Basic Properties of GT transitions & β^- decay "Expected" in r-Process Nuclei

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Understanding of r-process on the basis of Nuclear Physics
Kyoto, Yukawa, May. 22-24, 2019

Neptune driving Waves
波を操る海神ネプチューン

Neptune and the waves, or "steeds," he rides.

Walter Crane, 1892

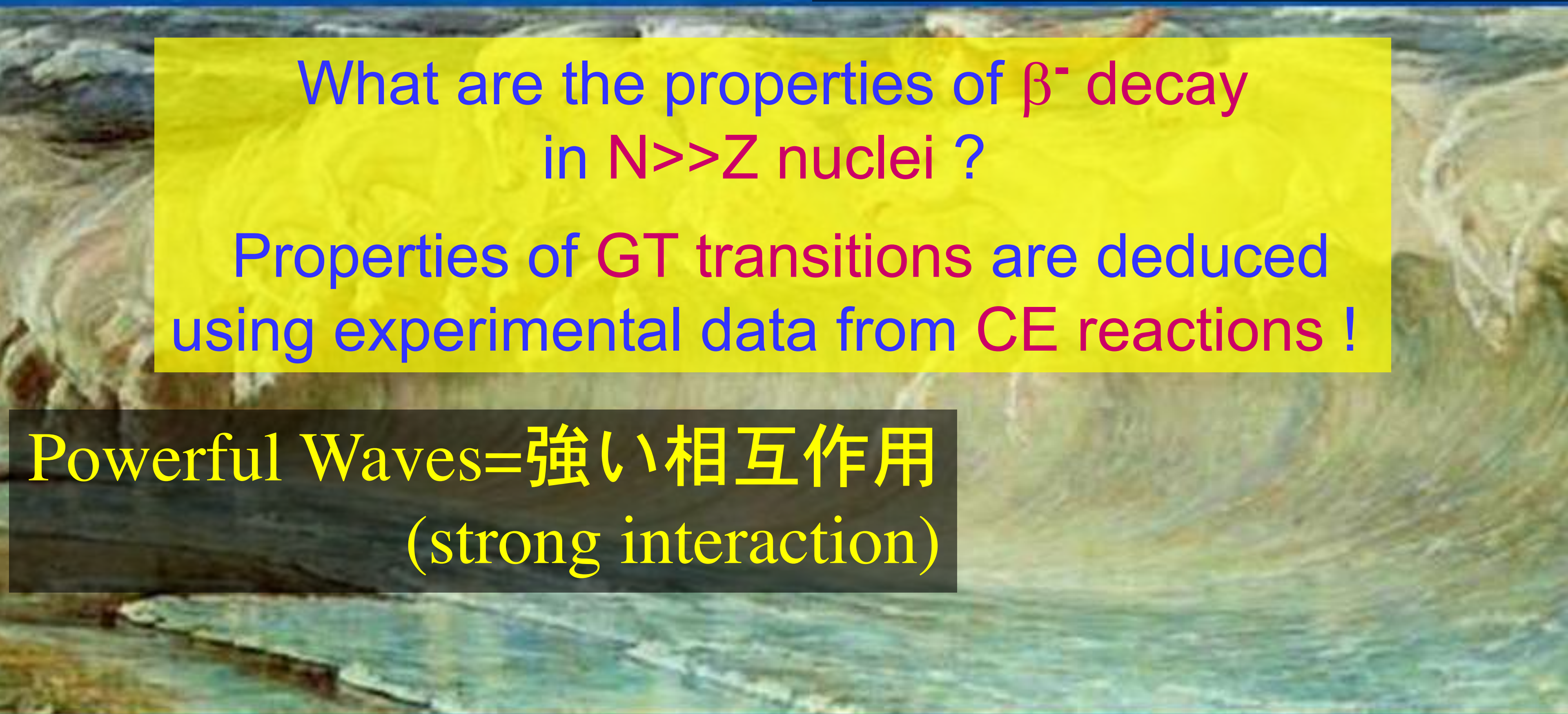
Neptune driving Waves
波を操る海神ネプチューン

Neptune=弱い相互作用
(weak interaction)

What are the properties of β^- decay in N>>Z nuclei ?

Properties of GT transitions are deduced using experimental data from CE reactions !

Powerful Waves=強い相互作用
(strong interaction)



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_ Walter Crane, 1892

Neptune driving Waves
波を操る海神ネプチューン

Neptune=弱い相互作用
(weak interaction)

In β decay

Gamow-Teller (caused by $\sigma\tau$ operator)

Fermi (caused by τ operator)

are called "allowed transitions,"

They are the dominant transition processes !

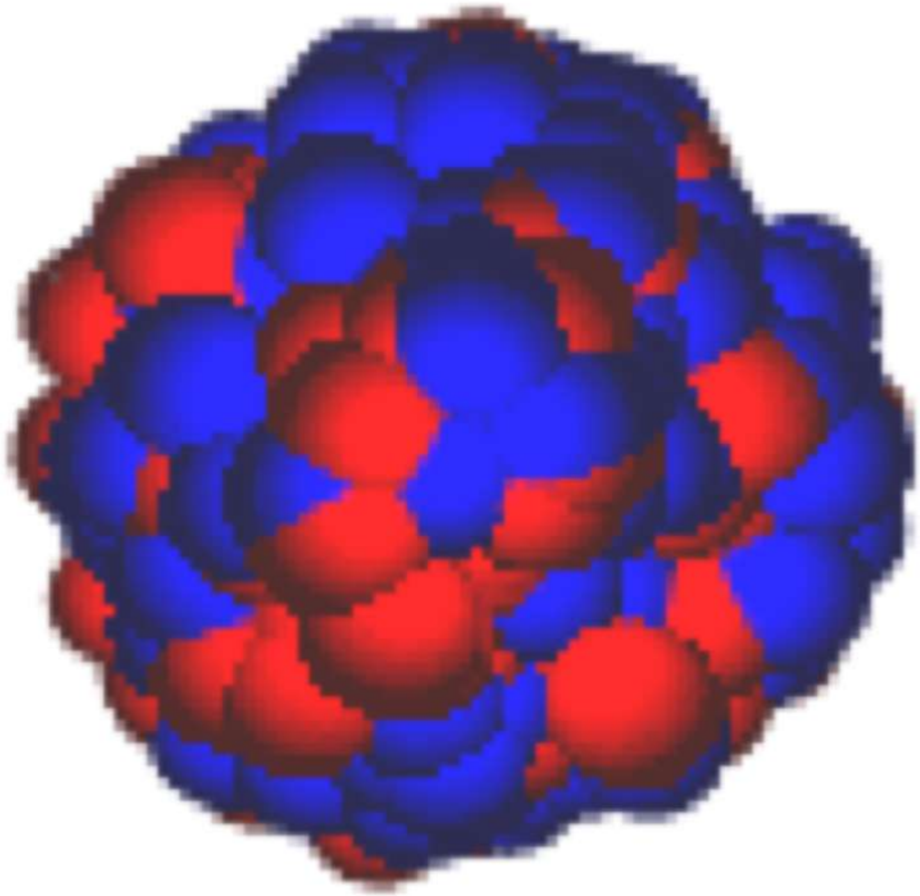
Powerful Waves=強い相互作用
(strong interaction)

Neptune and the waves, or "steeds," he rides.

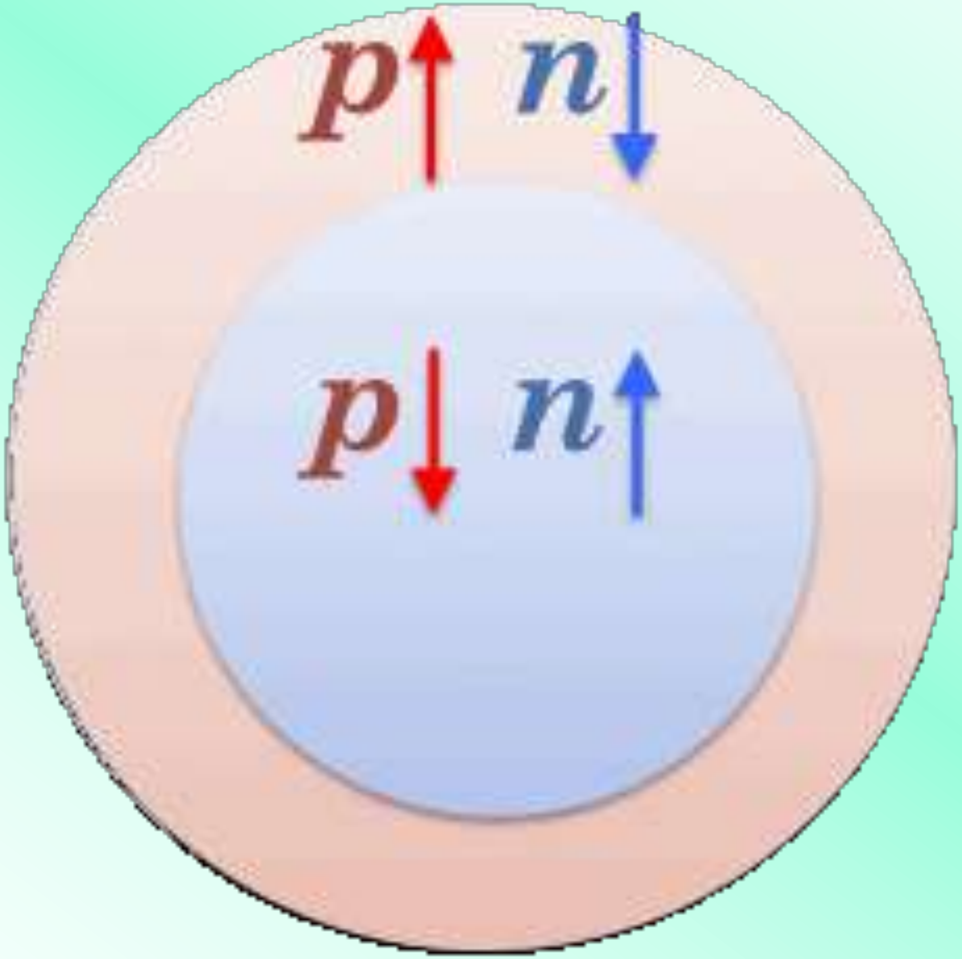
Walter Crane, 1892

IV Giant Monopole Resonance (IVGMR)

by P. Adrich



IV Spin Monopole Mode



WEB, Dpt. Phys. Tokyo U

**Basic common understanding of β-decay and Charge-Exchange reaction in the study of GT transitions

β decays :

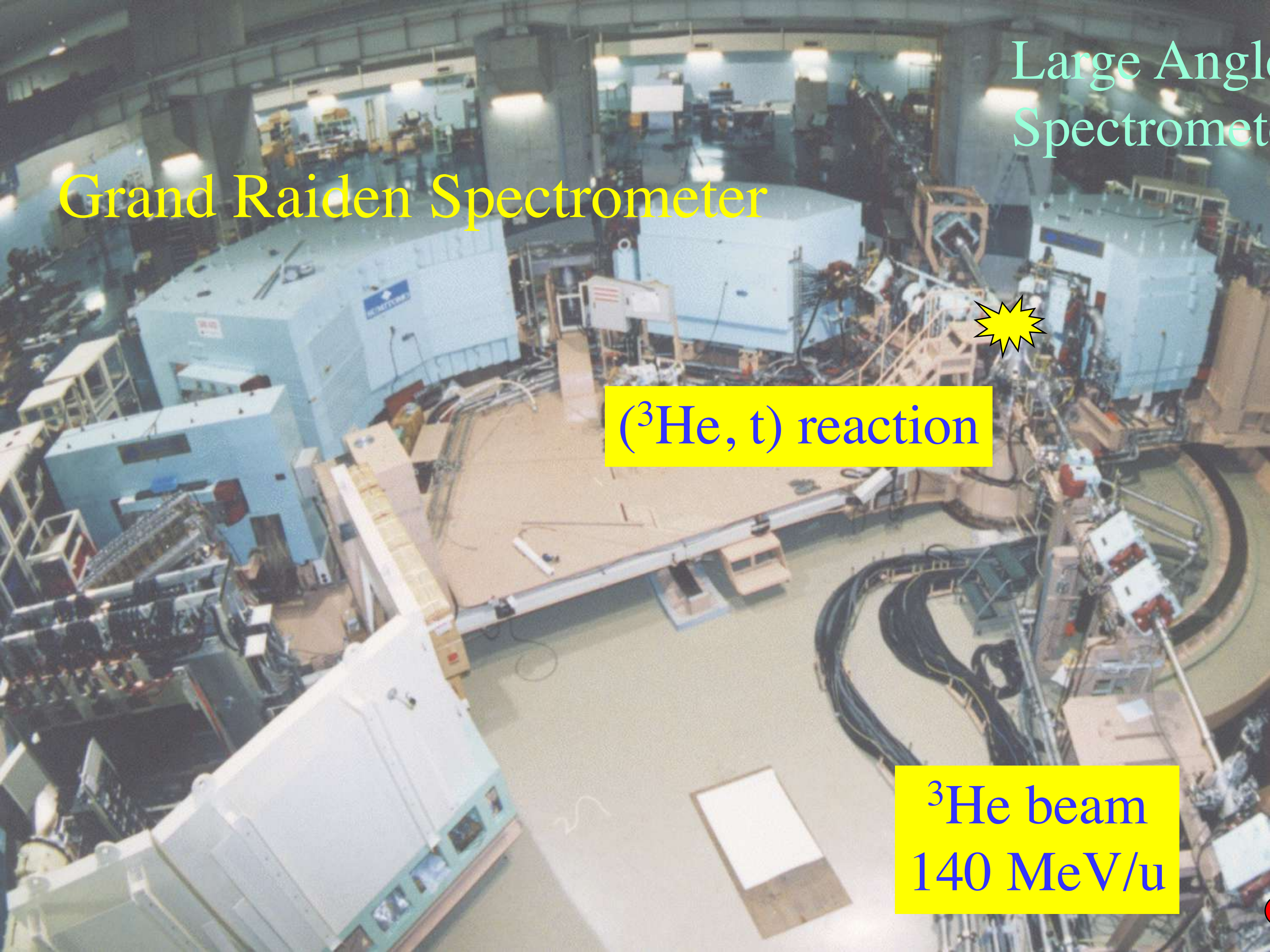
Absolute *B*(GT) values,

but usually the study is limited to low-lying states

(p, n) and (^{3}He,t) reaction at 0^o :

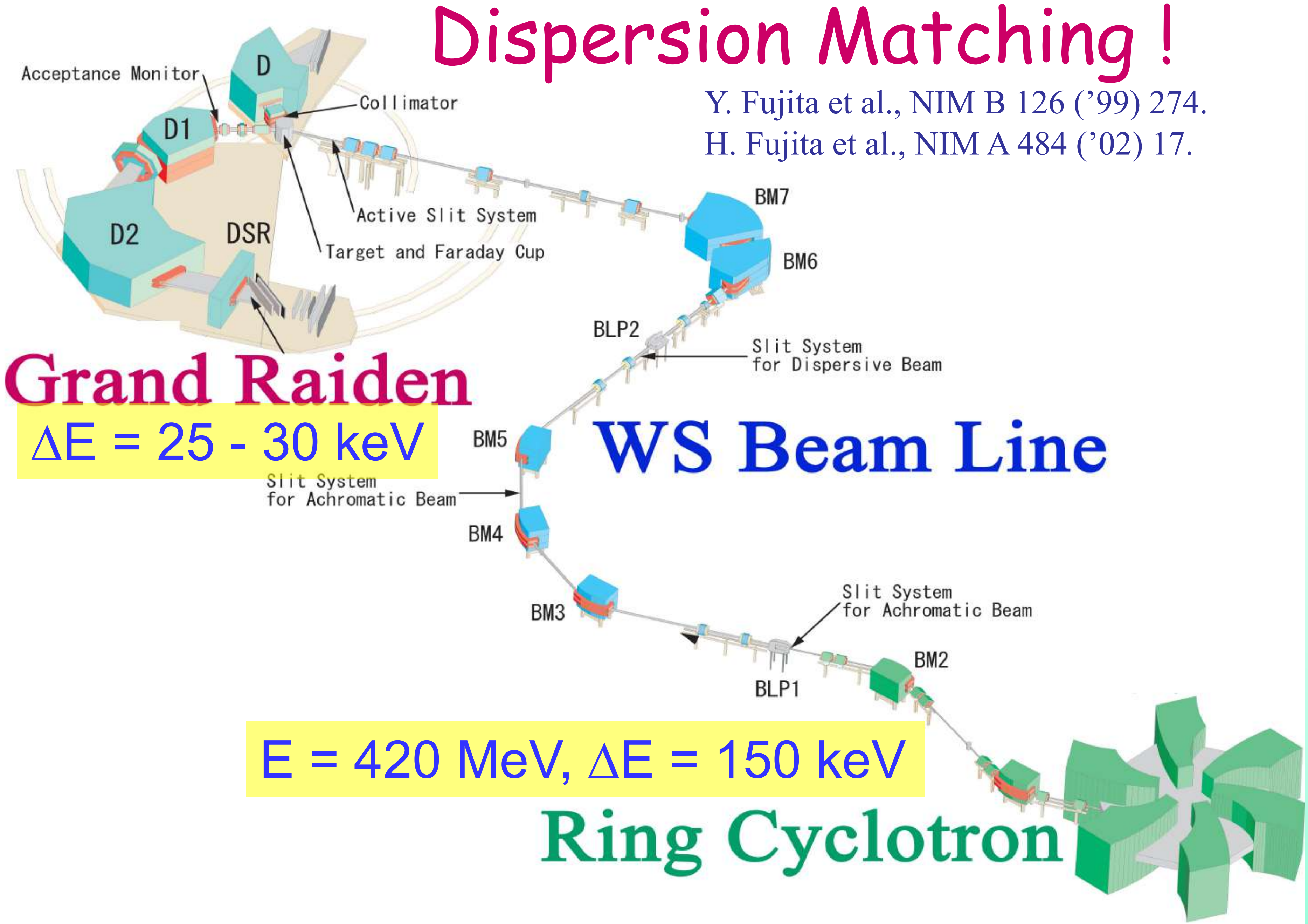
Relative *B*(GT) values, but Highly Excited States

** Both are important for the study of GT transitions!

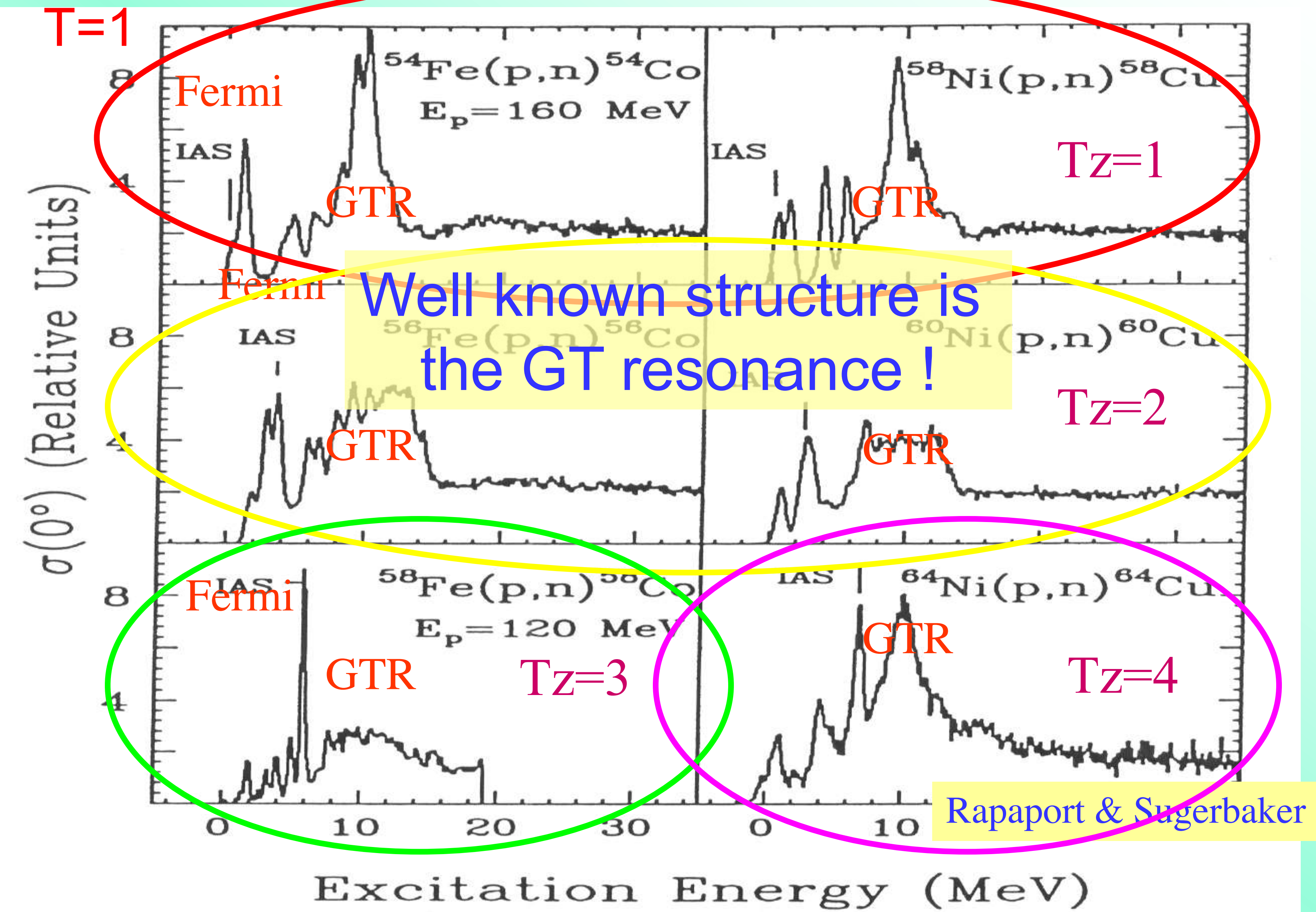

Large Angl
Spectromet
Grand Raiden Spectrometer
(3He, t) reaction
3He beam
140 MeV/u

Dispersion Matching !

