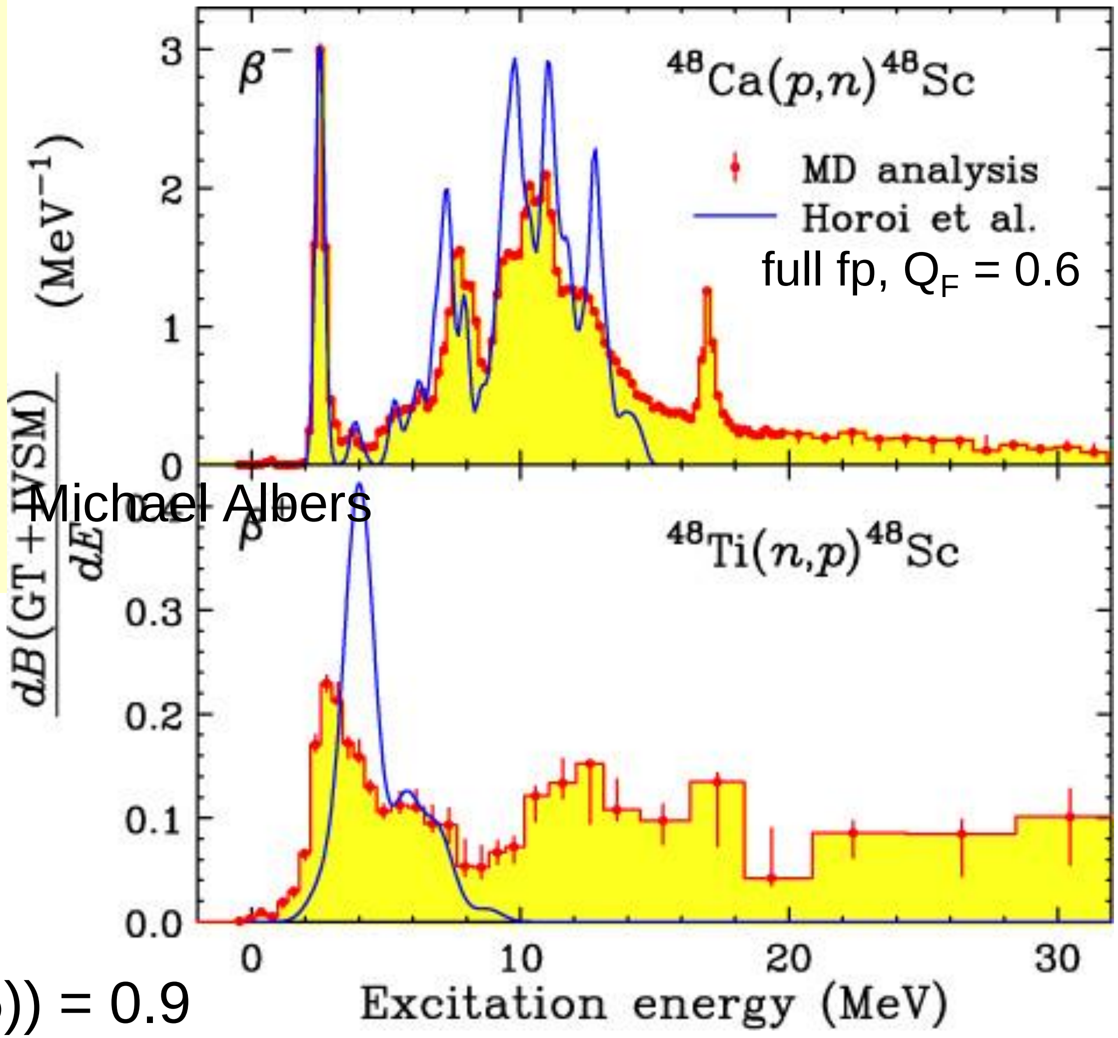
with quenched operator

Spectra agree qualitatively up to …

(p,n) : E_x = 15 MeV

(n,p) : 8 MeV

Strengths beyond … underestimated.



