Observation of Low- and High-Energy Gamow-Teller Phonon Excitations in Nuclei

GT : weak response caused by simple $\sigma\tau$ operator

International School
of Nuclear Physics
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Sep. 16 – Sep. 24, 2014

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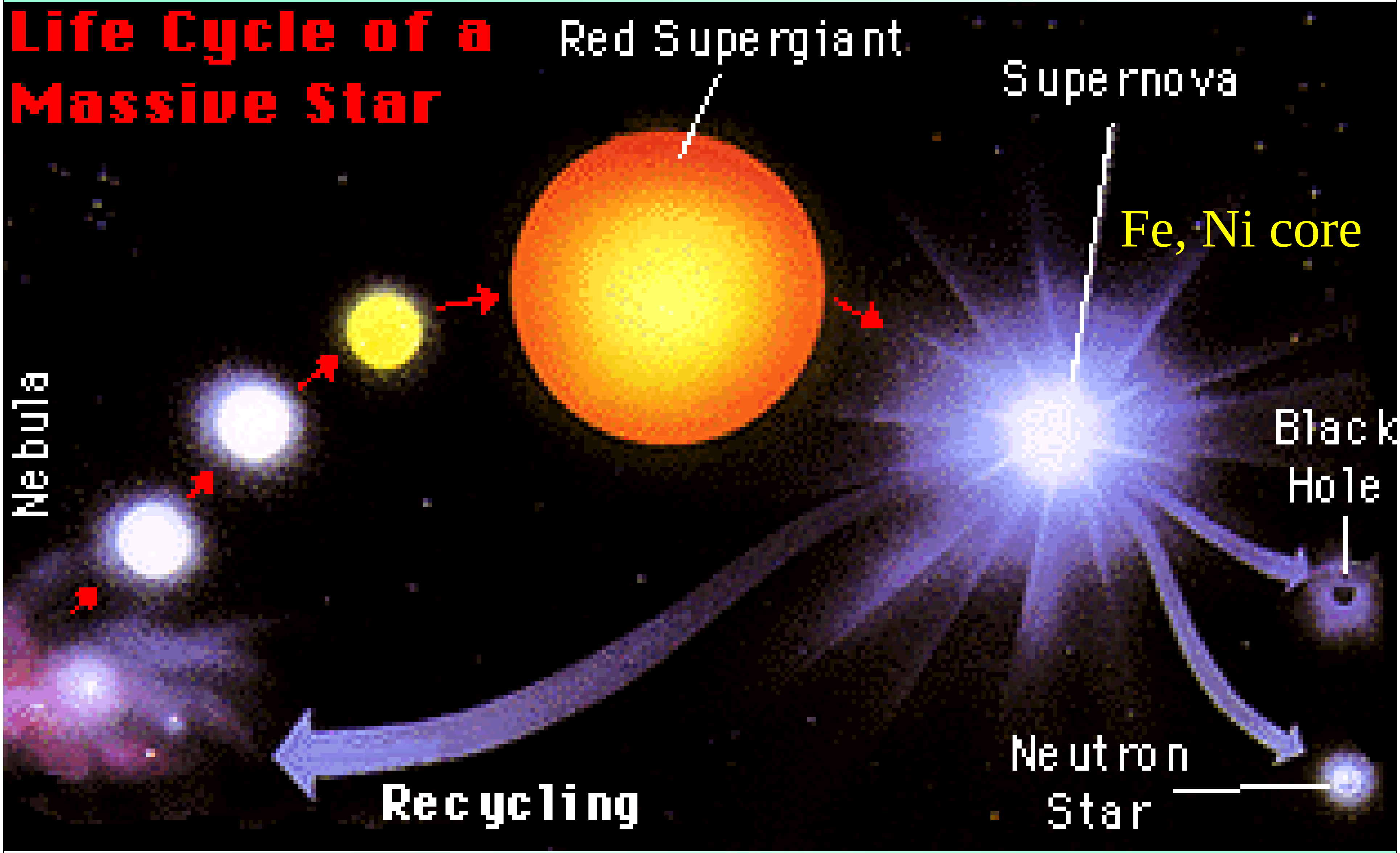
Stellar Evolution & Supernova Cycle