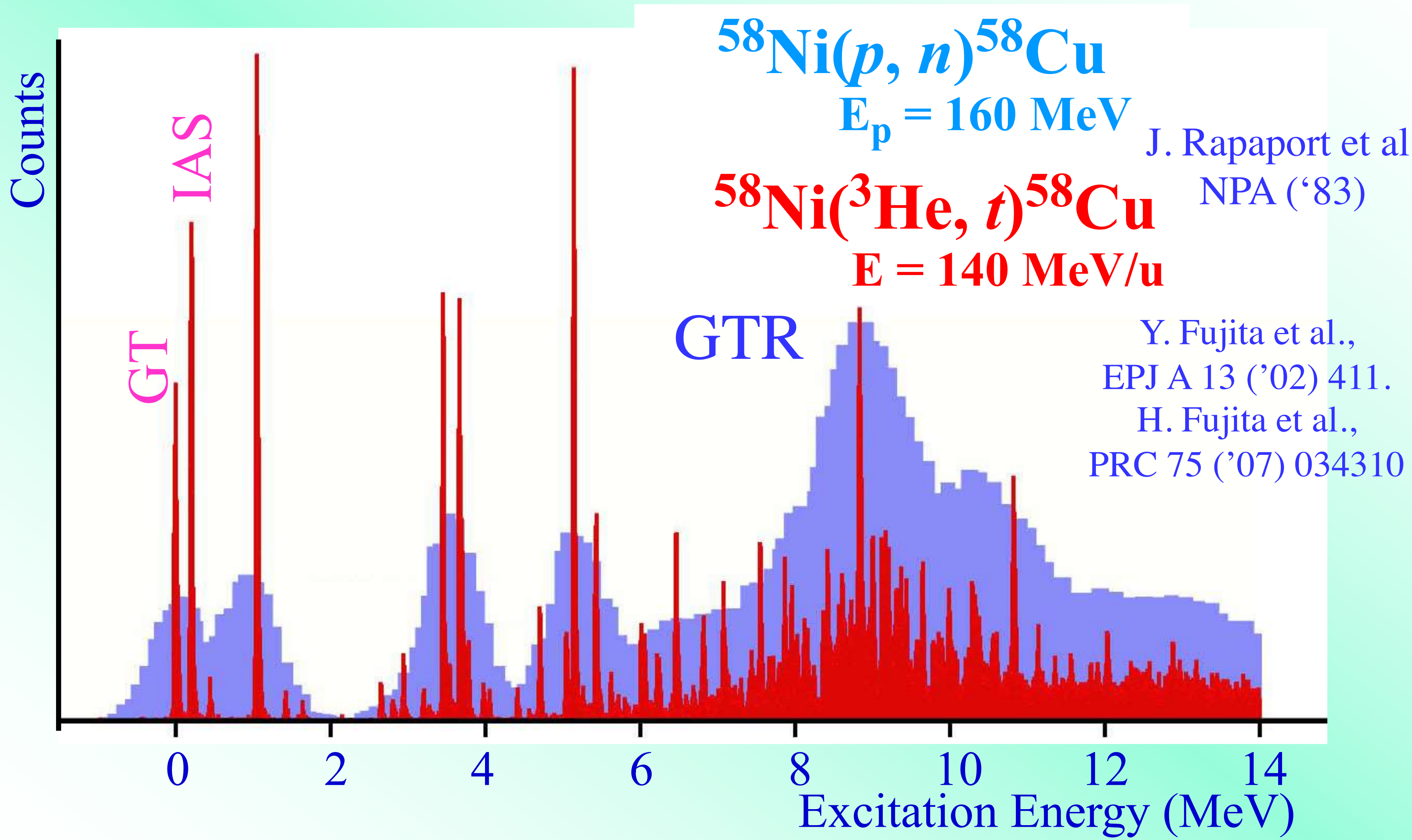
Y. Fujita et al., NIM B 126 ('99) 274.
H. Fujita et al., NIM A 484 ('02) 17.



(*p*, *n*) spectra for Fe and Ni Isotopes

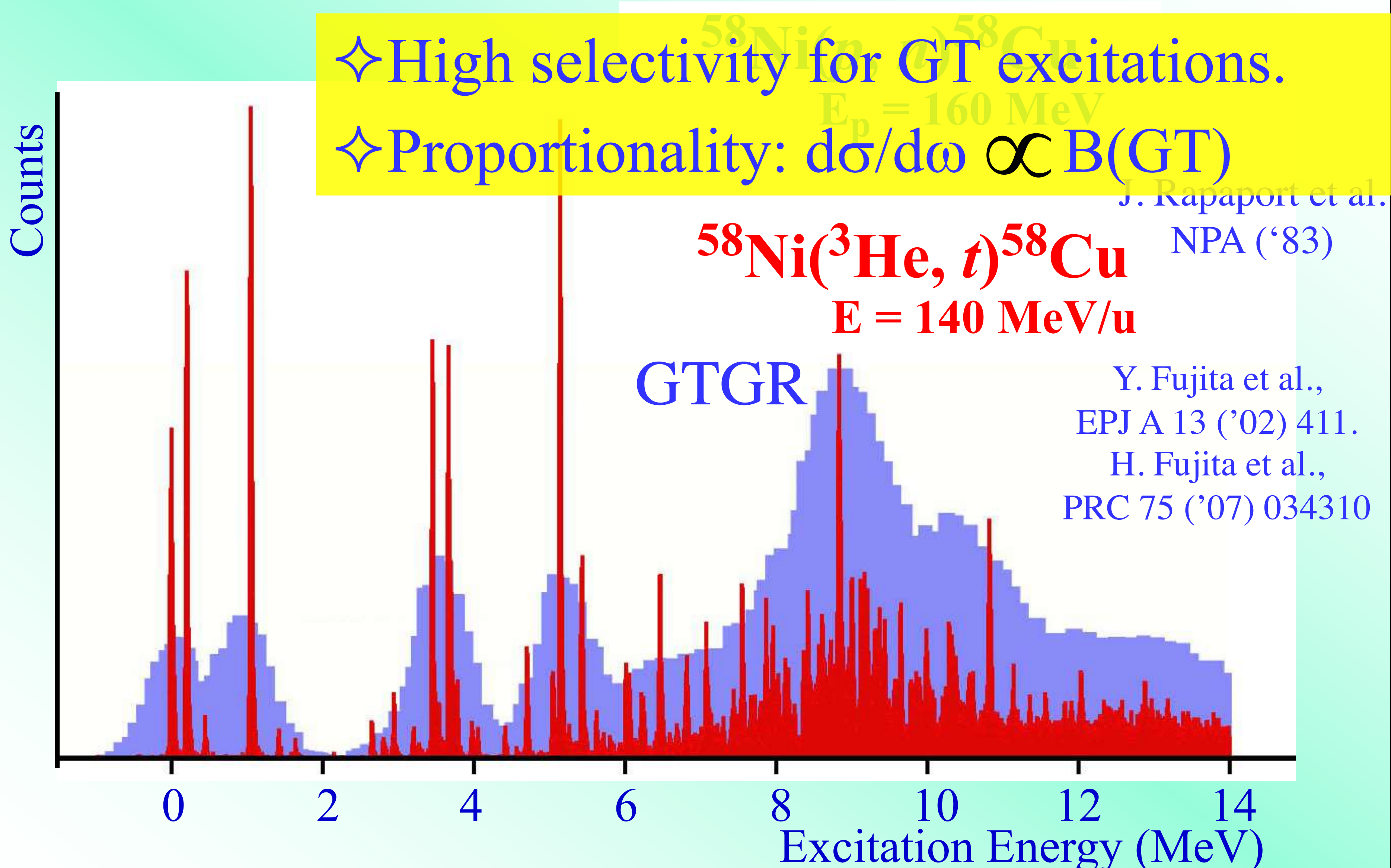


Comparison of (p, n) and (^{3}He,t) 0° spectra



Comparison of (p, n) and (^{3}He,t) 0° spectra

- ✧High selectivity for GT excitations.
- ✧Proportionality: $d\sigma/d\omega \propto B(GT)$



Gamow-Teller transition s

Mediated by $\sigma\tau$ operator (axial isovector-operator)

$\Delta S = -1, 0, +1$ and $\Delta T = -1, 0, +1$

($\Delta L = 0$, no change in radial w.f.)

→ no change in spatial w.f.

Accordingly, transitions among $j_>$ and $j_<$ configurations

$j_> \rightarrow j_>$, $j_< \rightarrow j_<$, $j_> \leftrightarrow j_<$

example $d_{5/2} \rightarrow d_{5/2}$, $d_{3/2} \rightarrow d_{3/2}$, $d_{5/2} \leftrightarrow d_{3/2}$

Note that Spin and Isospin are unique quantum numbers in atomic nuclei !

→ GT transitions are sensitive to Nuclear Structure !

→ GT transitions in each nucleus are UNIQUE !

β decay & Nuclear CE reaction

*β-decay GT tra. rate = $\frac{1}{t_{1/2}} = f\frac{\lambda^2}{K} B(\mathrm{GT})$

B(GT) : reduced GT transition strength

$\propto$ (matrix element)^2 = $|\langle f|\sigma\tau|i\rangle|^2$

*Nuclear (CE) reaction rate (cross-section)

= reaction mechanism

⊗ operator

⊗ structure

=(matrix element)^2

*At intermediate energies ($100 < E_{in} < 500$ MeV)

➡ $d\sigma/d\omega(q=0)$: proportional to B(GT)

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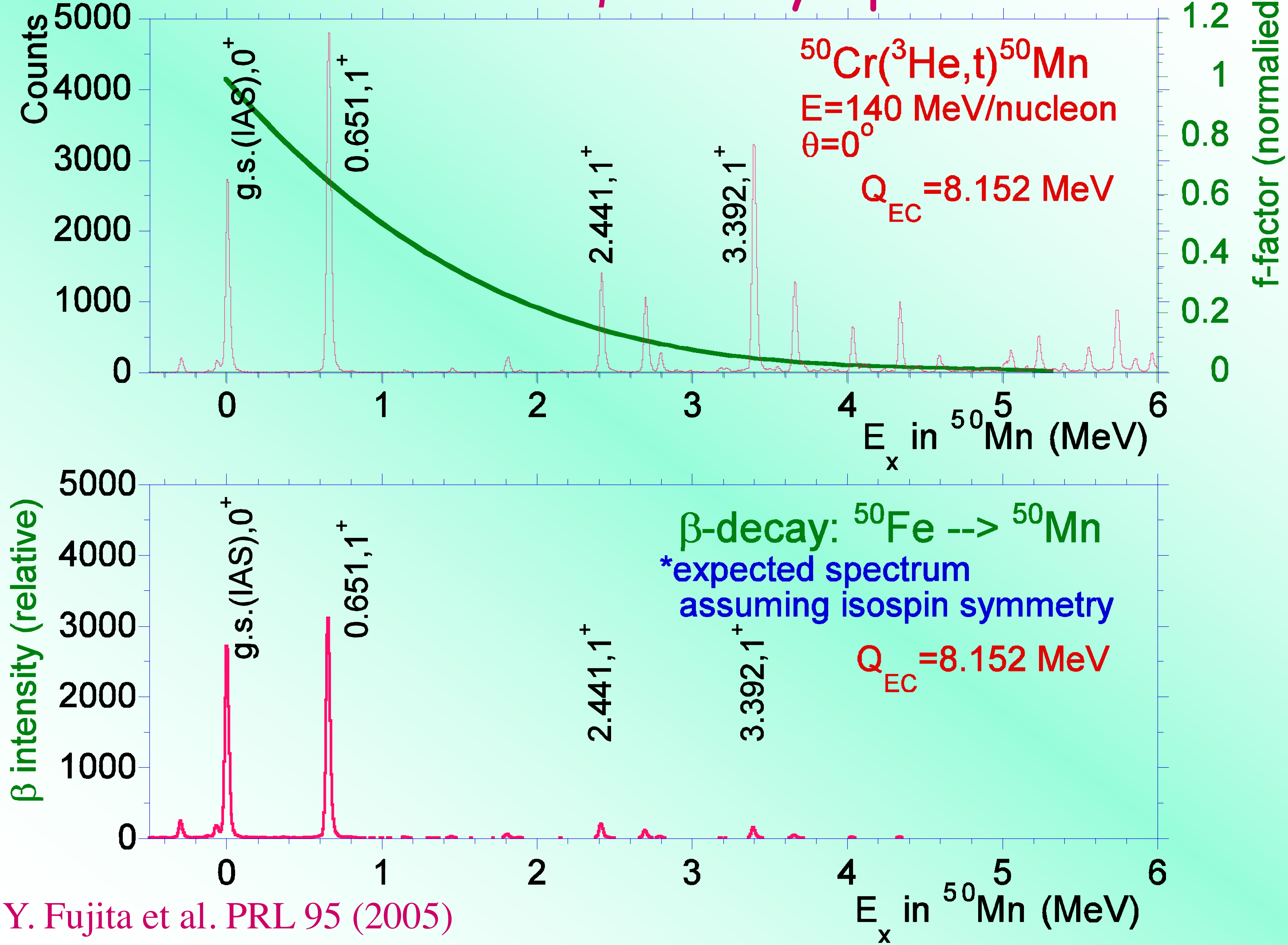
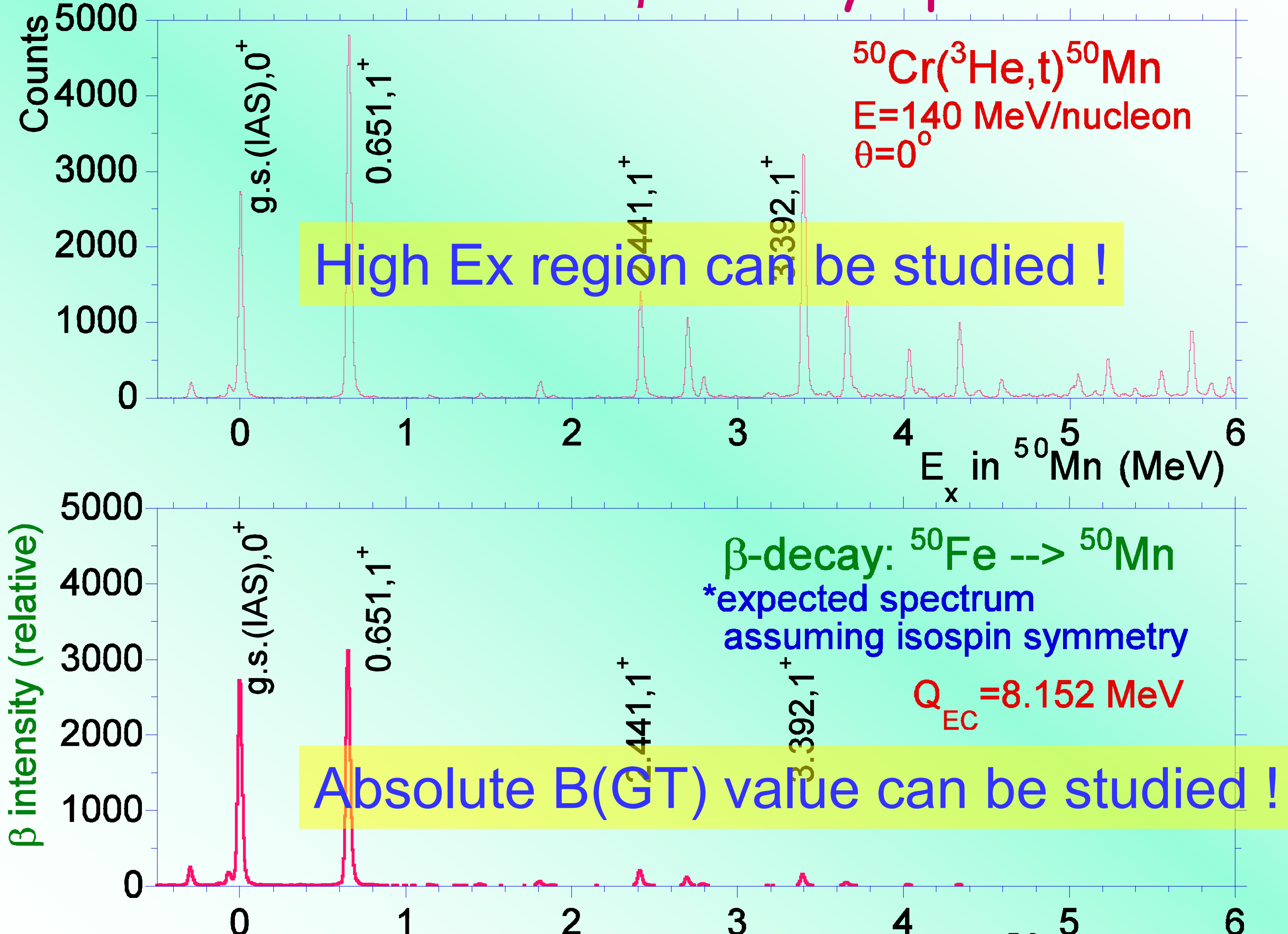
Simulation of β-decay spectrum