Michael Albers

(n,p) channel :

ΣB(GT$^+$;exp) = 1.9±0.3…

(w subtraction of IVSM)

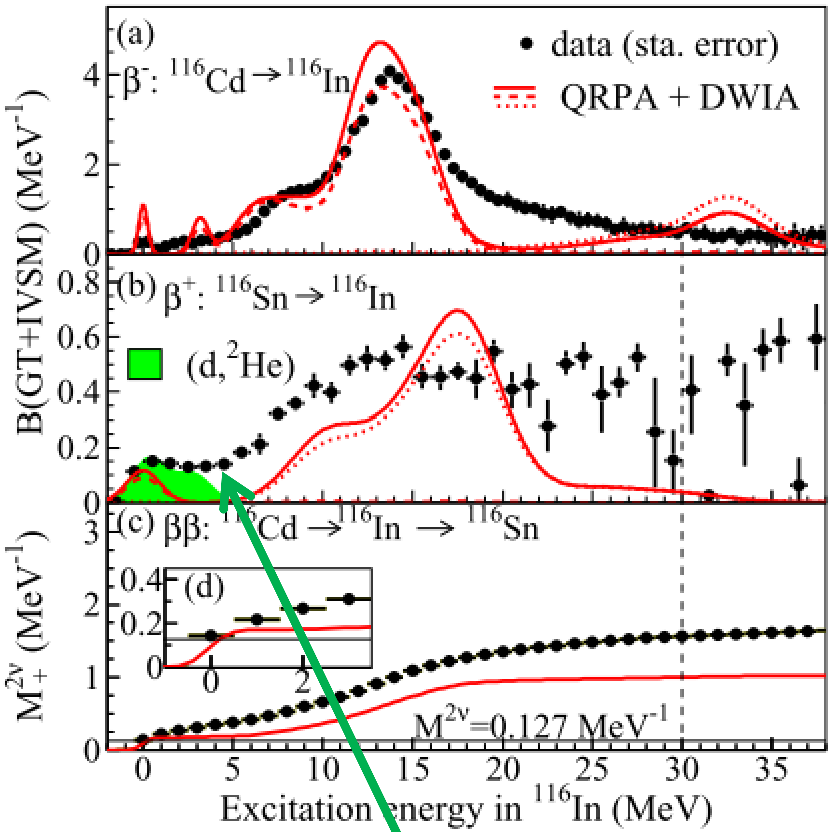
⬍

ΣB(GT$^+$;ShellModel(Q_F=0.6)) = 0.9

The “best” calculations fail to account for the spectra.

Necessity of larger model space? Correlations?, …

^{116}Cd case



β- : strengths in the low energy region to be pushed up
β+: extra strength of about 2 and/or strengths around 22 MeV to be pushed down

	Theo.			Exp.
	GT	IVSM	GT+IVSM	GT+IVSM
β+	0.4	5.4	6.8	11±1
β-	42	4	52	45±8

Interf. : ~15%

Strengths around 10 MeV are underestimated.

Extra g.s. correlation?

Missing correlations?

For example, comparing SM w/ QRPA

- Each has uncertainty of

Menendez, PRL100(2008)052503

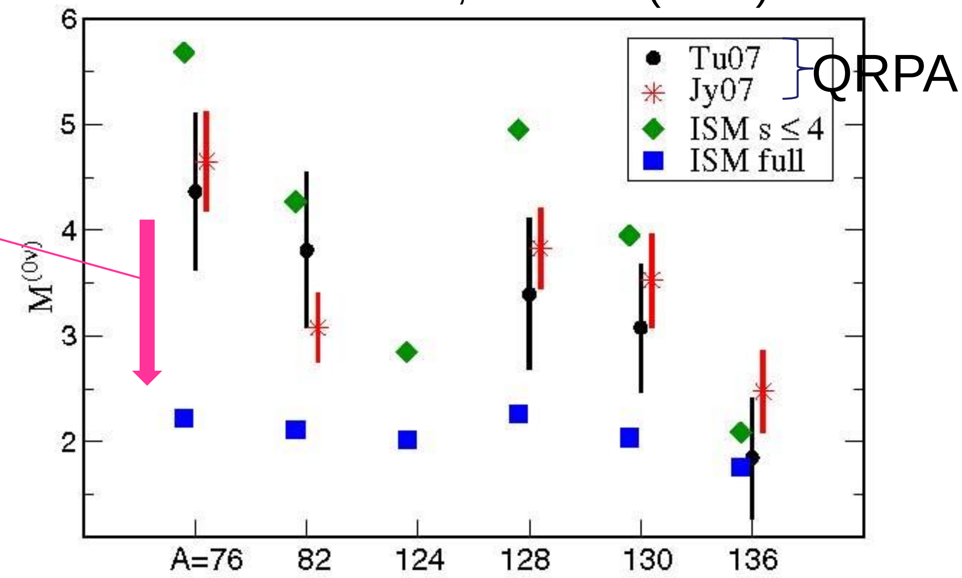


FIG. 3 (color online). The neutrinoless double beta decay NME's; comparison of ISM and QRPA calculations. Tu07; QRPA results from Ref. [20]. Jy07; QRPA results from Ref. [21]. ISM $s \leq 4$ and ISM; present work. The ISM results have uncertainties in the 20% range (see text).