Gamow-Teller transitions

Mediated by $\sigma\tau$ operator

ΔS = -1, 0, +1 and ΔT = -1, 0, +1

(ΔL = 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 $f_{7/2} \rightarrow f_{7/2}$, $f_{5/2} \rightarrow f_{5/2}$, $f_{7/2} \leftrightarrow f_{5/2}$

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 !

**Basic common understanding of β-decay and Charge-Exchange reaction

β decays :

Absolute *B*(GT) values,

but usually the study is limited to low-lying states

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

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

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

β-decay & CE Nuclear Reaction

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

$B(\mathrm{GT})$: 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

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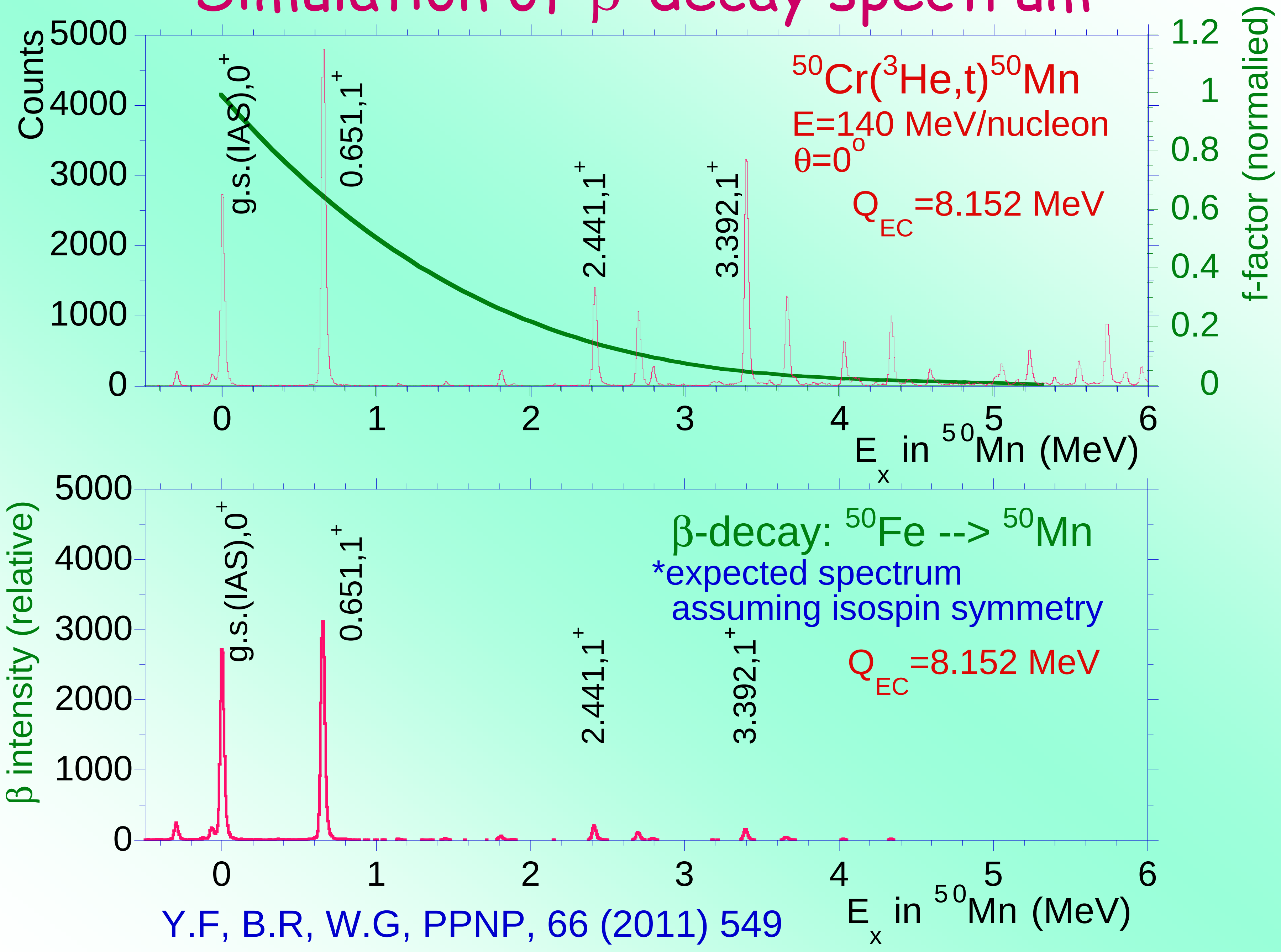
Simulation of β-decay spectrum