Y. Fujita et al. PRL 95 (2005)

Simulation of β-decay spectrum

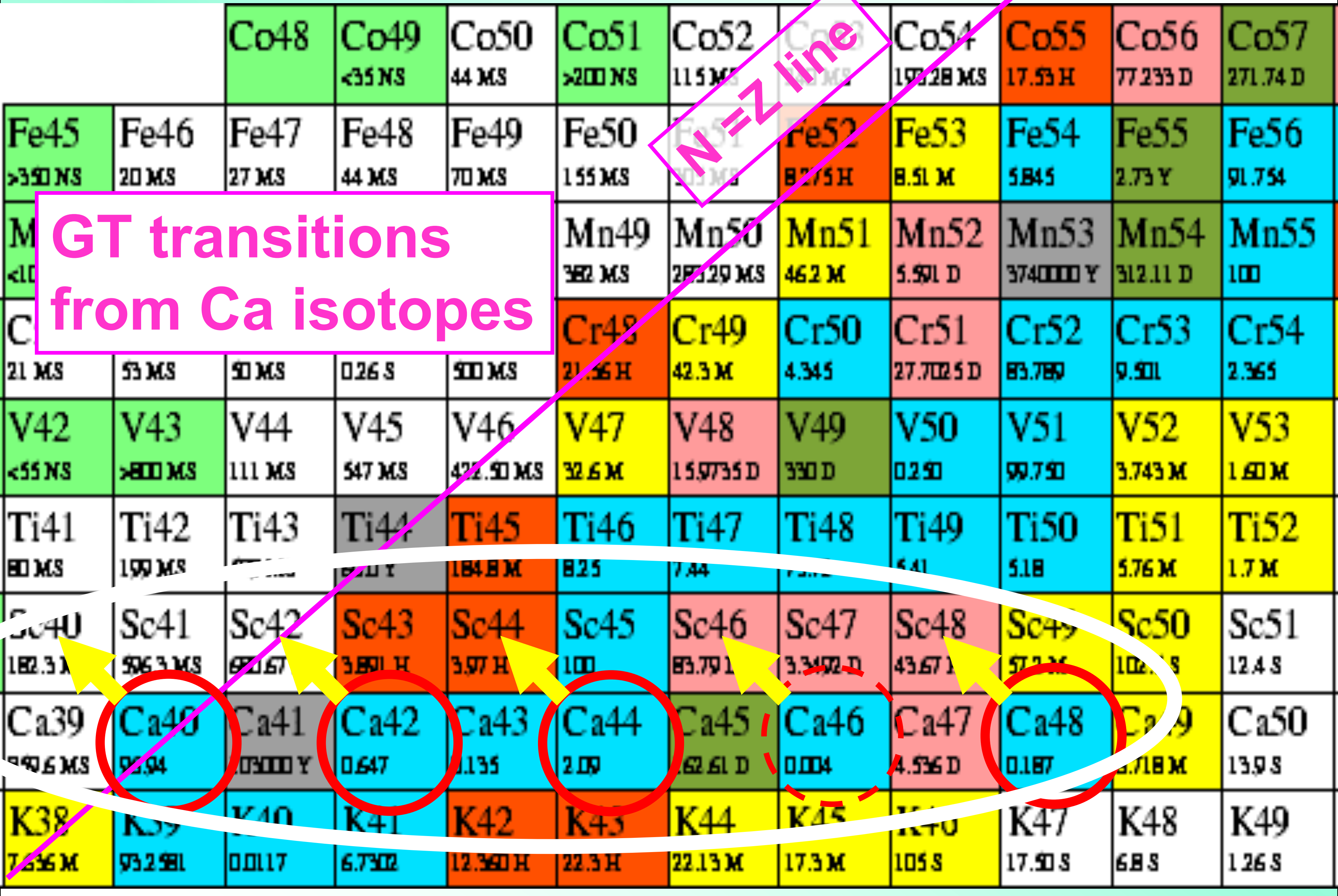


Y.F, B.R, W.G, PPNP, 66 (2011) 549

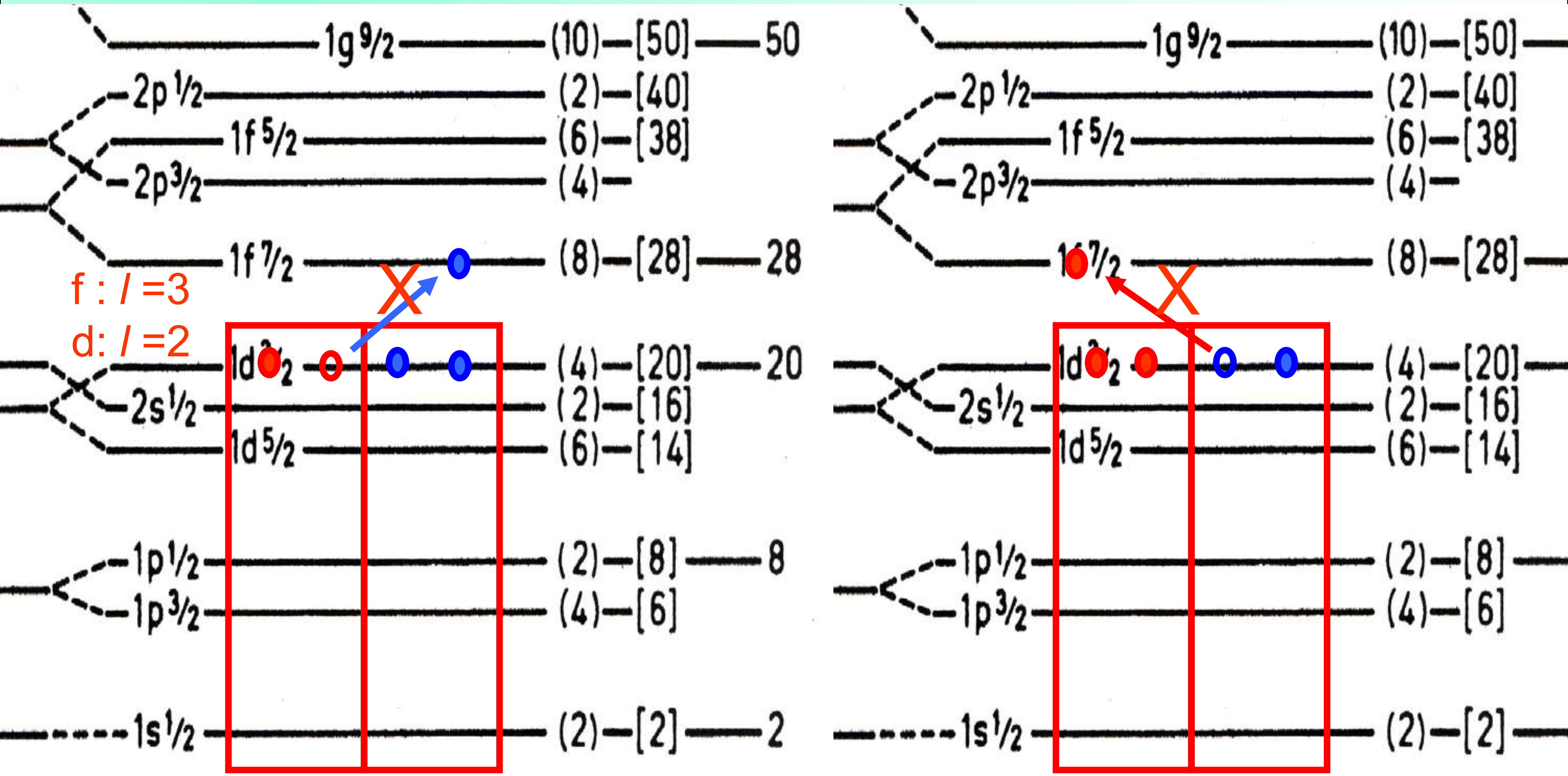
**GT transitions in each nucleus are UNIQUE !

- Ca isotopes -

Nuclear Chart *f*-shell Nuclei



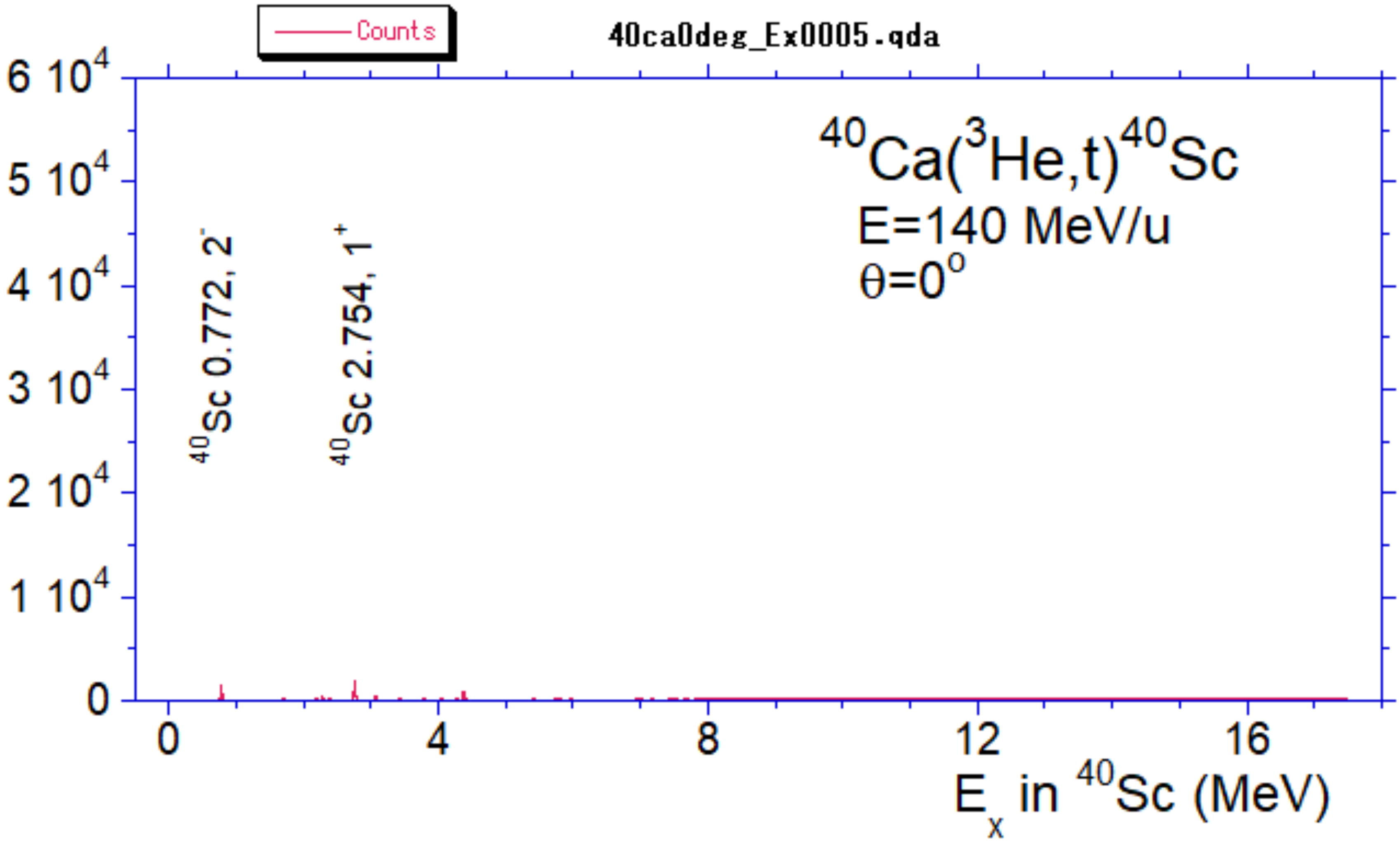
1p-1h Excitations in
^{40}Ca: CE+ Reaction ^{40}Ca : CE- Reaction



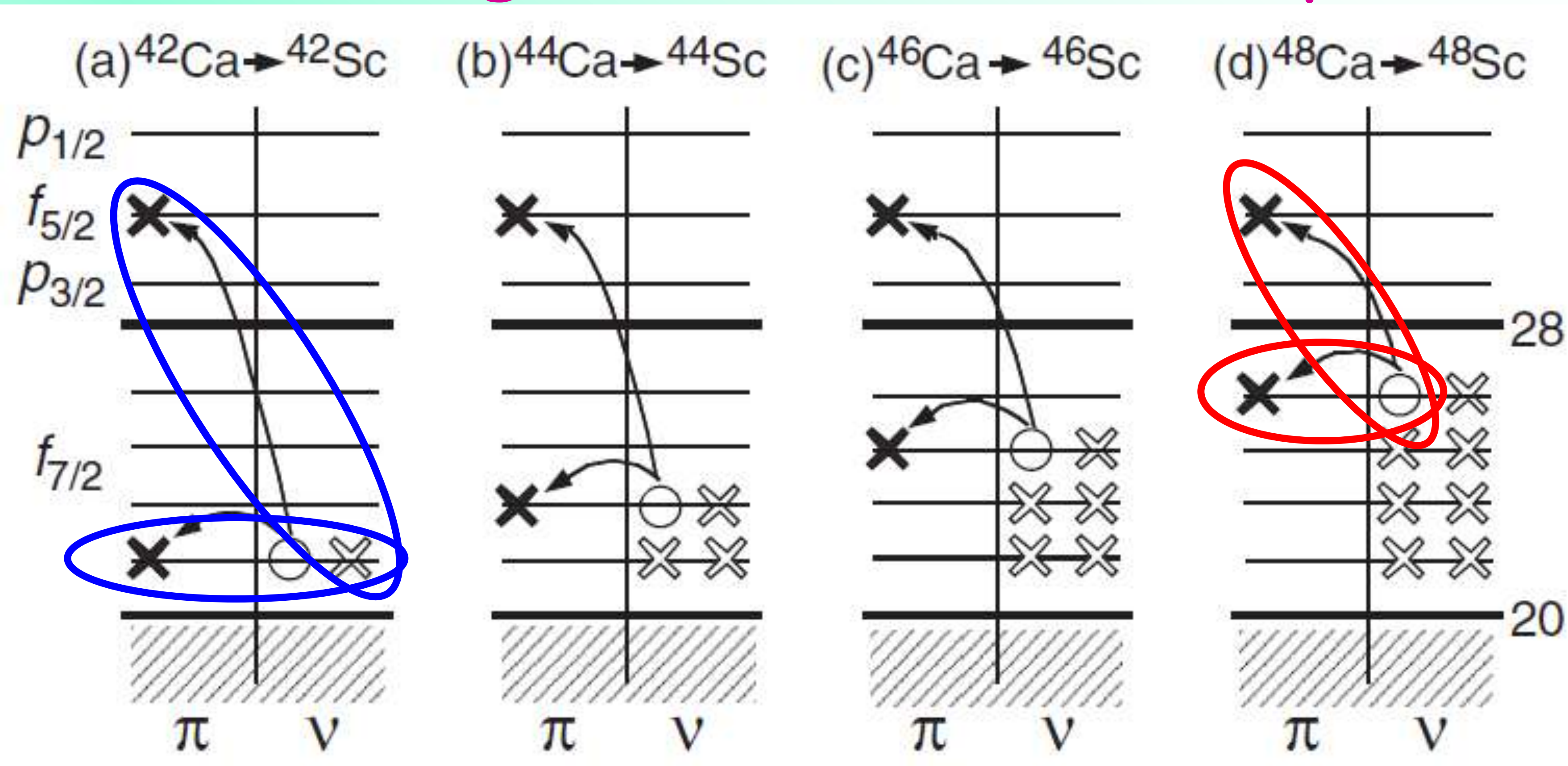
from ^{4}He, ^{16}O, ^{40}Ca : no GT transition is allowed !

(no GT transition from *LS*-closed Doubly Magic Nuclei)

$^{40}Ca(^{3}He,t)^{40}Sc$



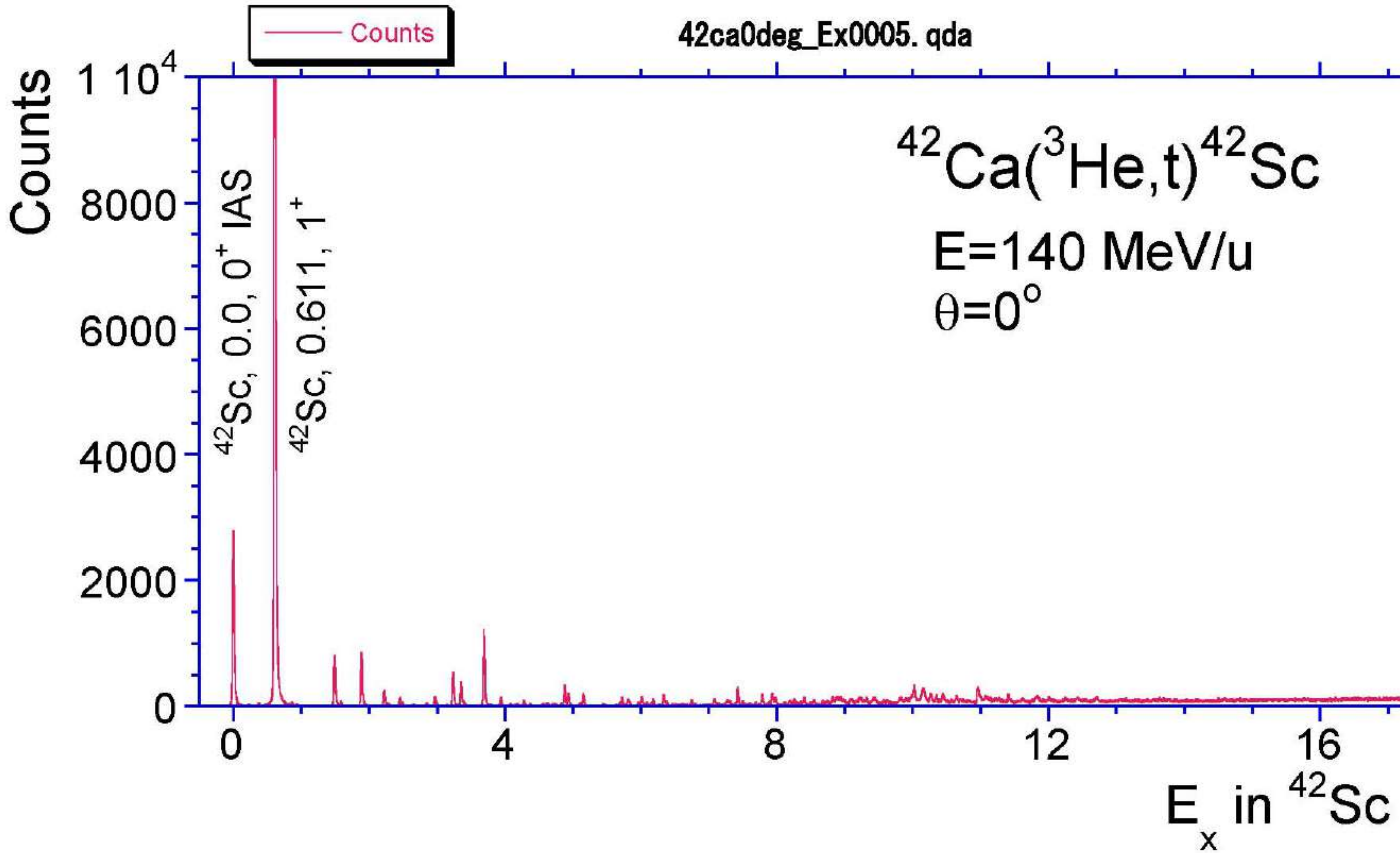
GT Configurations in Sc isotopes



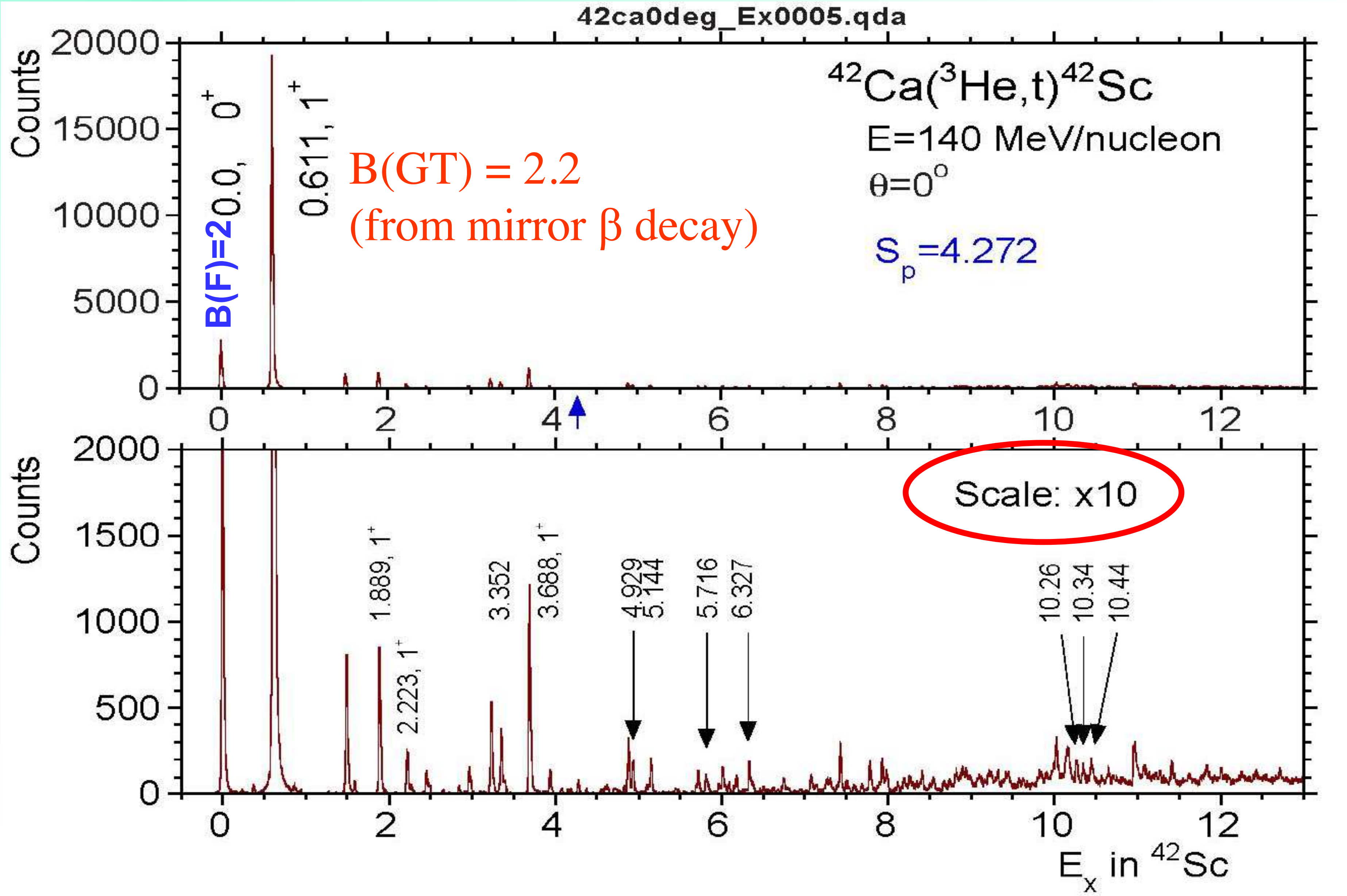
particle-particle nature → particle-hole nature

particle-particle int. (attractive) → particle-hole int. (repulsive)