- SM predictions …

  20-50% smaller than QRPA.

- Concerns…

SM : limited model space

QRPA :

sufficient correlation?

Different theories with different model spaces and different correlations

How do theories converge …

Ab-initio (more correlations)

Efficiency

No-core shell model

Only light nuclei

Shell model

Renormalization of transition operator

Holt and Engel, arXiv:1304.4202
Engel and Hagen, PRC79,064317(2009)

Coupled cluster Calculation

Non-perturbative
Higher order corr.
G. Hagen et al. (ORNL+Oslo...)

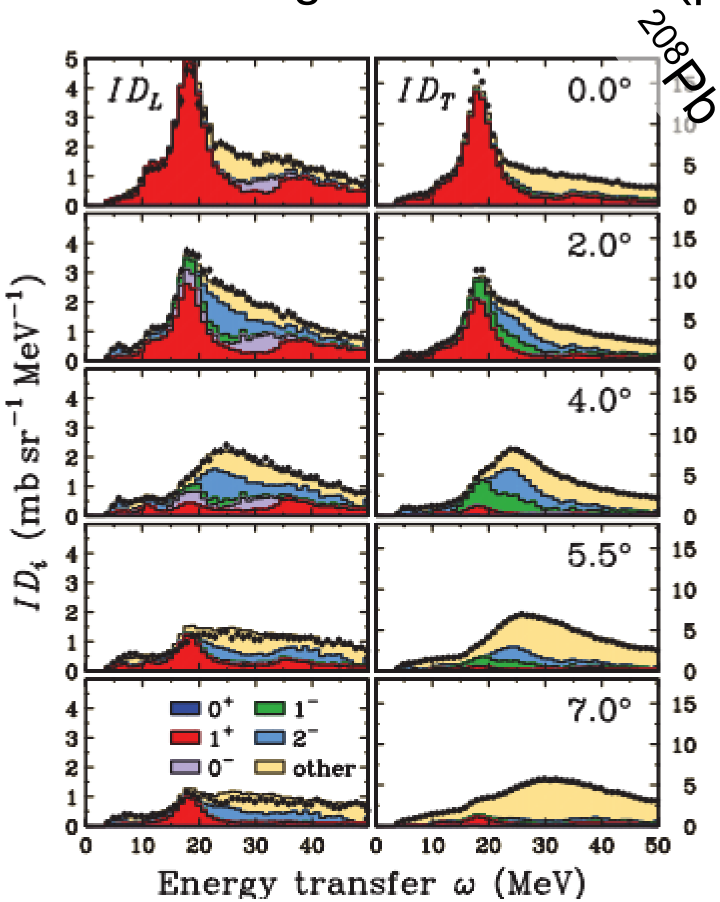
RPA + (n-n/p-p pair)

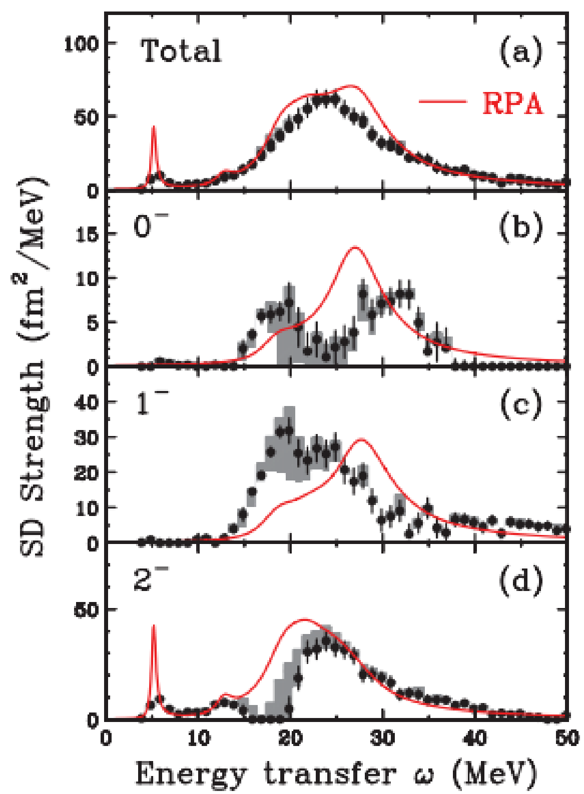
Generator Coor. meth.
p-n pair,
large (deform) fluctuation
N. Hinohara et al. (UNC-CH)