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

β-decay & Nuclear Reaction

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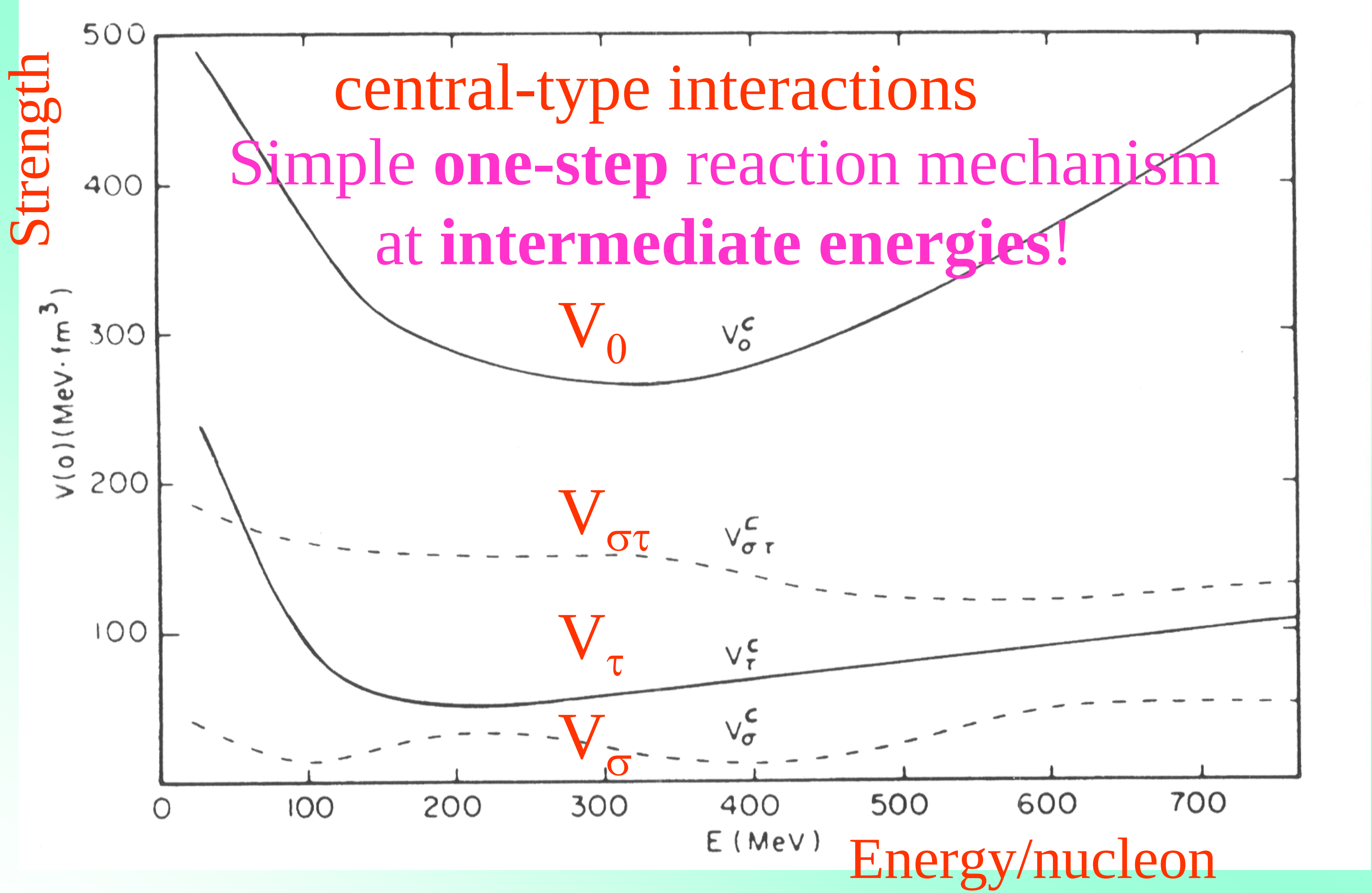
*At intermediate energies ($100 < E_{\mathrm{in}} < 500$ MeV)