$^{42}Ca(^{3}He,t)^{42}Sc$



$^{42}Ca(^3He,t)^{42}Sc$ in 2 scales



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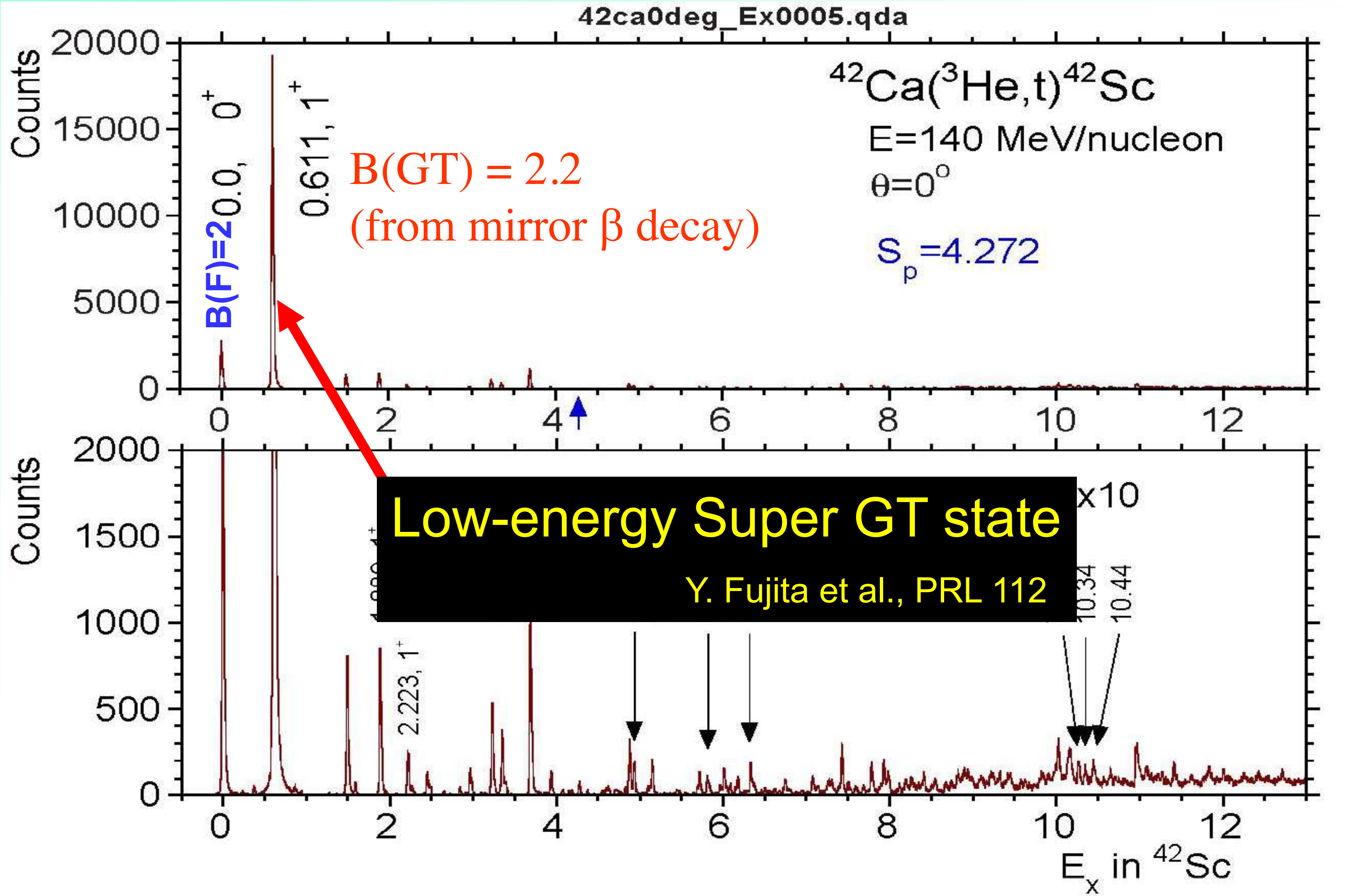
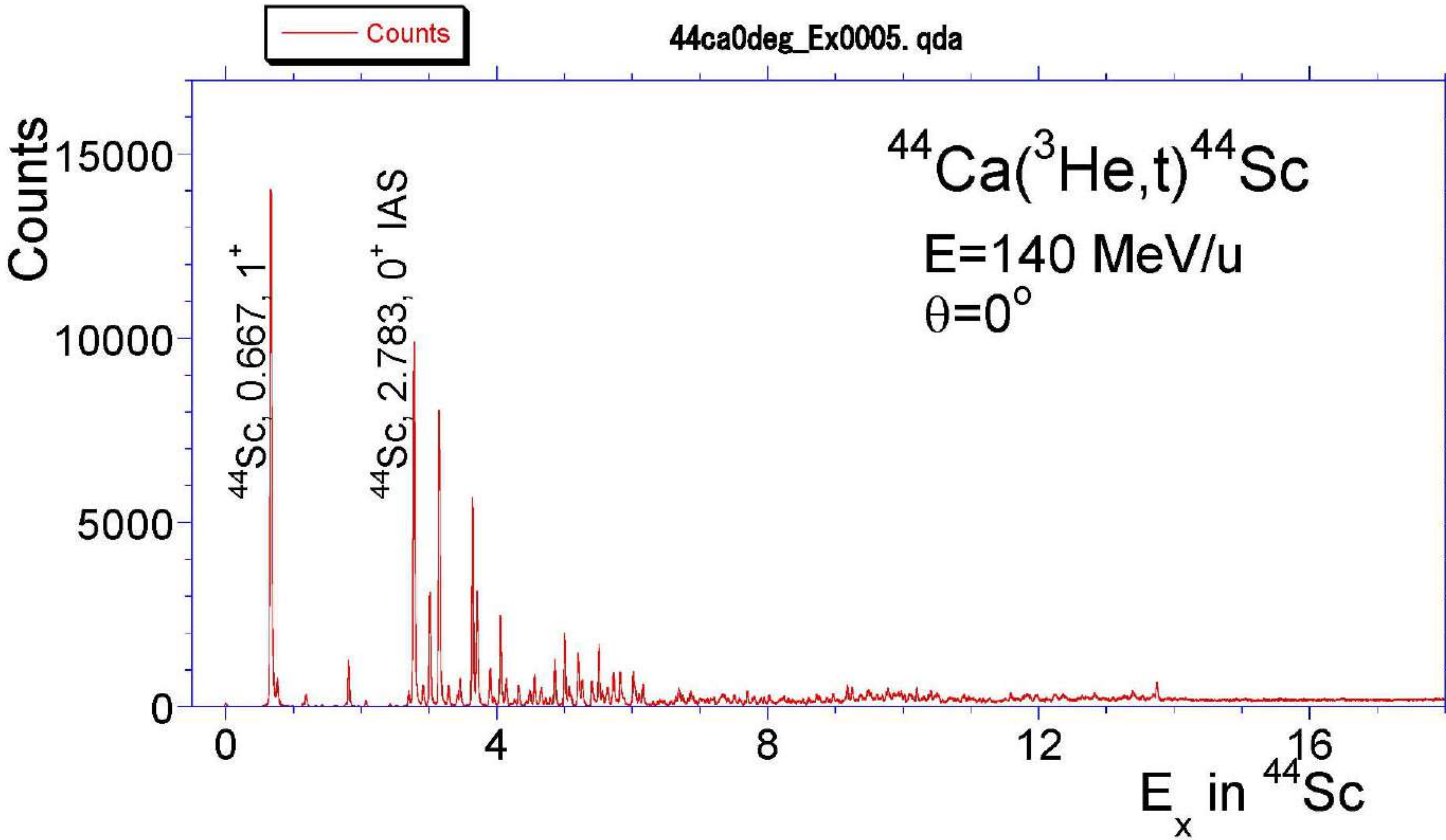
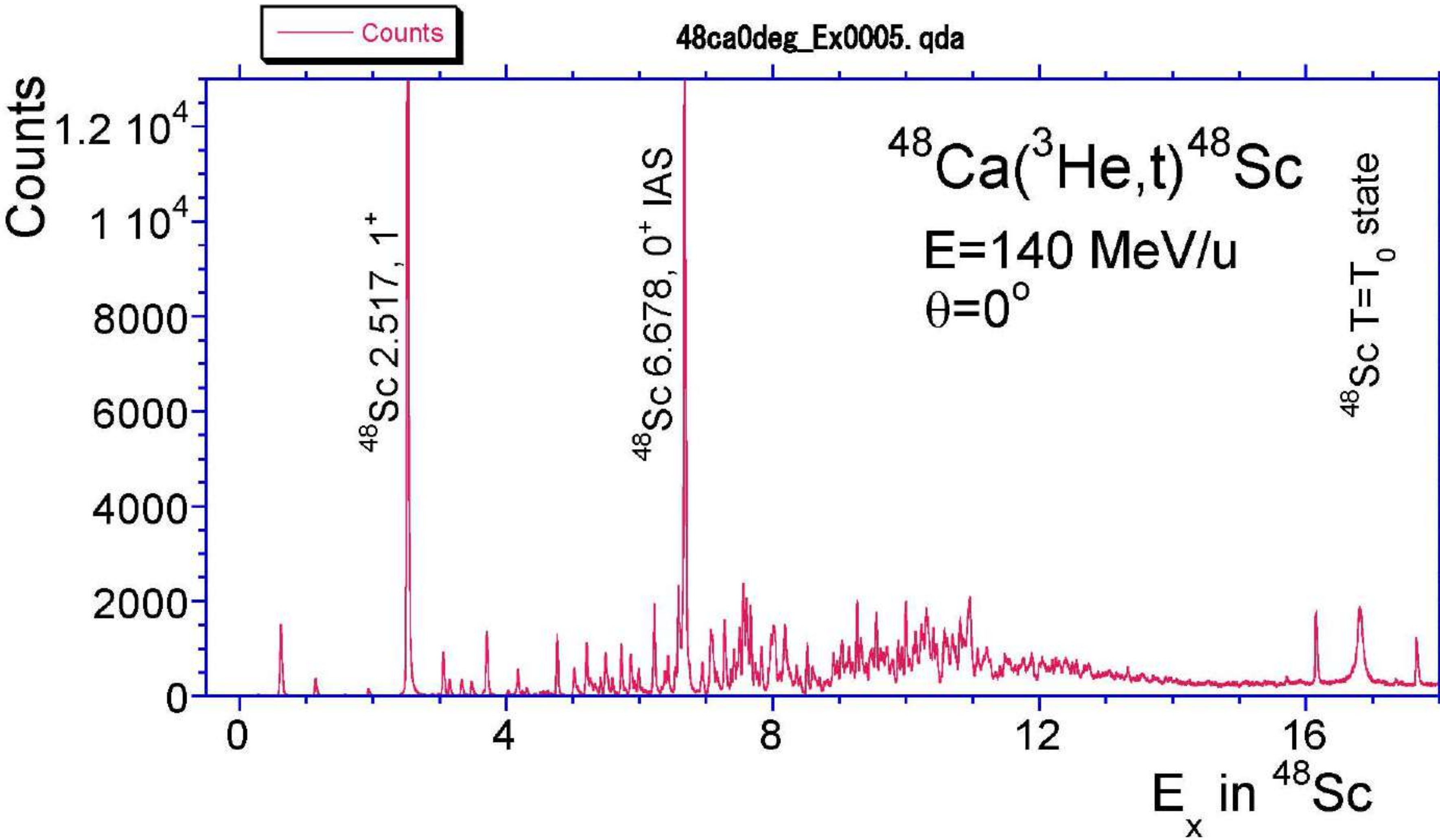