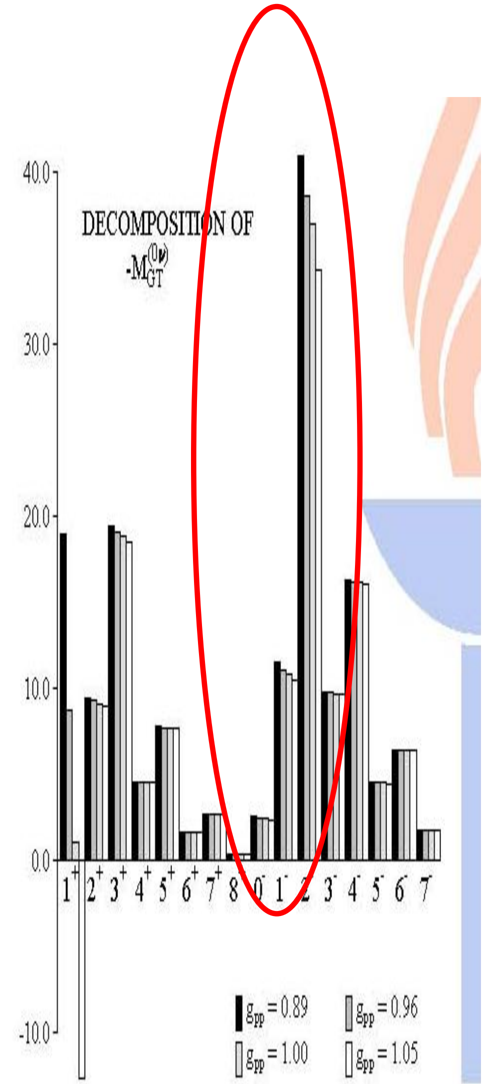
… anyways, the first convergence may appear for the ^{48}Ca case

What can be done further experimentally?

breakthrough at RCNP via (p→,n→) meas…







Wakasa et al., PRC85, 064606 (2012)

Ingredients most important for neutrinoless mode can be directly probed…
Measurement on ^{48}Ca would be interesting…

Summary

- Half-lives, transfer and (p,n)/(n,p) reactions
  →constrains the structure theories
- We measured 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
  at 300 MeV
- Currently, the understanding of nuclear correlations is not enough!

→ Challenges w/ more sophisticated frameworks!

→ A new tool, (p→,n→) at RCNP

→ 0-, 1-, 2-, (important for neutrinoless mode)