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

Nucleon-Nucleon Int. : E_{in} dependence at q=0



central-type interactions

Simple **one-step** reaction mechanism at **intermediate energies**!

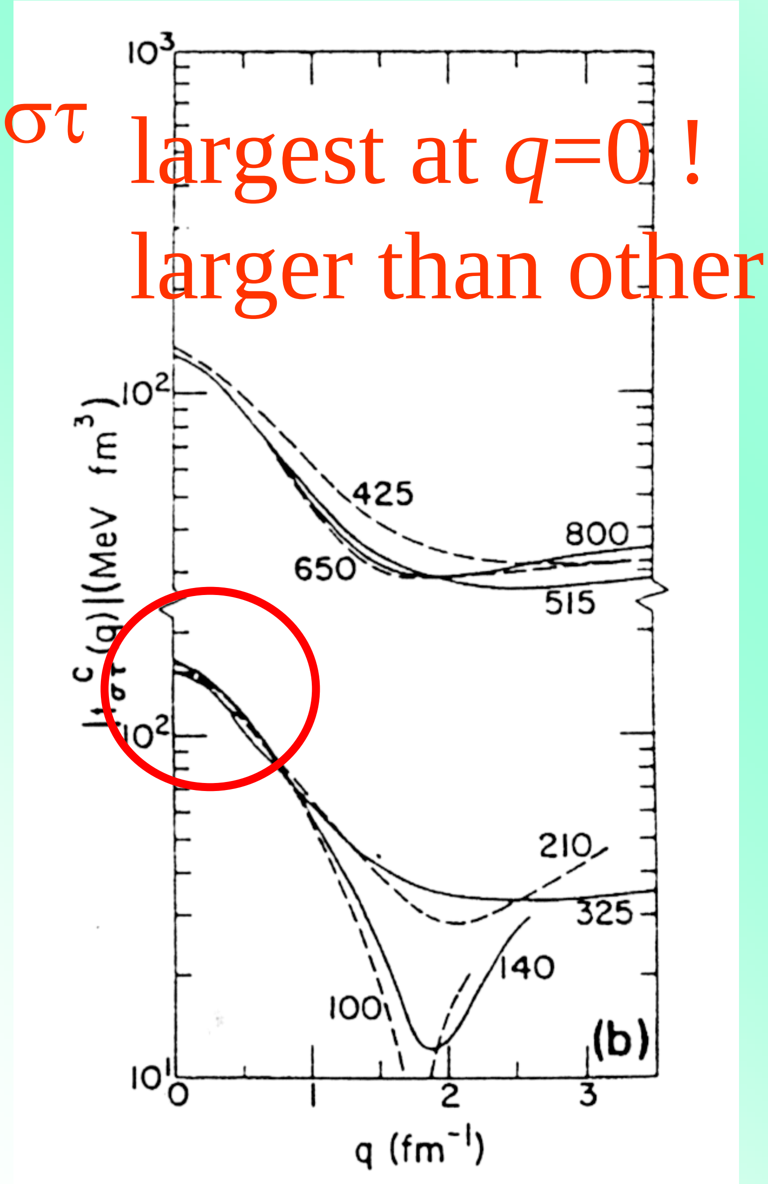
Love & Franey PRC 24 ('81) 1073

N.-N. Int. : στ & Tensor-τ *q*-dependence

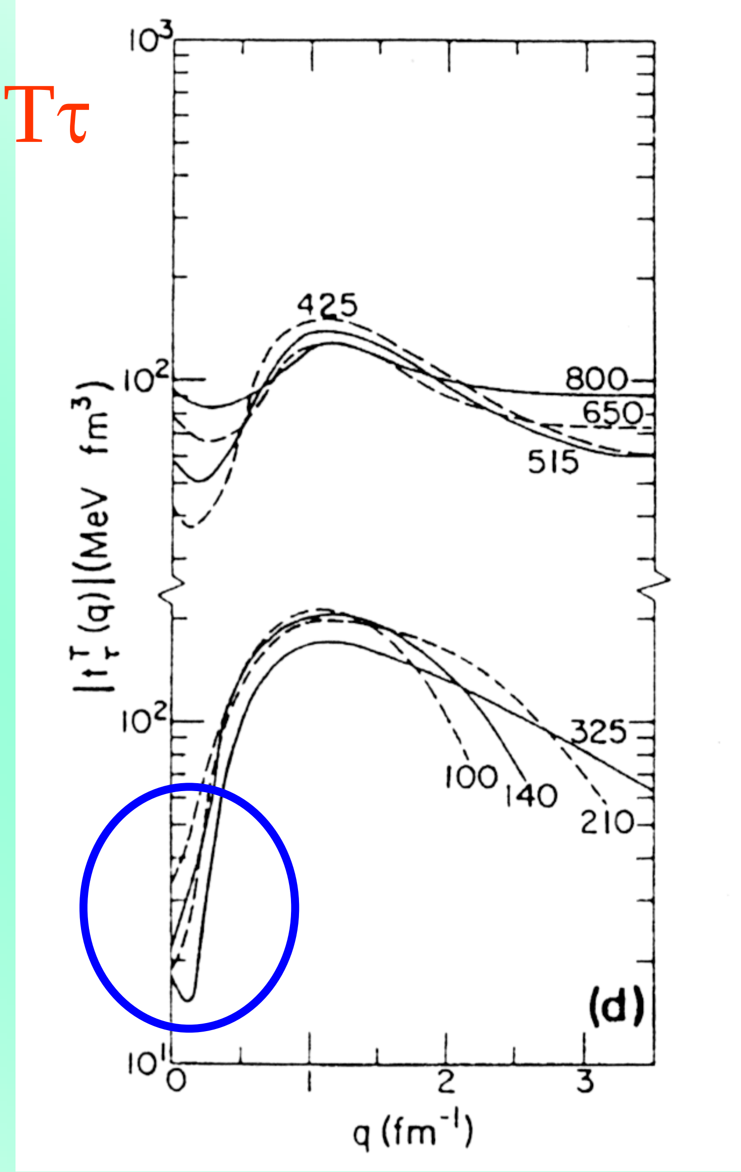
στ

largest at *q*=0 !

larger than others !