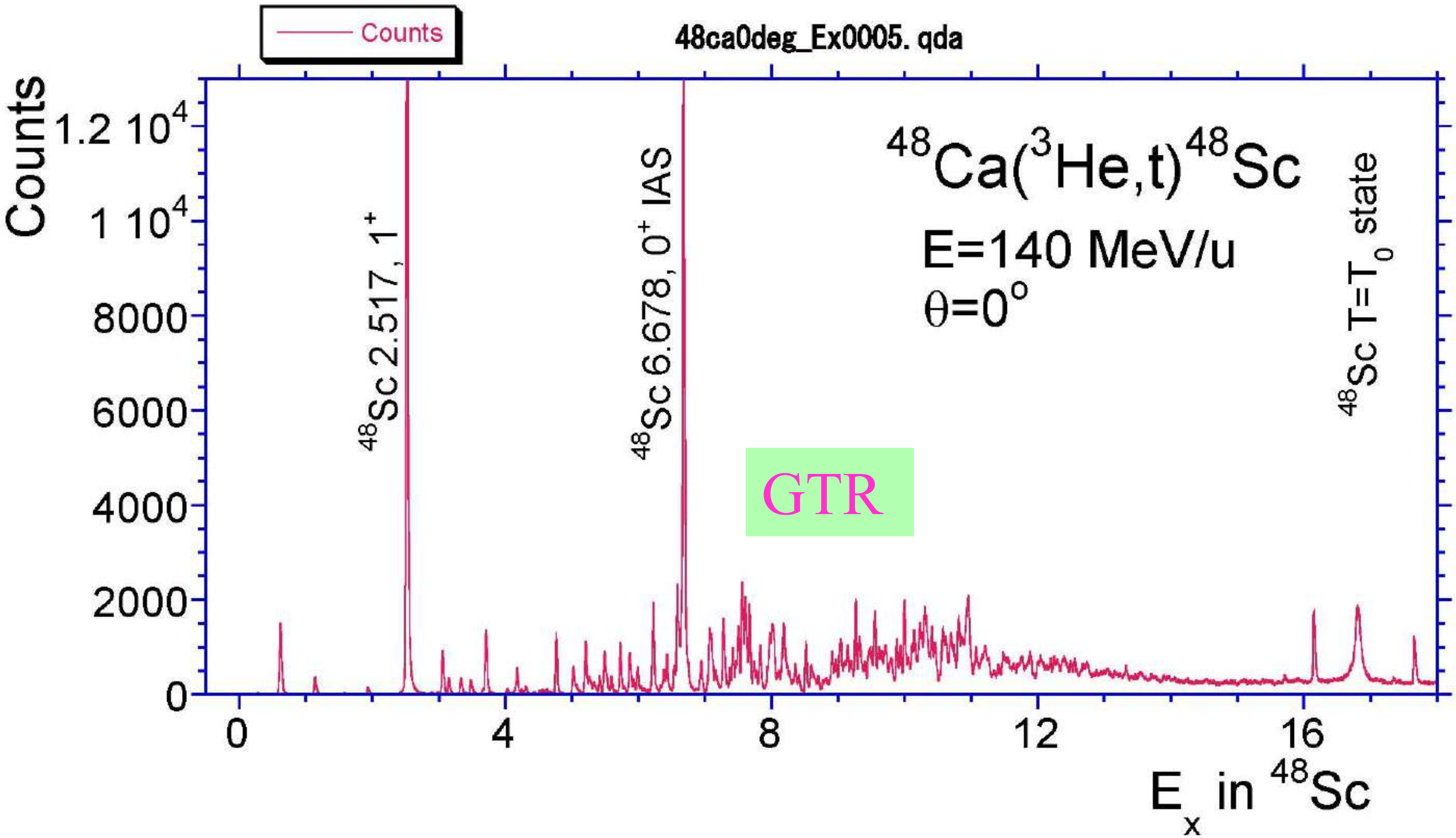
$^{44}Ca(^{3}He,t)^{44}Sc$



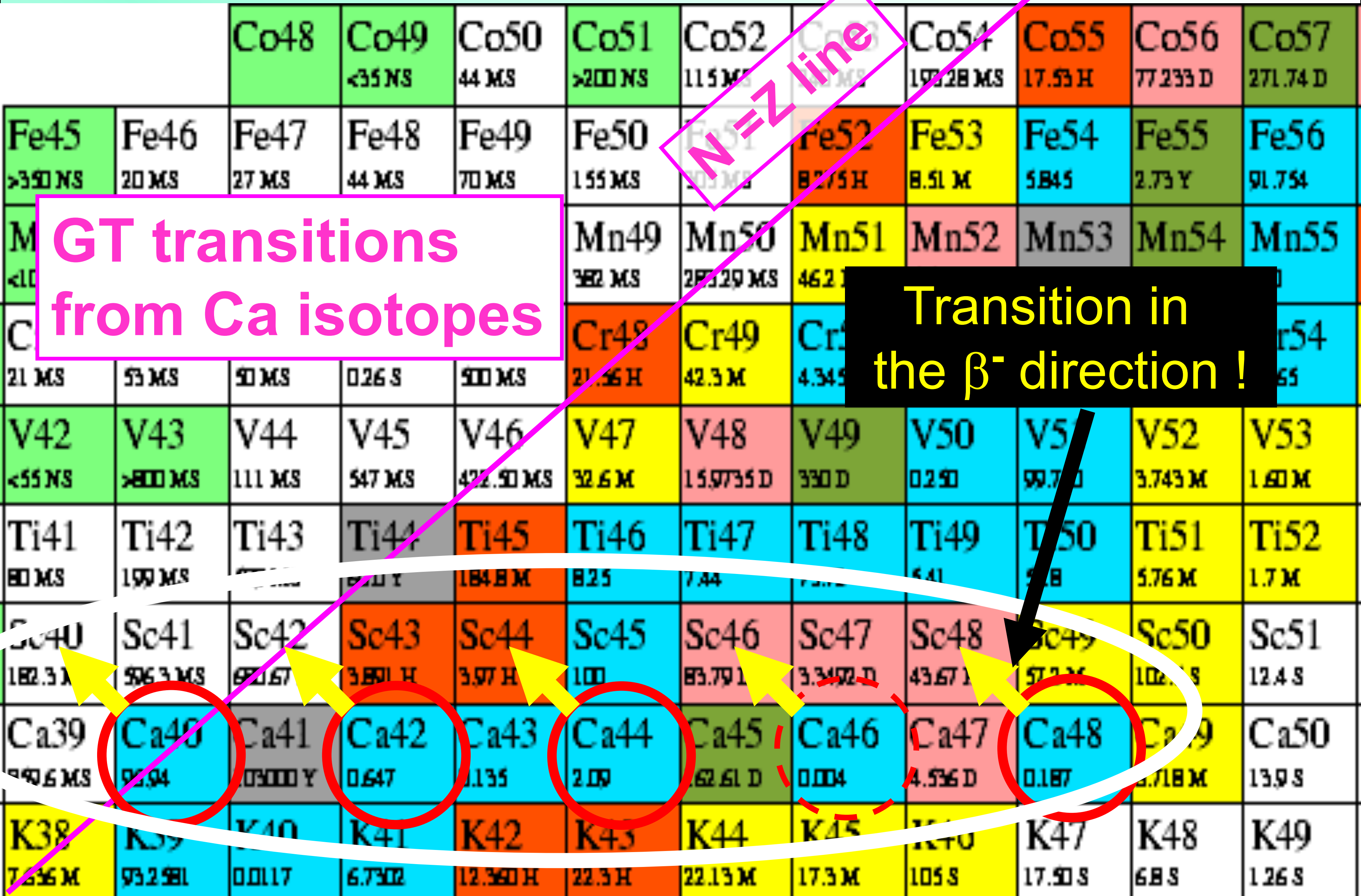
$^{48}Ca(^{3}He,t)^{48}Sc$



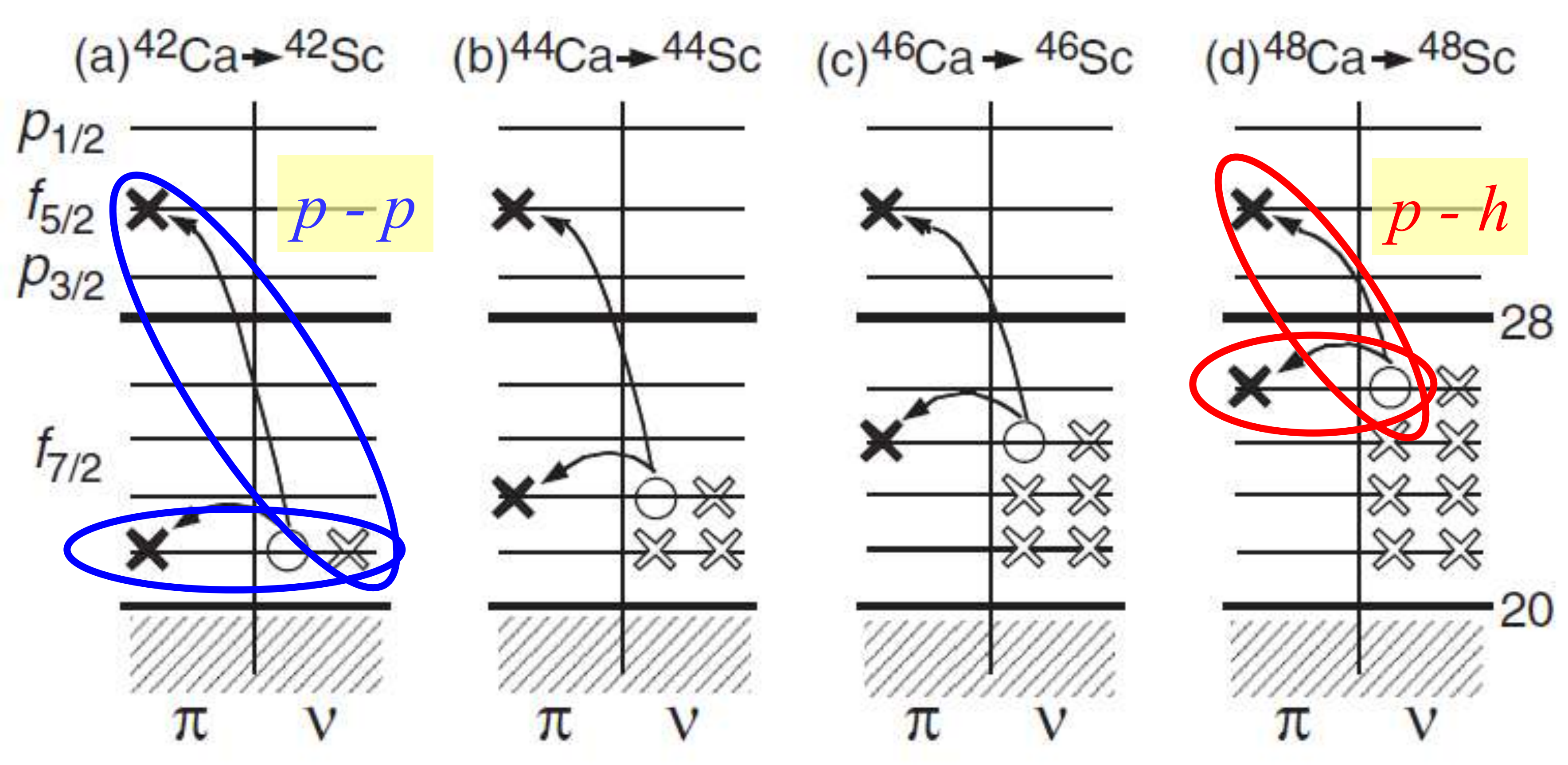
$^{48}Ca(^{3}He,t)^{48}Sc$



Nuclear Chart *f*-shell Nuclei



GT Configurations in Sc isotopes

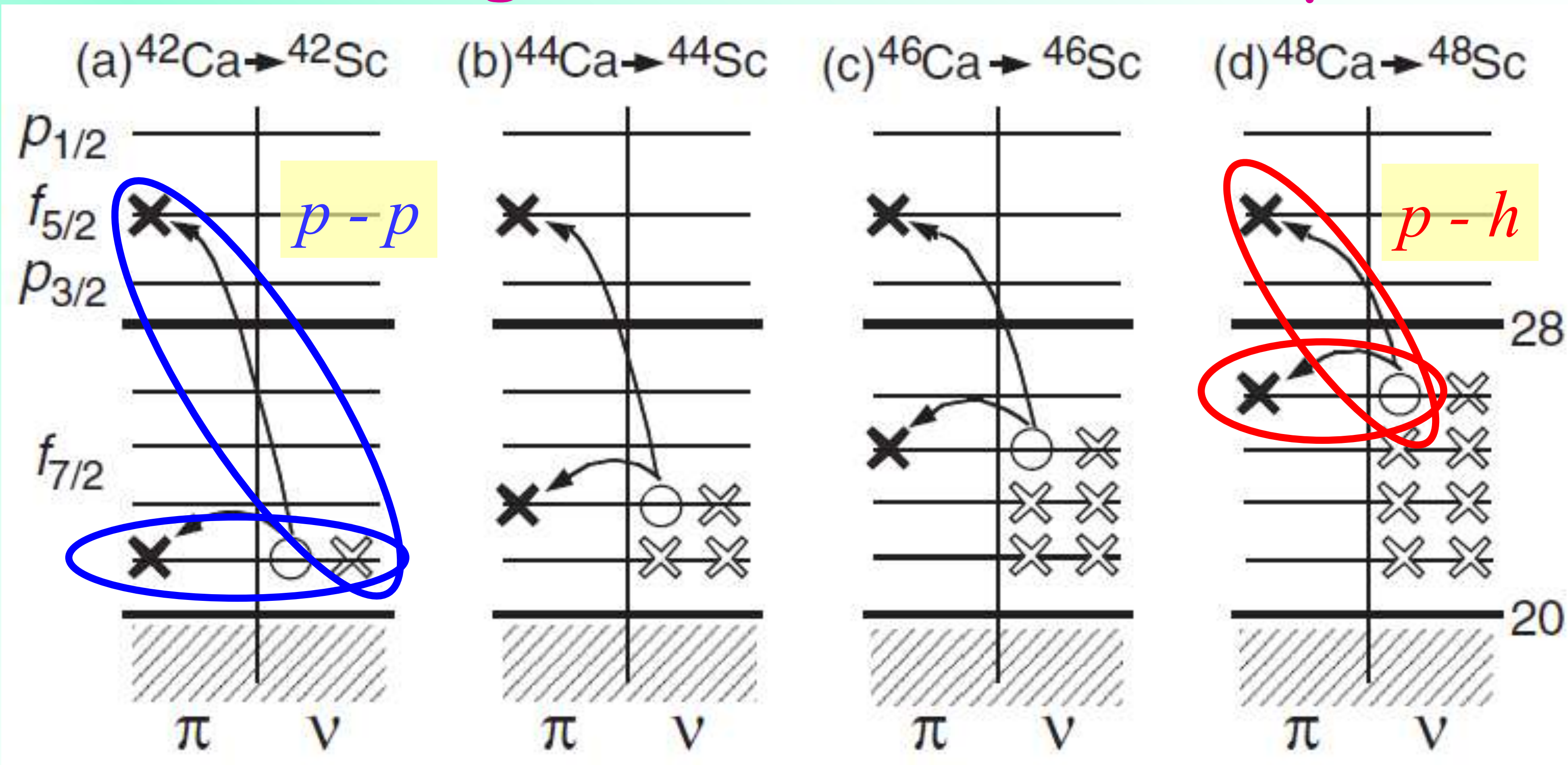


particle-particle int. (attractive) → particle-hole int. (repulsive)

Low-energy
Super GT state
Is formed !

Gamow-Teller
Resonance
Is formed !

GT Configurations in Sc isotopes



particle-particle int. (attractive) → particle-hole int. (repulsive)

Low-energy
Super GT state
Is formed !

Gamow-Teller
Resonance
Is formed !

Main Player:
Isovector interaction !

Role of Residual Int. (repulsive case)

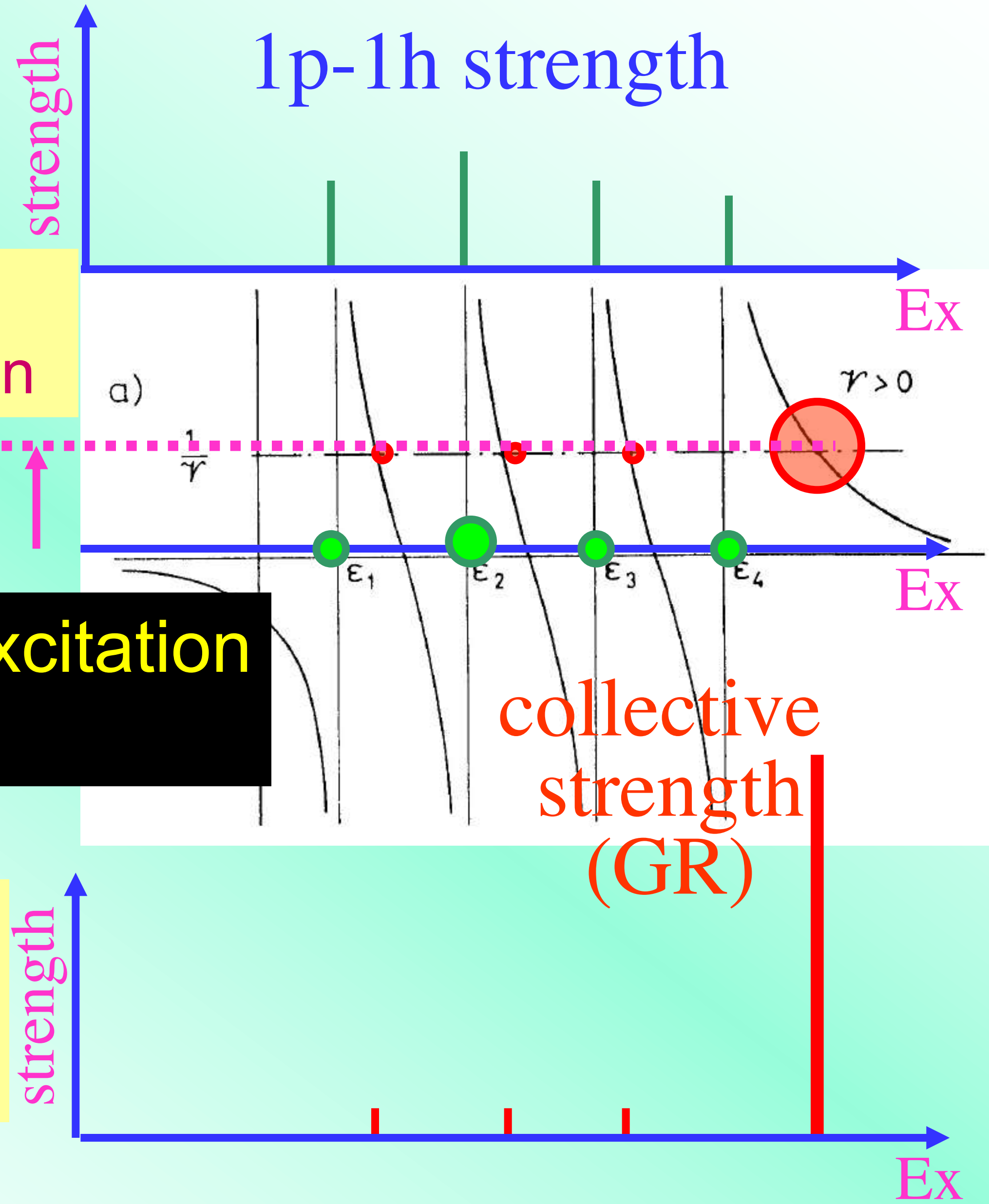
Single particle-hole strength distribution

Graphical solution of the RPA dispersive eigen-equation

positive = repulsive

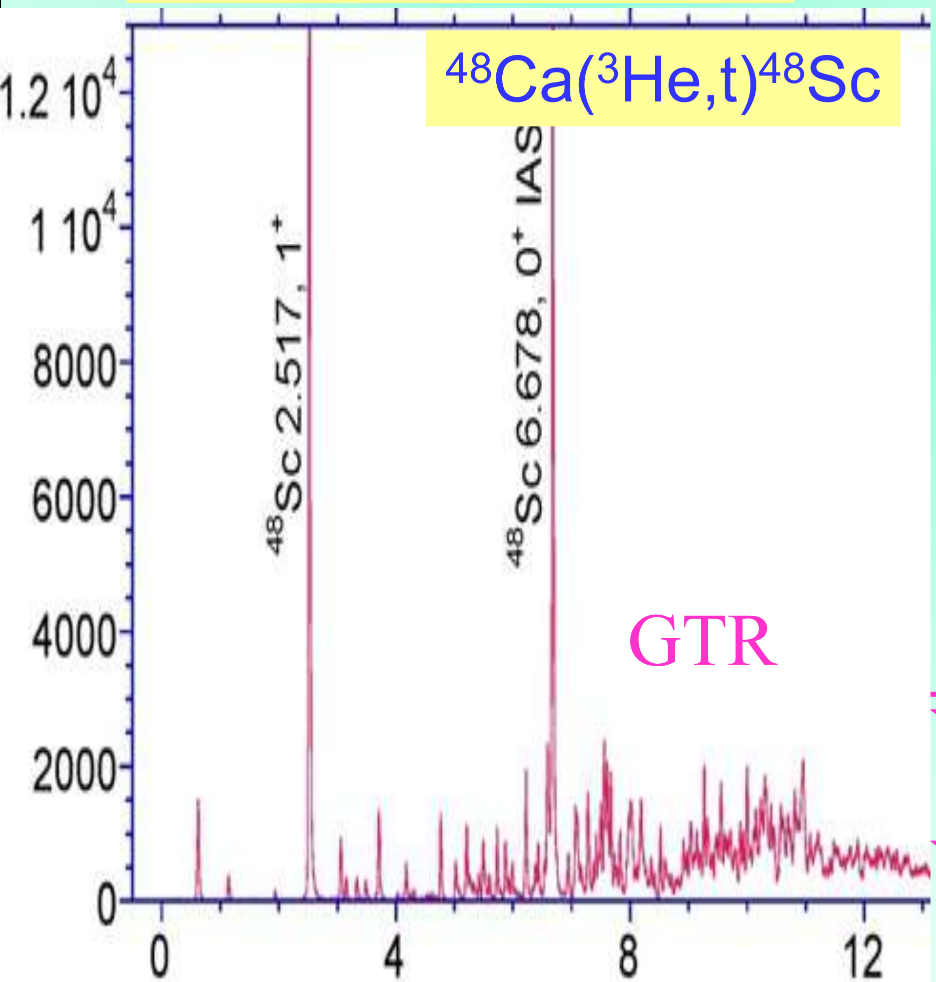
p - *h* configuration + IV excitation = repulsive

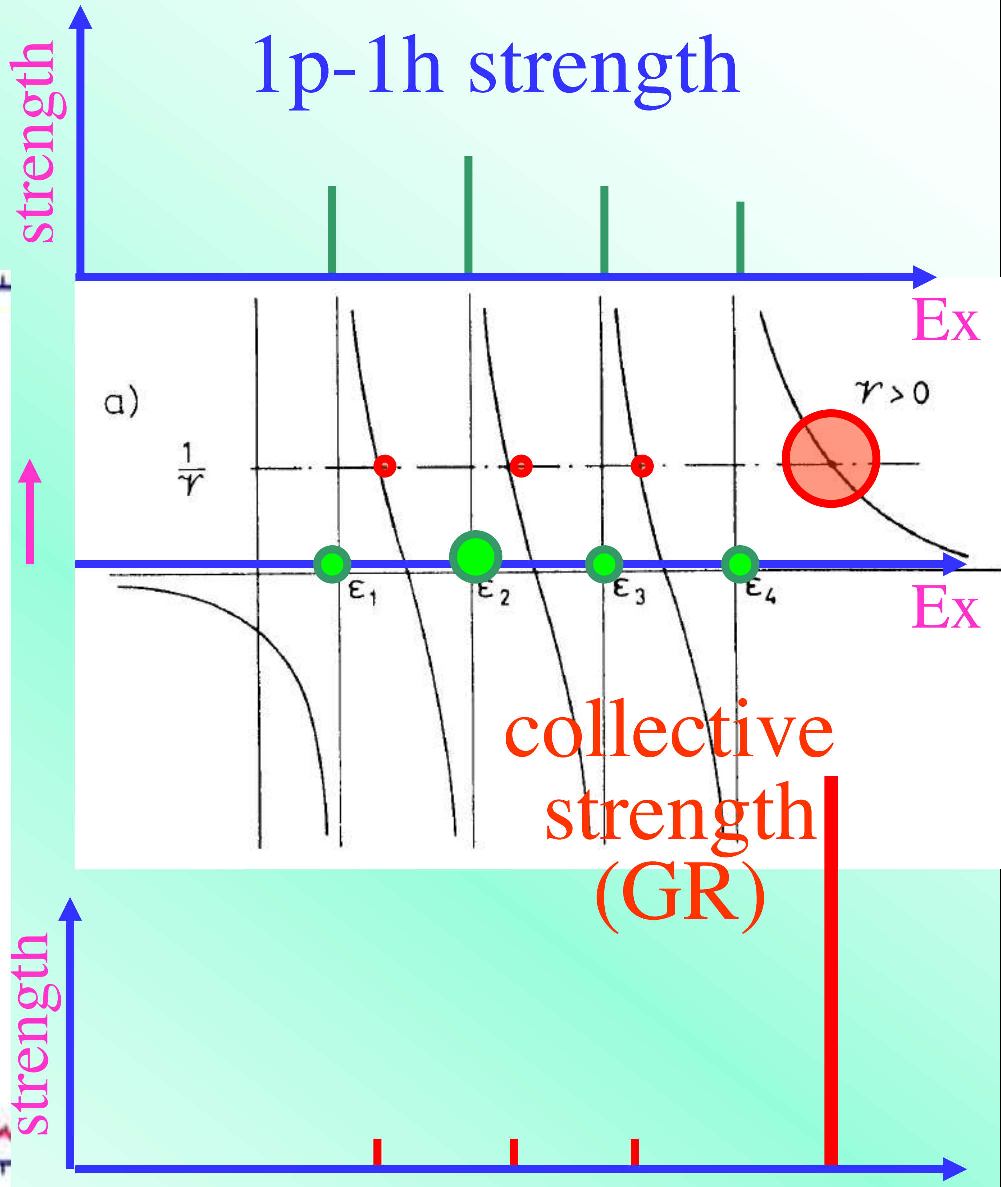
Collective excitation formed by the repulsive residual interaction