Summary

Multipole decomposition analysis

MDA

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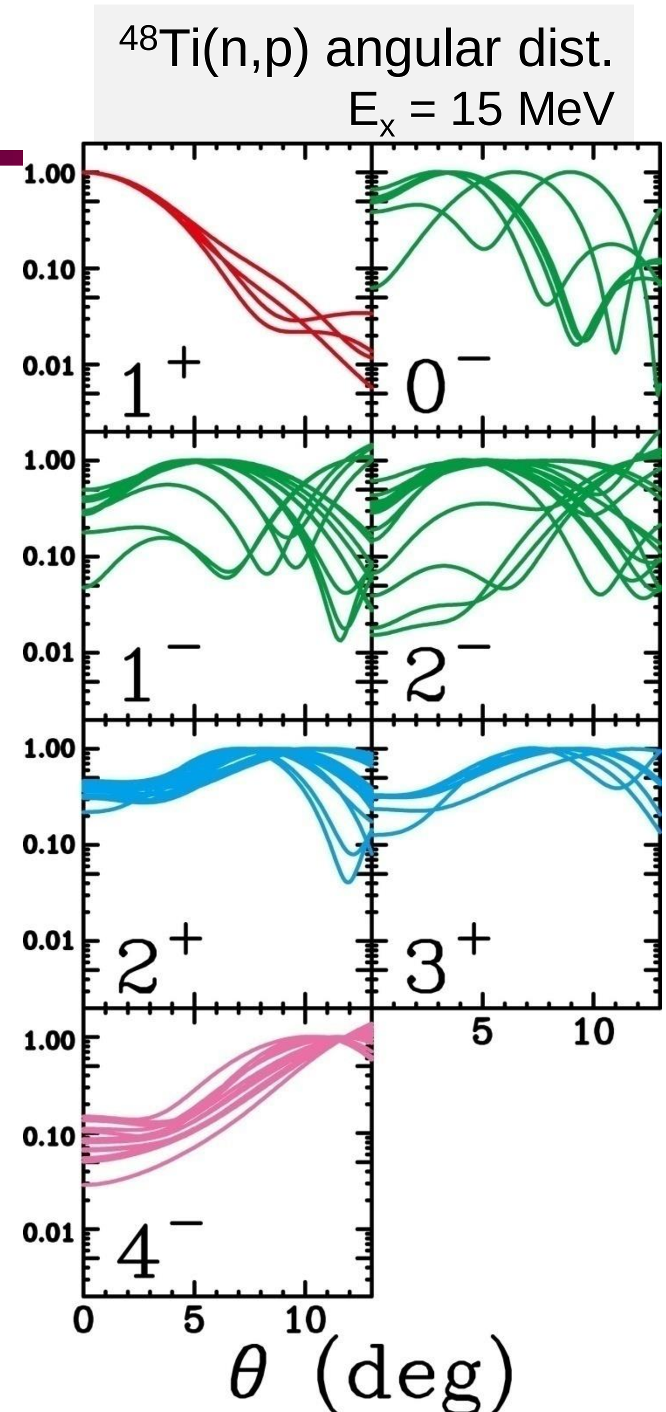
  pure 1p-1h configurations

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

radial wave functions … W.S. / H.O.

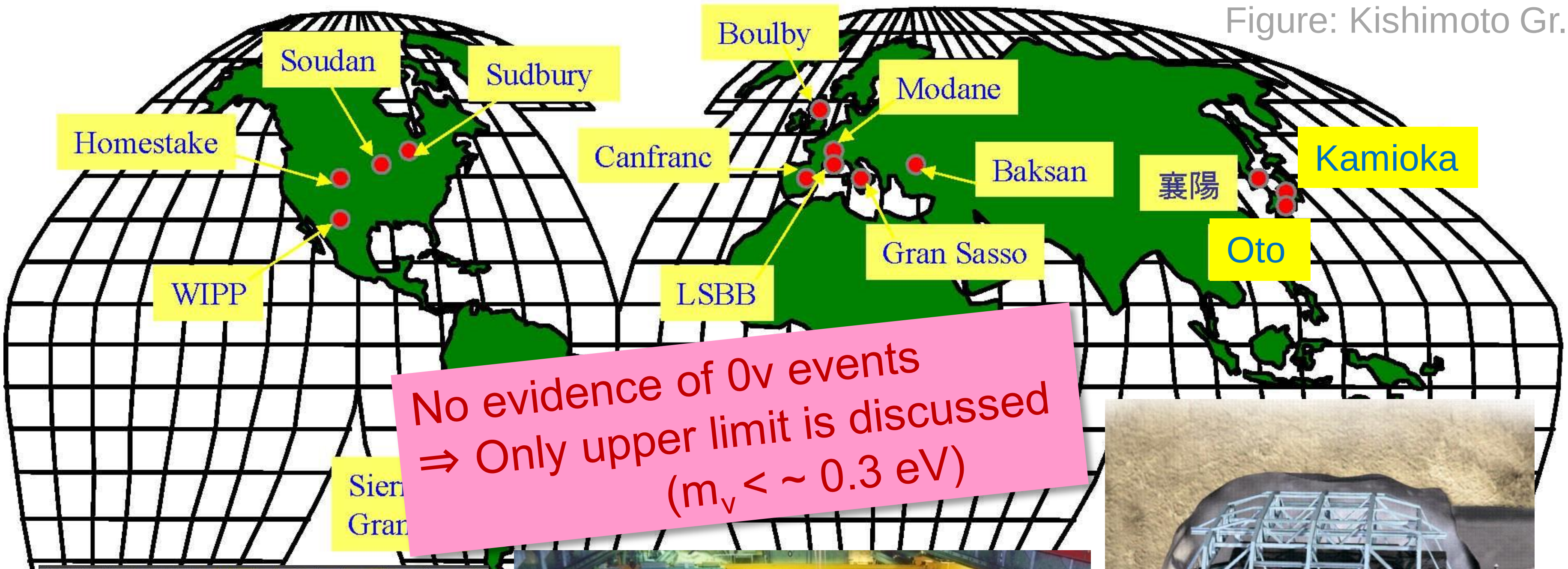


Study of Gamow-Teller transition strengths in the intermediate nucleus ^{116}In of the ^{116}Cd double-β decay via the $^{116}Cd(p,n)$ and $^{116}Sn(n,p)$ reactions at 300 MeV

Masaki Sasano (RIKEN)

0ν labs

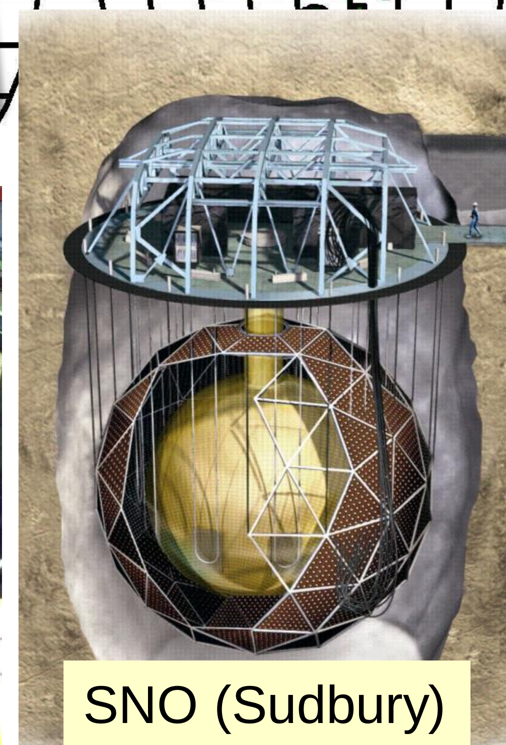
Figure: Kishimoto Gr.



No evidence of 0ν events
⇒ Only upper limit is discussed
($m_\nu <\sim 0.3$ eV)

GERDA (Gran Sasso)

NEMO3 (Modane)



SNO (Sudbury)

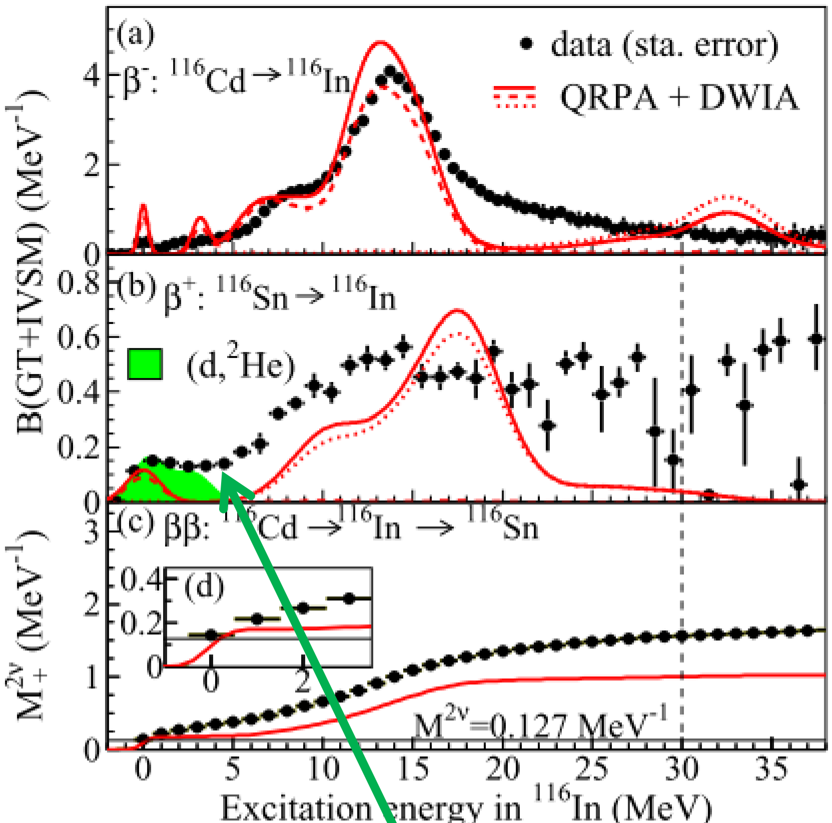
QRPA calculation with a large model space

QRPA prediction (GT + IVSM)
(Rodin et al., Tuebingen Univ.)
Large model space (34 levels)
⇒ Enough for 2hw excitation by Rodin et al.