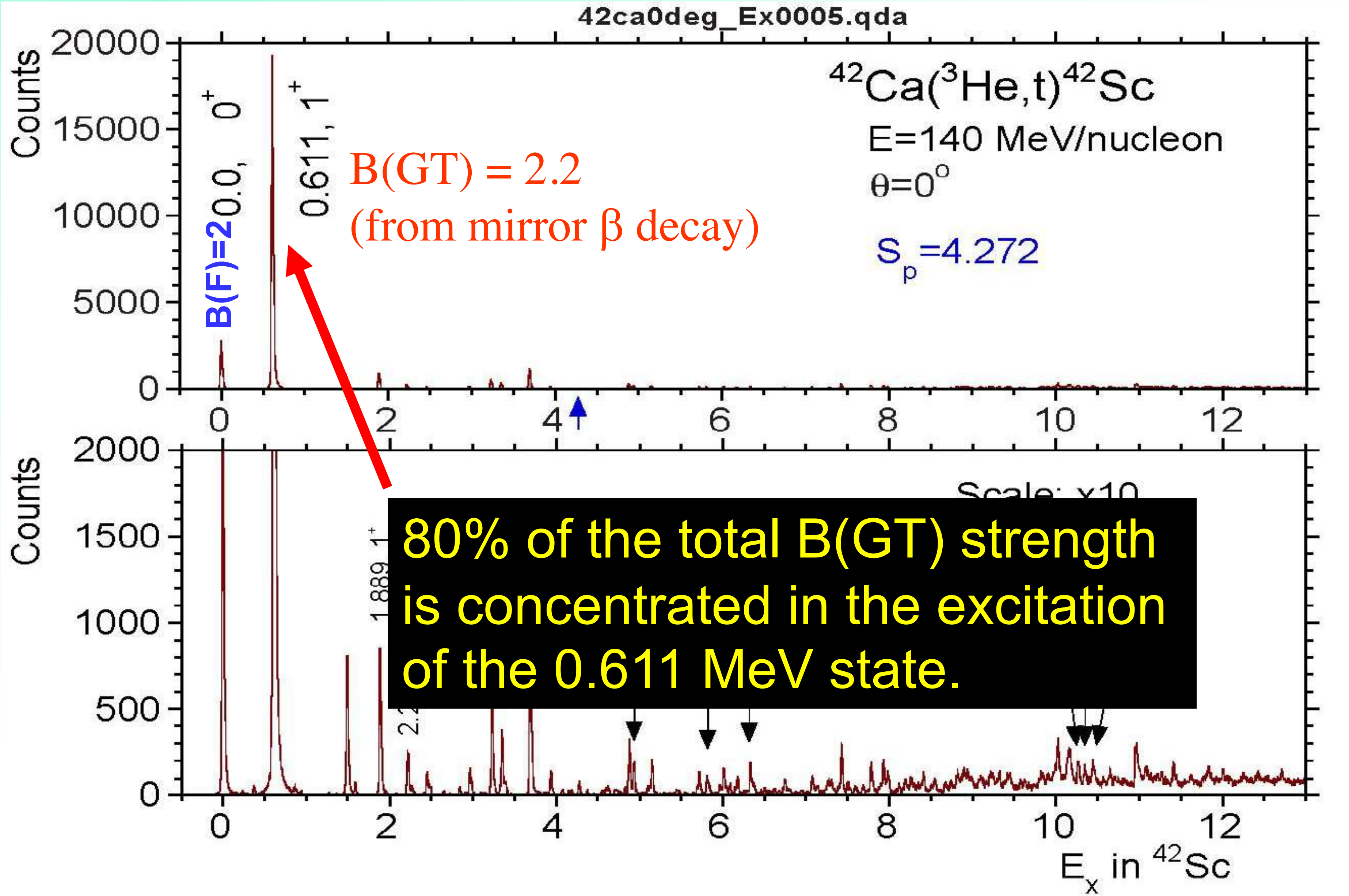
Role of Residual Int. (repulsive)

GTR is formed by the
IV-type Repulsive
residual interaction



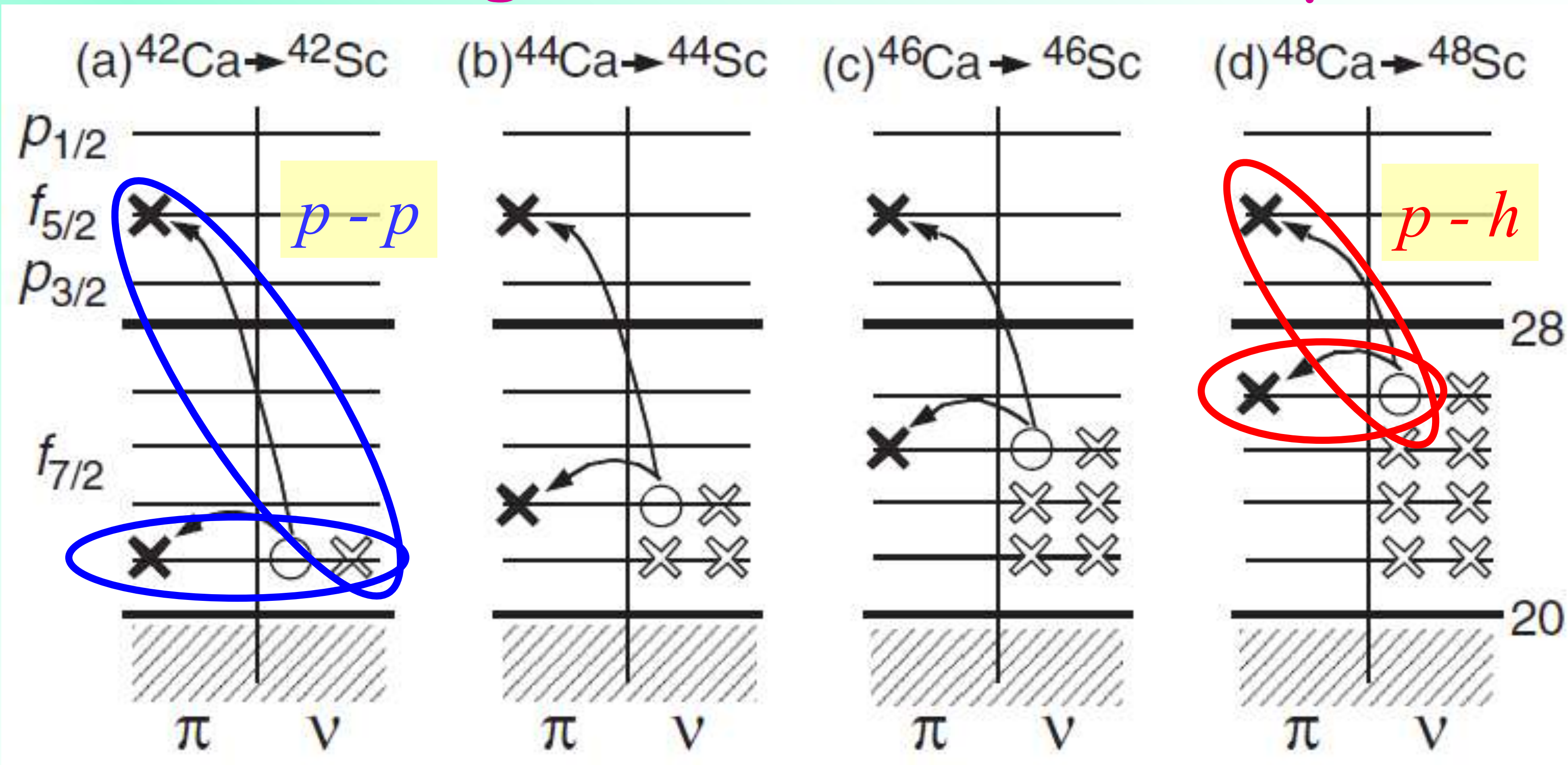


$^{42}Ca(^{3}He,t)^{42}Sc$ in 2 scales



80% of the total B(GT) strength is concentrated in the excitation of the 0.611 MeV state.

GT Configurations in Sc isotopes



particle-particle int. (attractive) → particle-hole int. (repulsive)

Low-energy Super GT state Is formed

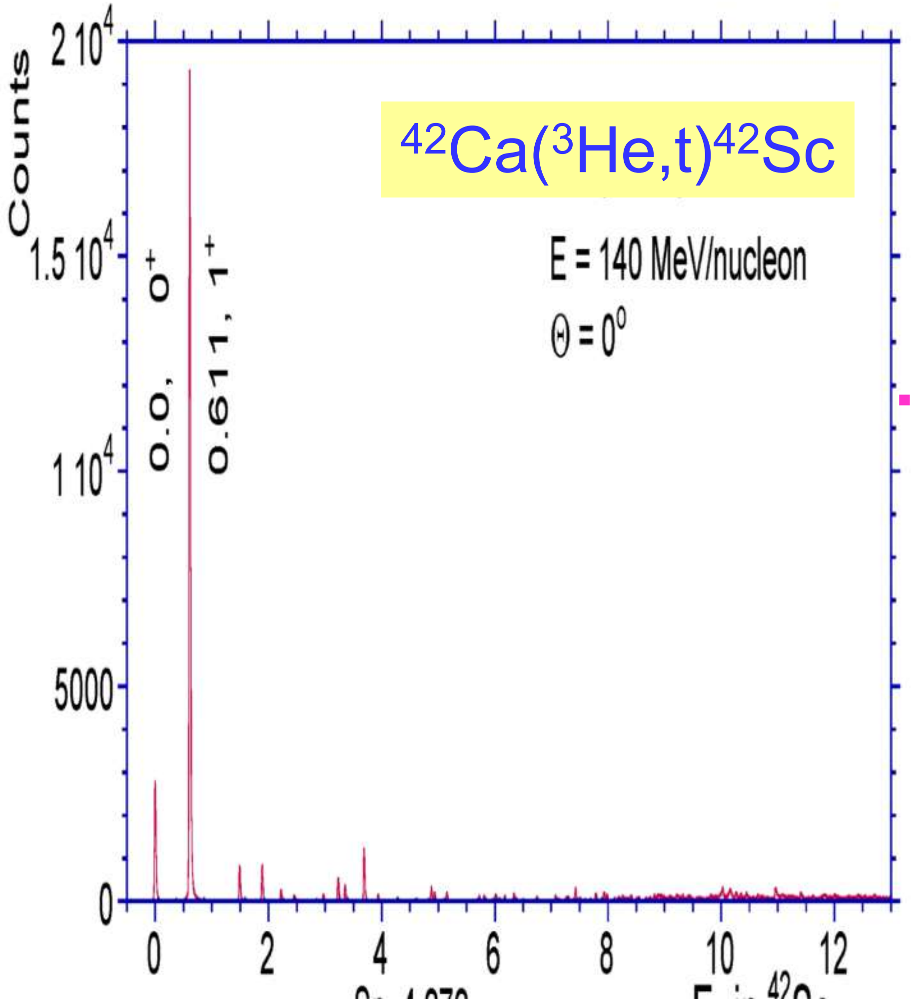
Main Player:
Isoscalar interaction !

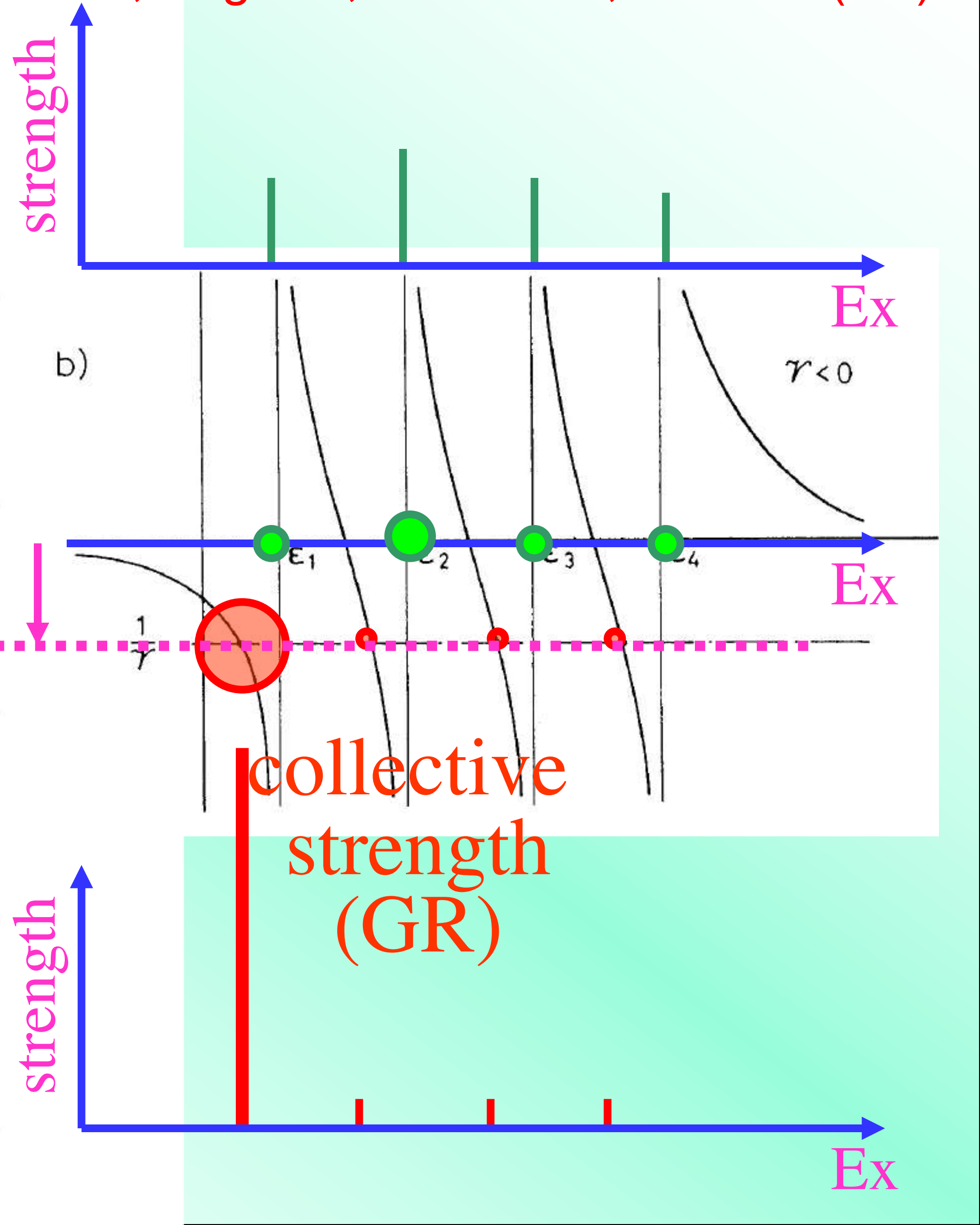
Gamow-Teller Resonance Is formed !

Role of Residual Int. (attractive)

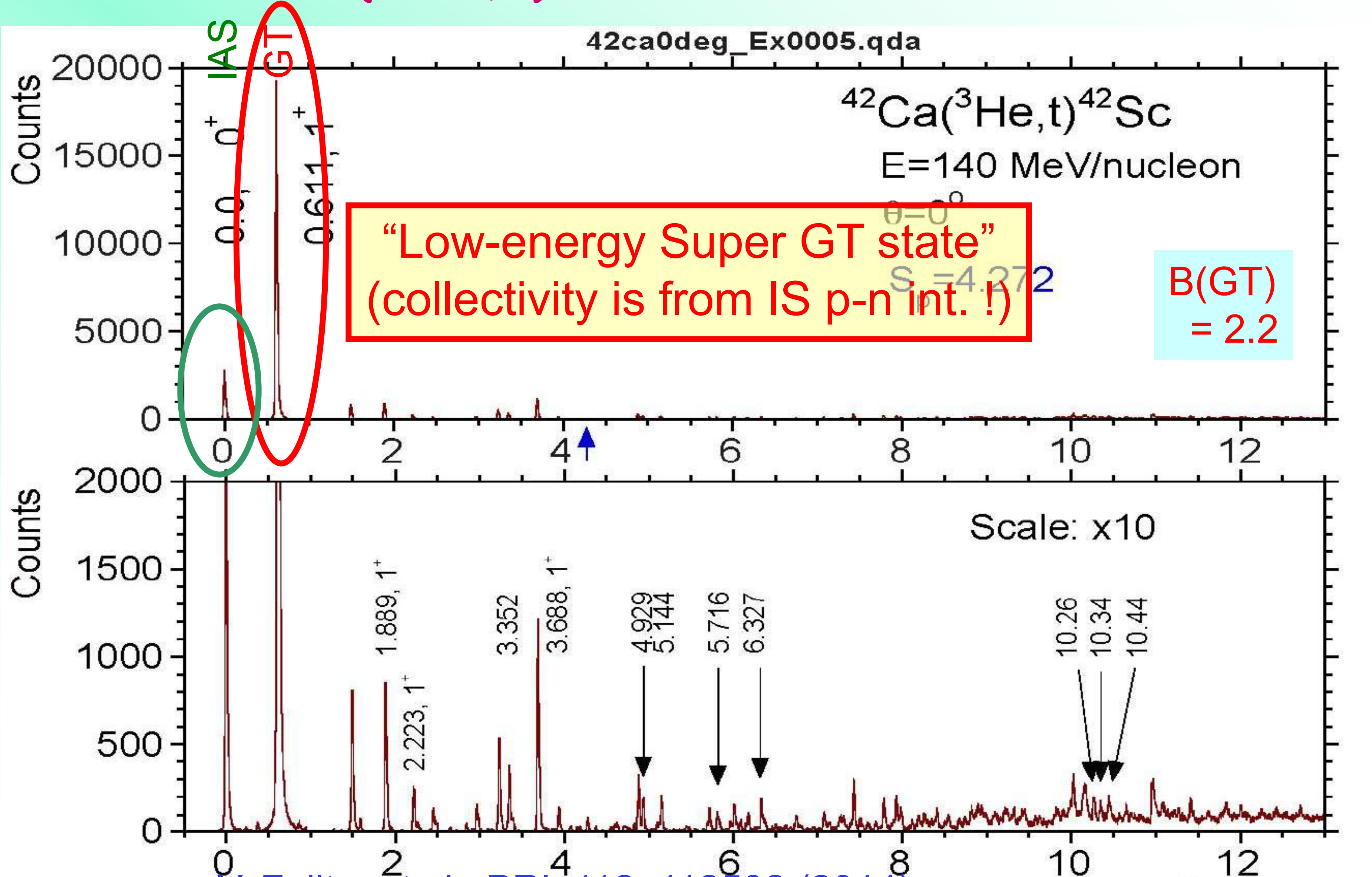
Bai, Sagawa, Colo et al., PRC 90 ('14)

Collective excitation formed by the attractive IS residual interaction



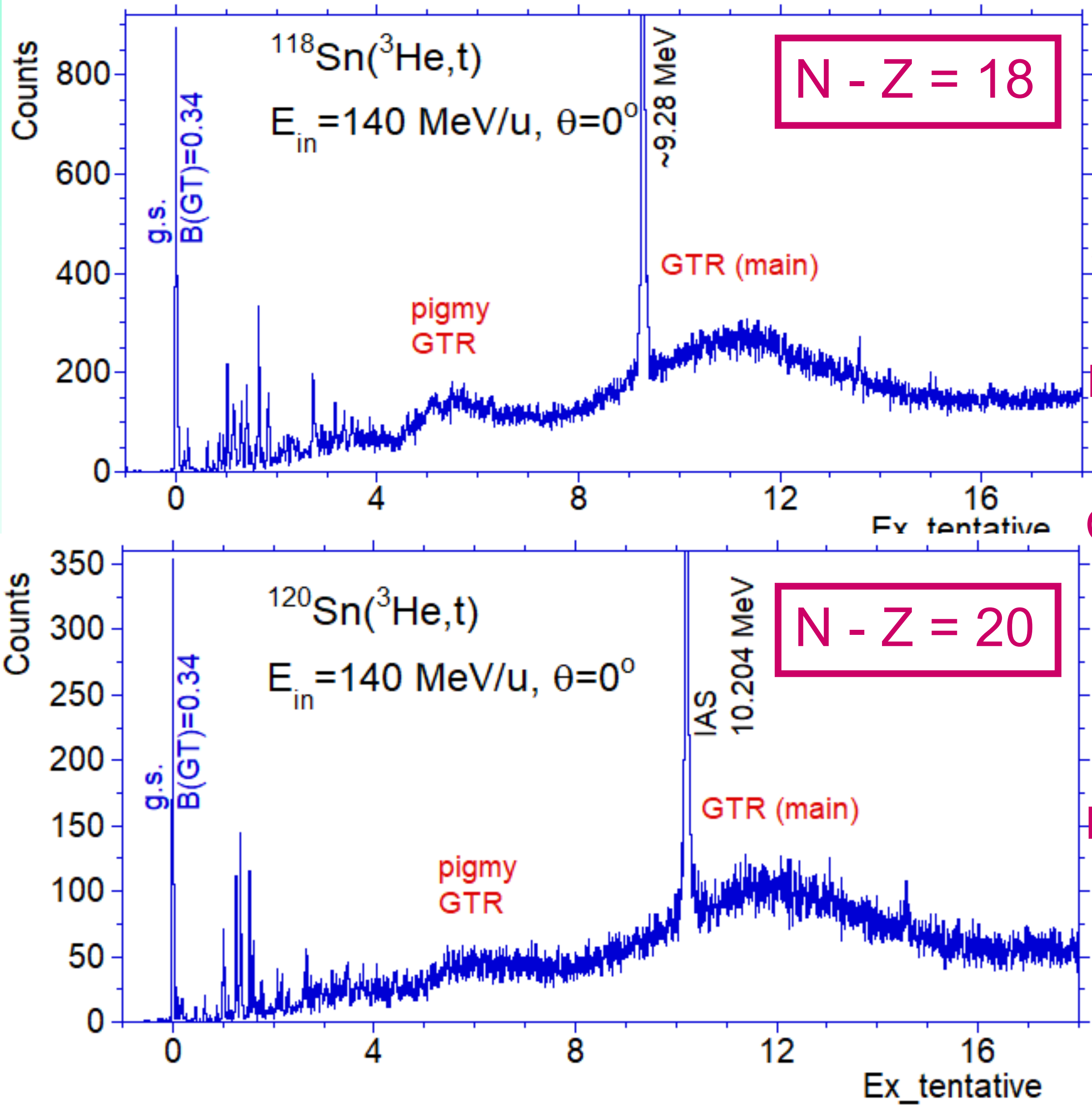


$^{42}Ca(^{3}He,t)^{42}Sc$ in 2 scales



Y. Fujita, et al., PRL 112, 112502 (2014).
PRC 91, 064316 (2015).

GT transitions in $^{A}Sn \rightarrow {}^{A}Sb$ CE reactions



Scenario

A) In N>>Z nuclei, GT ex. has *p – h* nature.

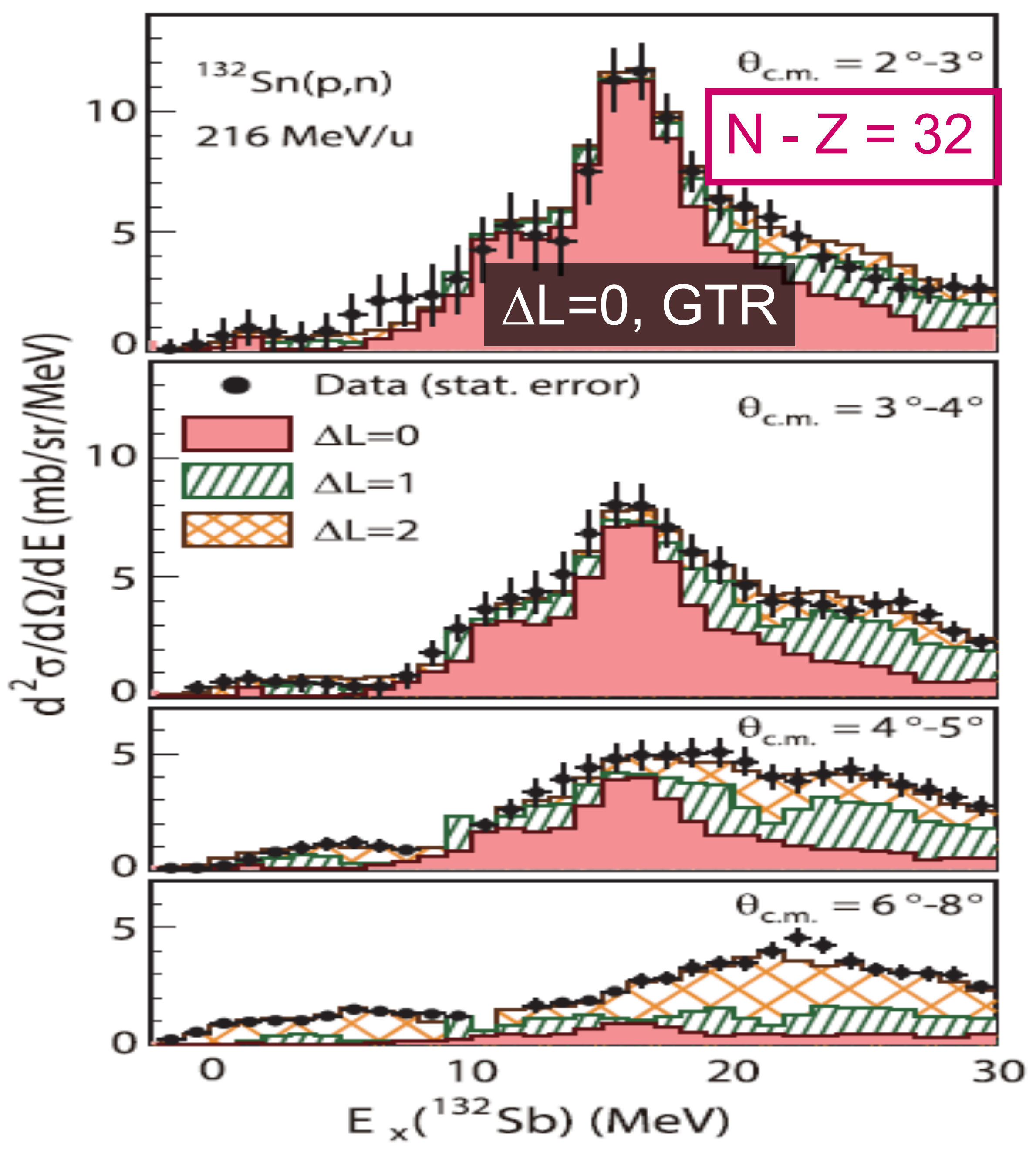
B) In *p – h* configurations, IV-type int. is active.

C) Due to the repulsive nature of IV residual interaction, the GT strength is pushed up.

D) With increasing N-Z, the GT strength is pushed up more.

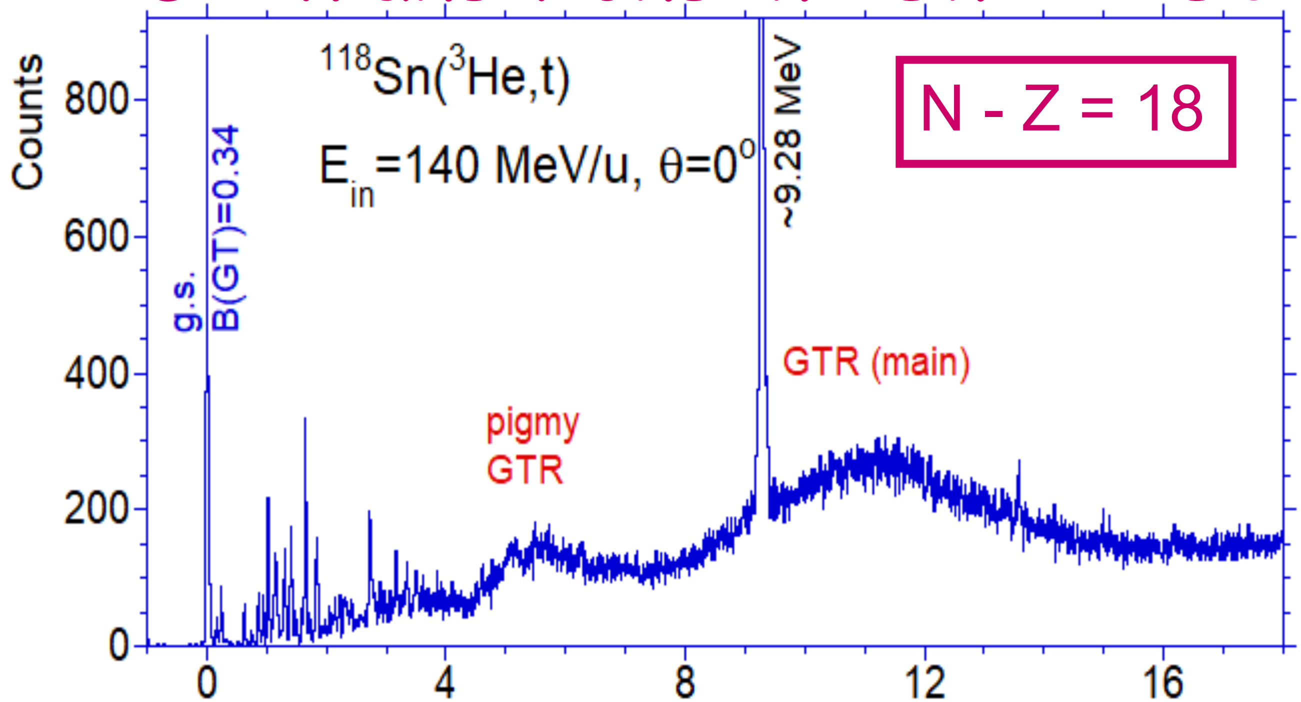
$^{132}Sn(p, n)^{132}Sb$ @ RIBF RIKEN
(Angular-dis. Ana.)

The result of MDA
(Multi-Pole Decomp. Ana.)
shows that GTR is
at Ex ~ 16.3 MeV
width Γ ~ 4.7 MeV.



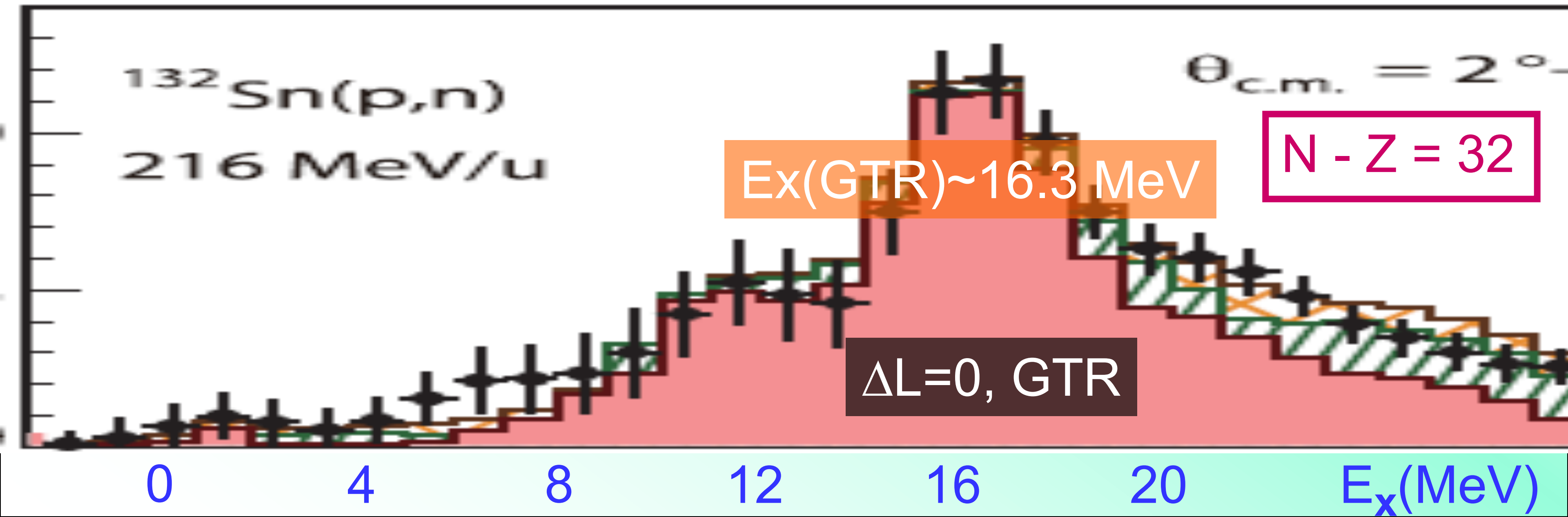
J. Yasuda et al.,
PRL 121, 132501 (2018)

GT transitions in $^{A}Sn \rightarrow {}^{A}Sb$ CE reactions



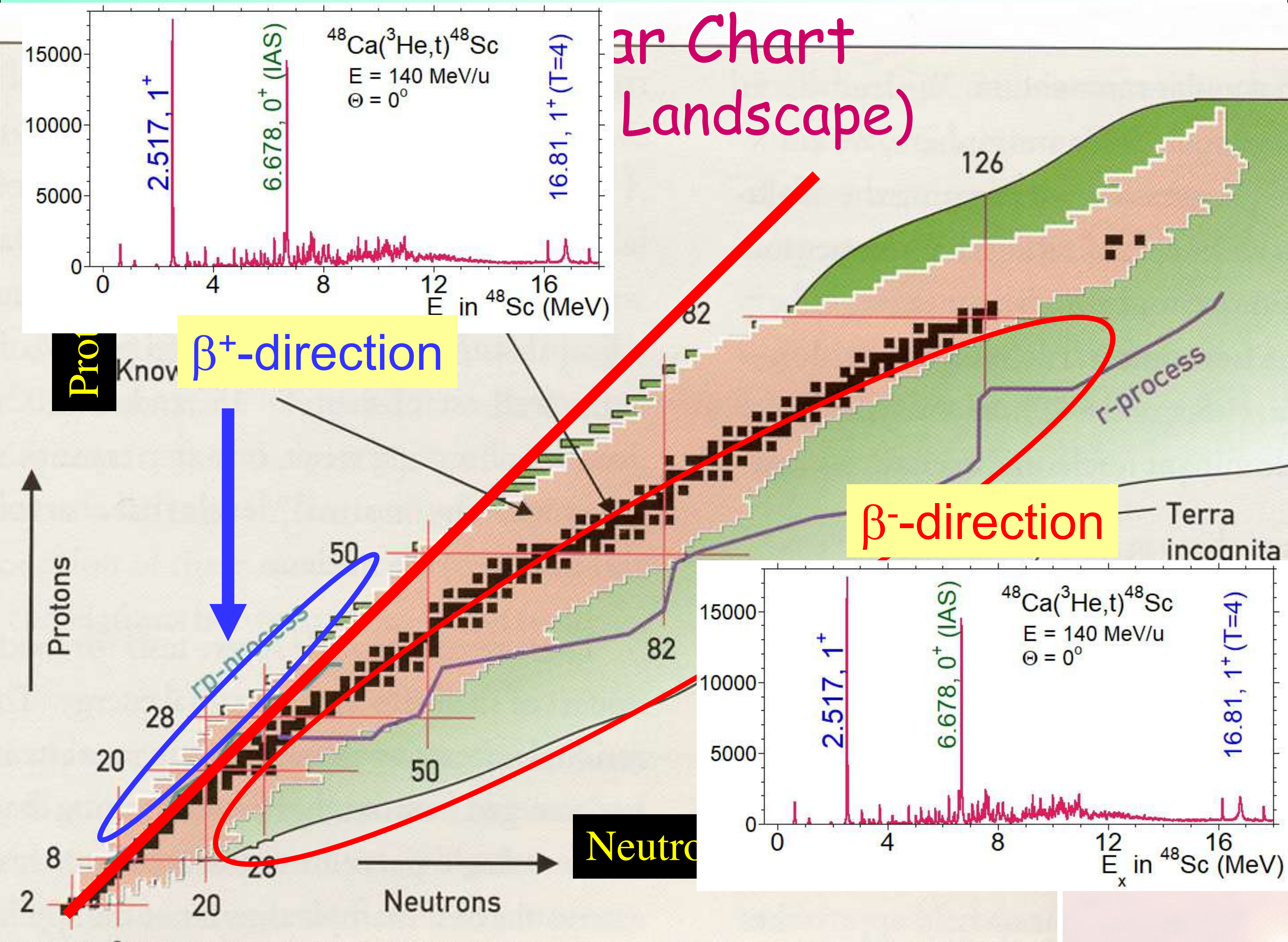
N - Z = 18

Ikeda Sum Rule
B(GT) ~ 3(N –Z)



N - Z = 32

ar Chart
Landscape)



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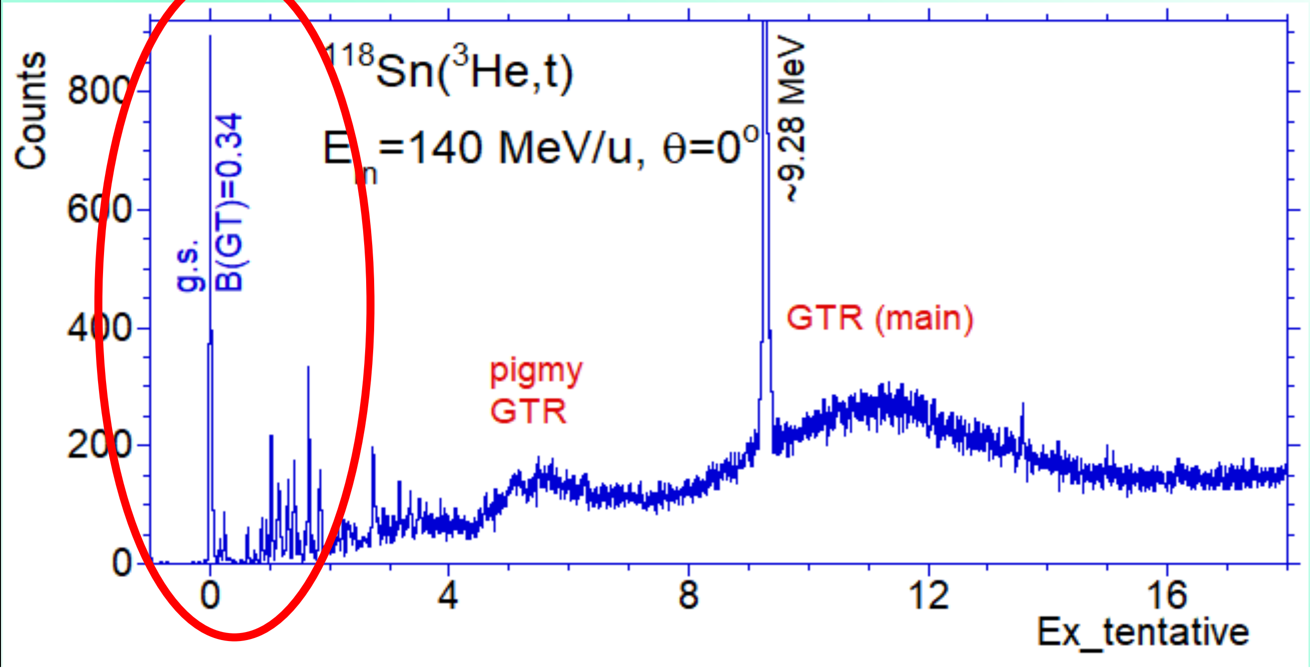