- quenching factor, 0.843 & g_{pp} = 0.5
  ⇒adjusted for M(2v) and β decays from the 116In g.s.

Transition density
+ DWIA calculation (DW81) (K. Amos, A. Faessler and V. Rodin, Phys. Rev. C **76,** 014604 (2007))
Base: H.O. b=2.23 fm
NN int. : FL325MeV
Global optical potential by Cooper & Hama
⇒ Cross sections
⇒ Strengths
⇒ Smearing with escape width & exp. res.
(Rodin & Urin, Phys. of Atomic Nuclei, 66 (2009), 2128)

Comparison



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Interf. : ~15%

Strengths around 10 MeV are underestimated.
Extra g.s. correlation?

Summary

- Study of beta-type transitions in DBD nuclei can guide / constrain the structure theories used in the prediction of NME.
- We measured 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

  at 300 MeV.
- MD analysis $\rightarrow$ B(GT$^{+/-}$) distribution (E_x < 30 MeV)

- ^{48}Ca $\rightarrow$ ^{48}Sc $\rightarrow$ ^{48}Ti [PRL103(2009)012503]
  - $\Sigma B(GT^-) = 15.3 \pm 2.2$

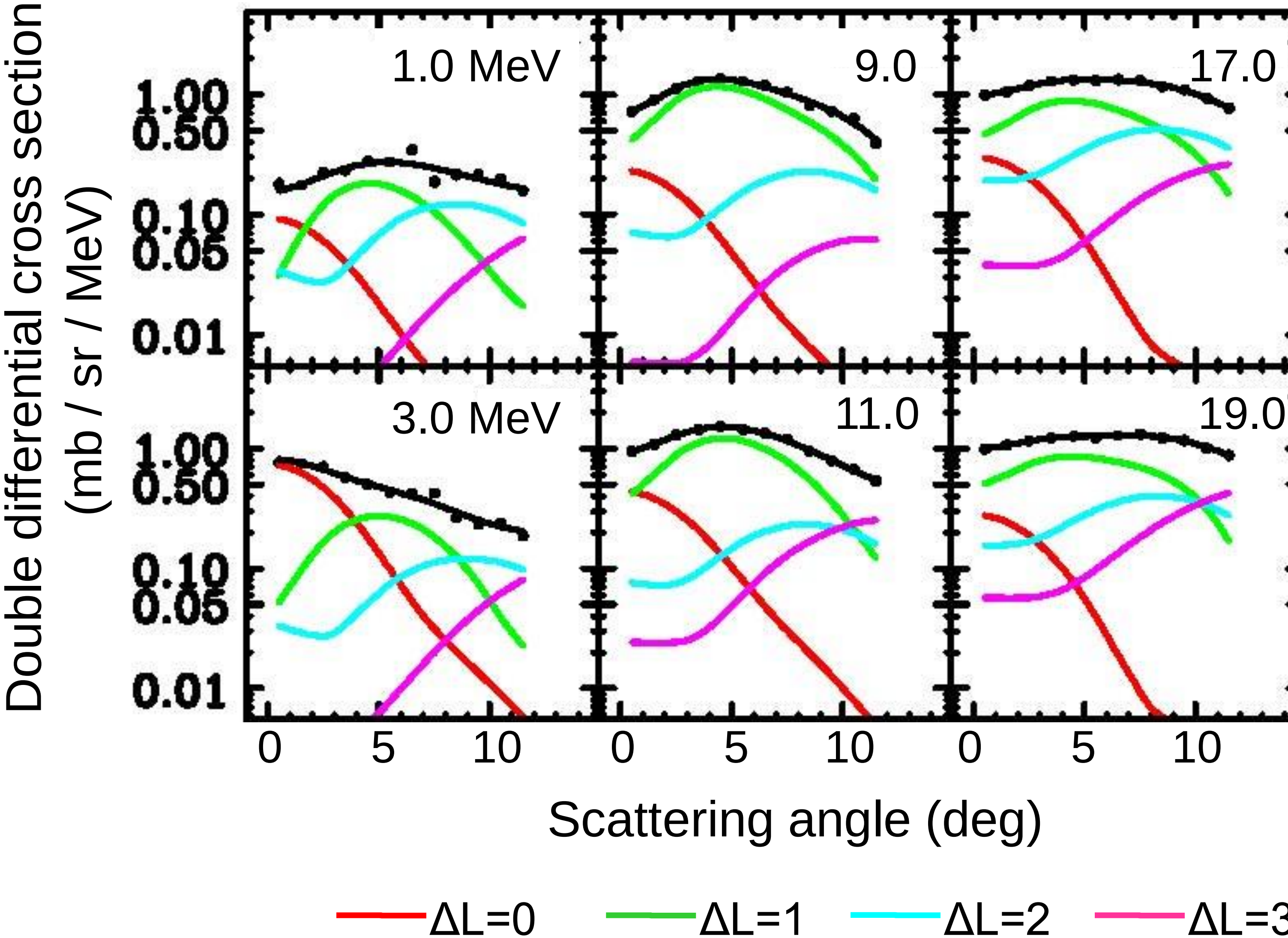
    $\Sigma B(GT^+) = 2.8 \pm 0.3$
  - shell model predictions :

    B(GT$^-$): good agreement up to GTGR (E_x < 15 MeV).

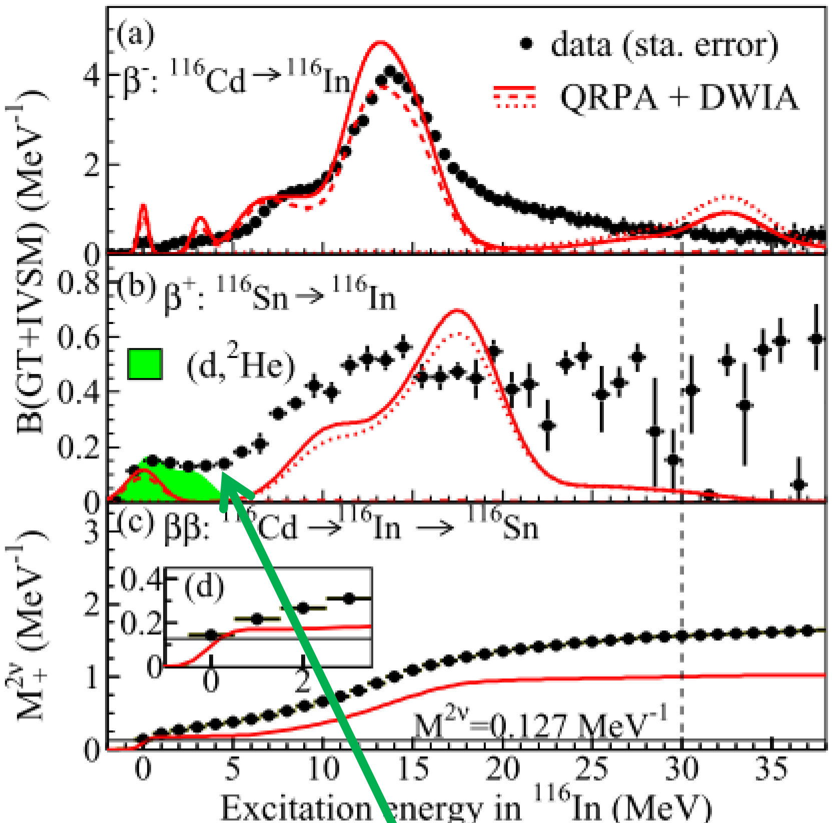
    B(GT$^+$): reasonable for E_x < 8 MeV,

    underestimation for E_x > 8 MeV
- Watch out! Current predictions of 0ν-NME might be a way off!

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



^{116}Cd



β- : strengths in the low energy region to be pushed up
β+: extra strength of about 2 and/or strengths around 22 MeV to be pushed down

	Theo.			Exp.
	GT	IVSM	GT+IVSM	GT+IVSM
β+	0.4	5.4	6.8	11±1
β-	42	4	52	45±8

Interf. : ~15%

Strengths around 10 MeV are underestimated.
Extra g.s. correlation?