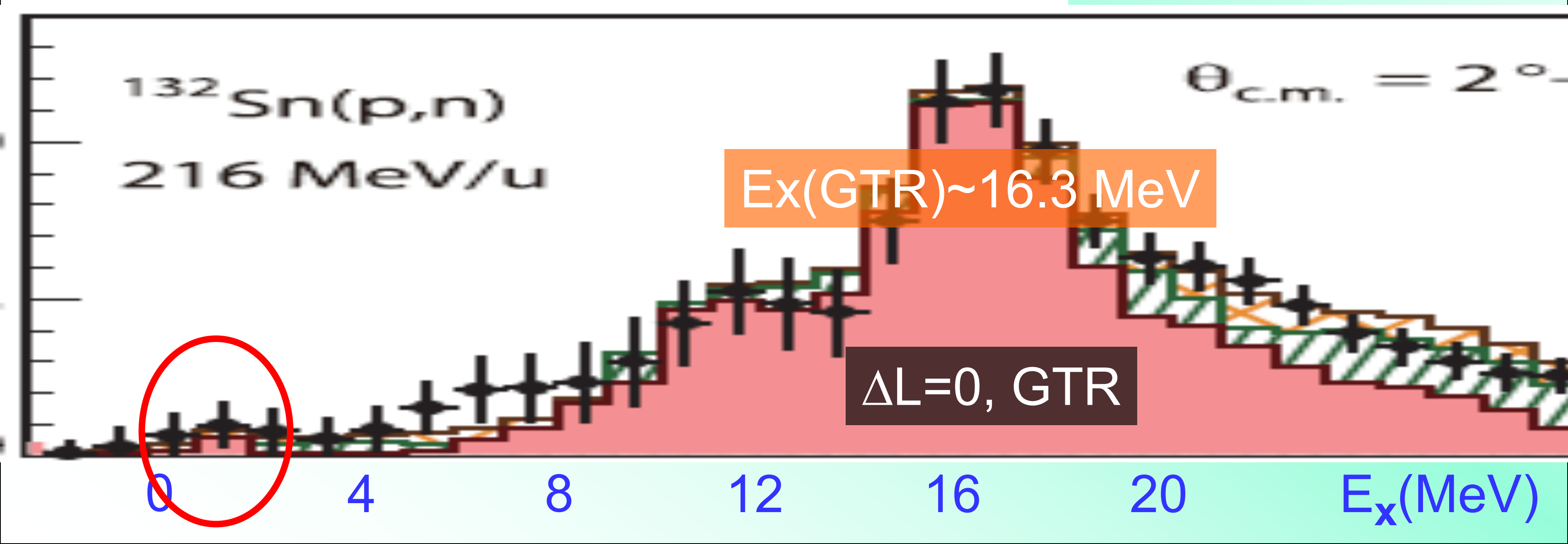

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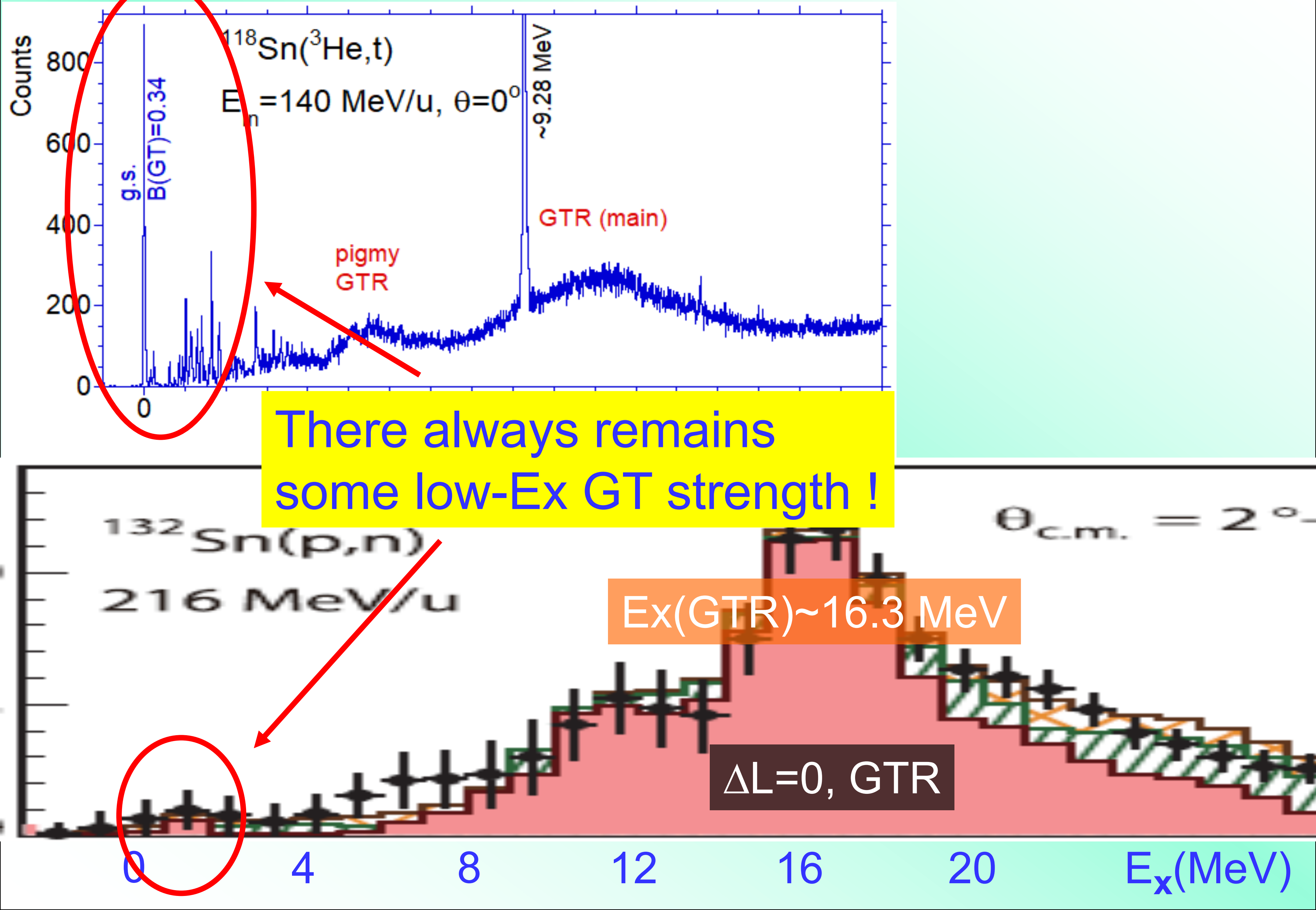
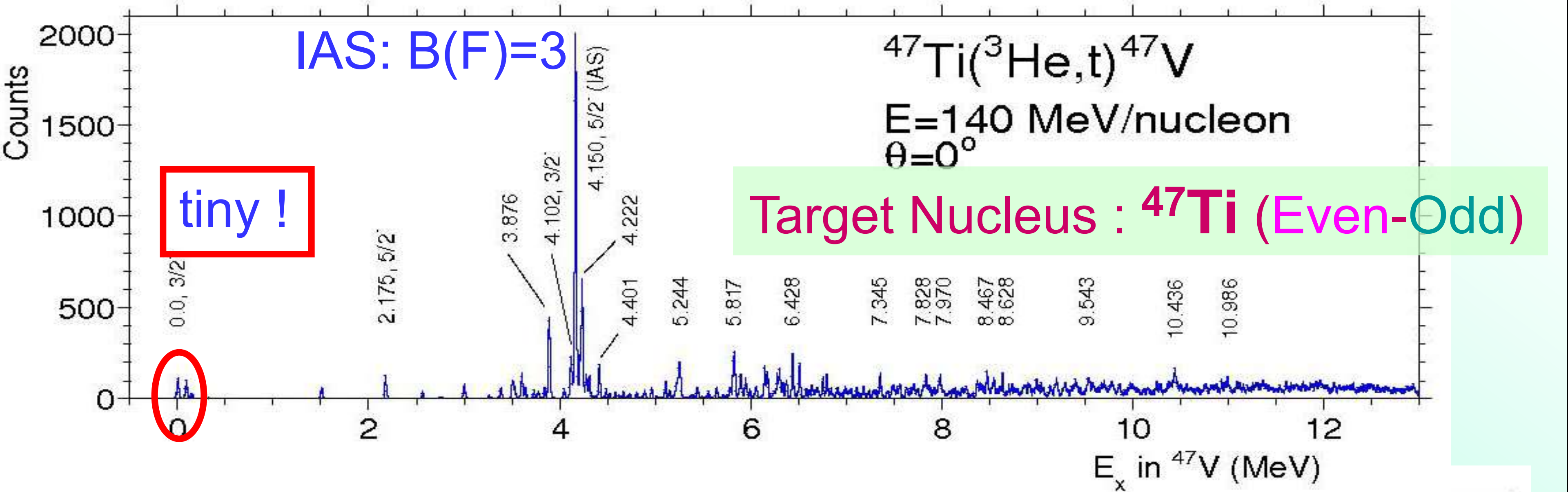
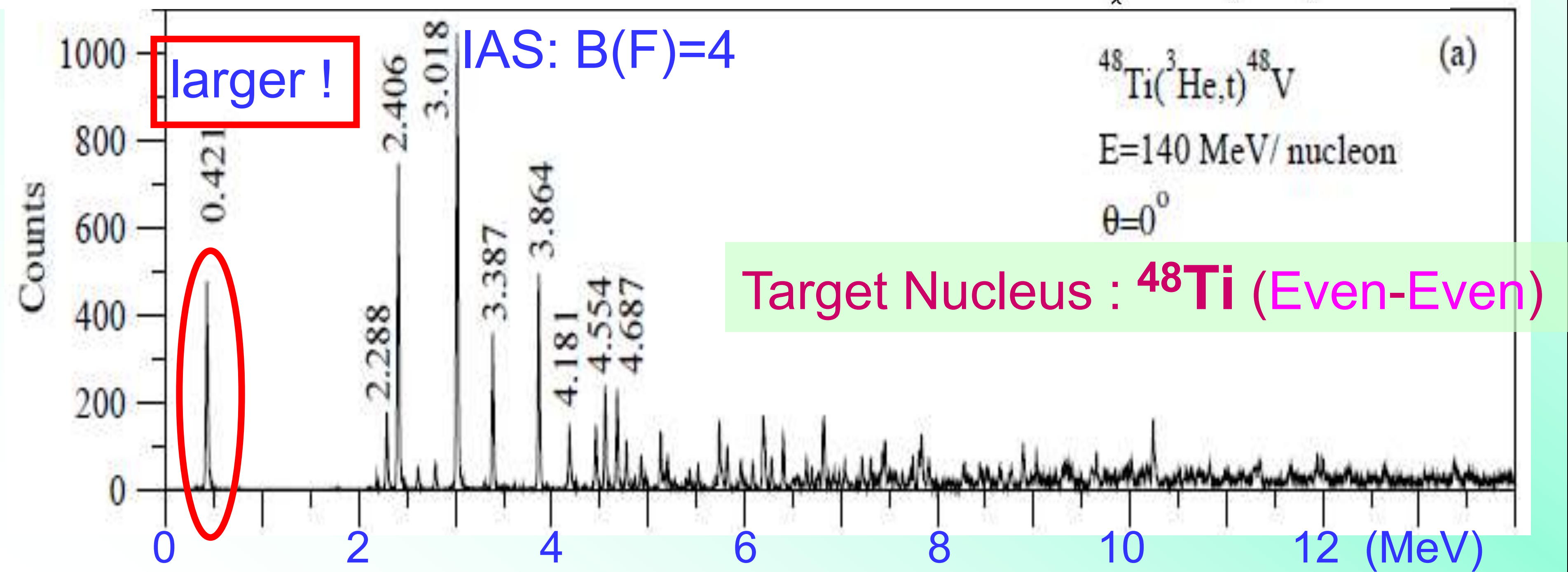


Low-Ex GT strength: Even-Odd vs. Even-Even

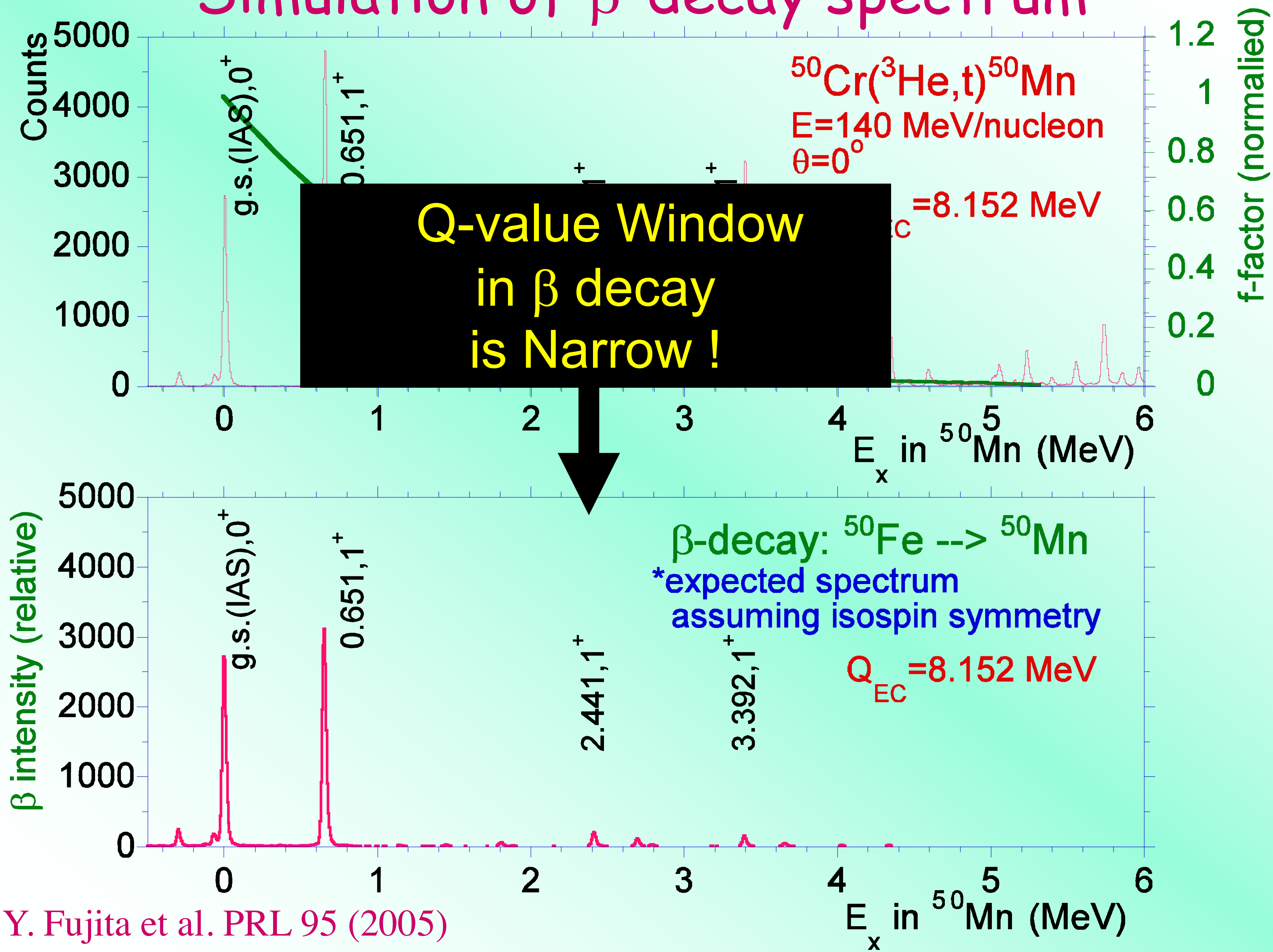




Interpretation of CE results into β^- decay results

*** Q-value limitation

Simulation of β-decay spectrum



Y. Fujita et al. PRL 95 (2005)

Interpretation of CE results into β^- decay results

*** Q-value limitation

GTR region usually makes no contribution !

Fermi transition cannot make contribution !

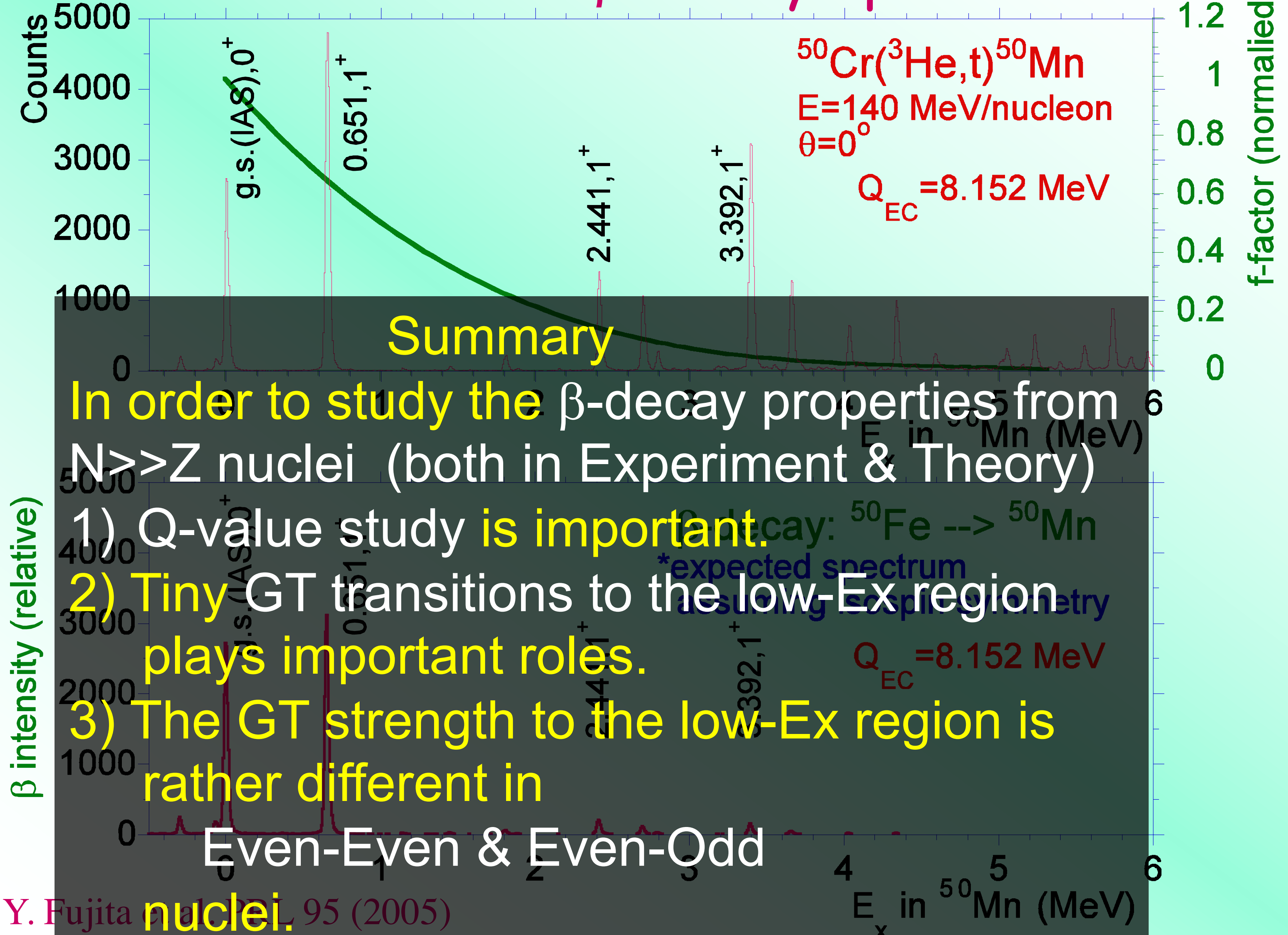
[Y. Fujita et al. PPNP 66 (2011) 549]

*** GT transitions to the low-Ex region although weak, have large weight.

*** GT transitions to the low-Ex region: different in Even-Even & Even-Odd nuclei !

➔ **T1/2** can be largely different !

Simulation of β-decay spectrum



Summary

In order to study the β-decay properties from N>>Z nuclei (both in Experiment & Theory)

1) Q-value study is important.

2) Tiny GT transitions to the low-Ex region plays important roles.

3) The GT strength to the low-Ex region is rather different in Even-Even & Even-Odd nuclei.

Y. Fujita et al. PRL 95 (2005)


End of publicity