Tτ



Love & Franey PRC 24 ('81) 1073

β-decay & Nuclear Reaction

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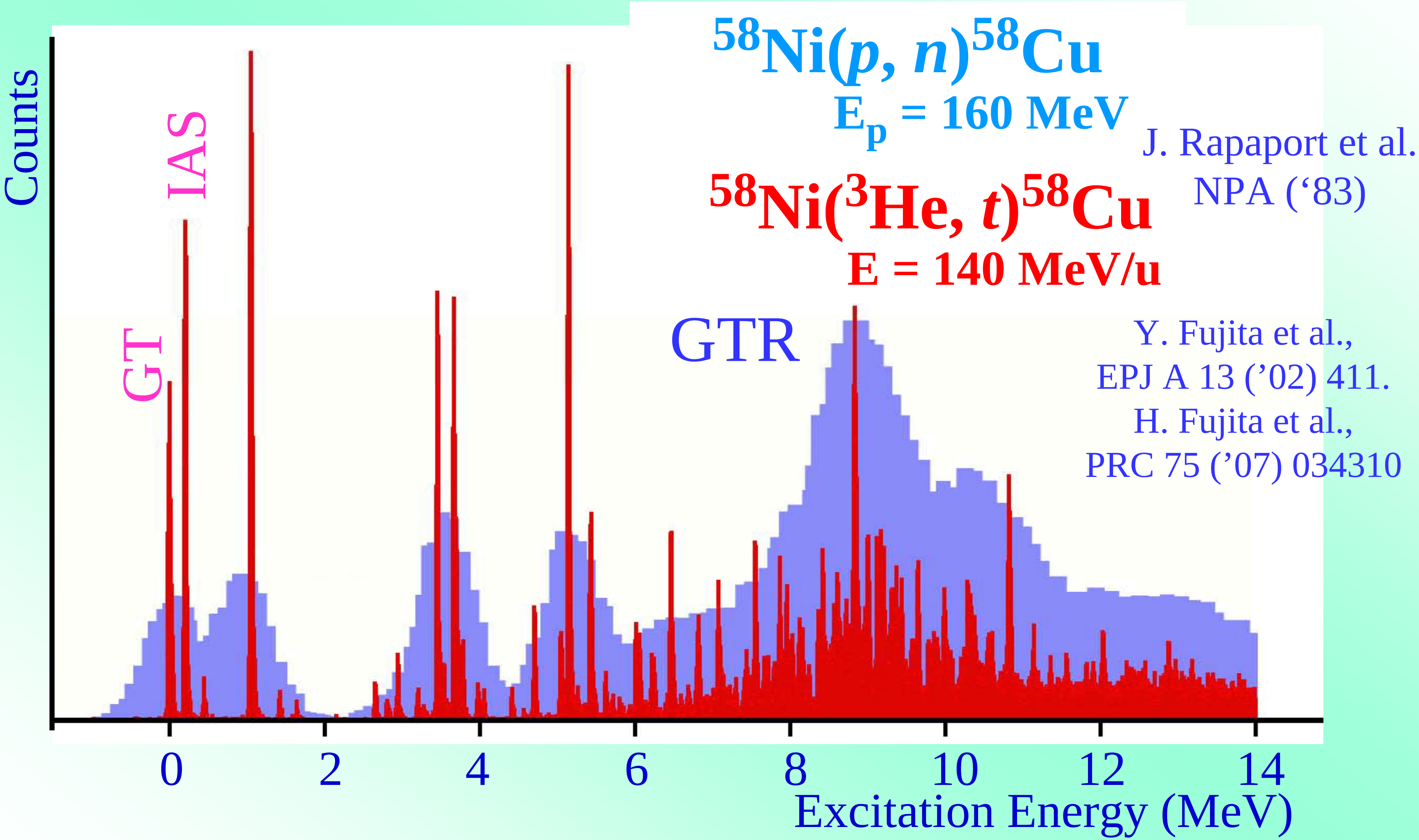
Comparison of (p, n) and (^{3}He,t) 0° spectra



J. Rapaport et al.
NPA ('83)

Y. Fujita et al.,
EPJ A 13 ('02) 411.
H. Fujita et al.,
PRC 75 ('07) 034310

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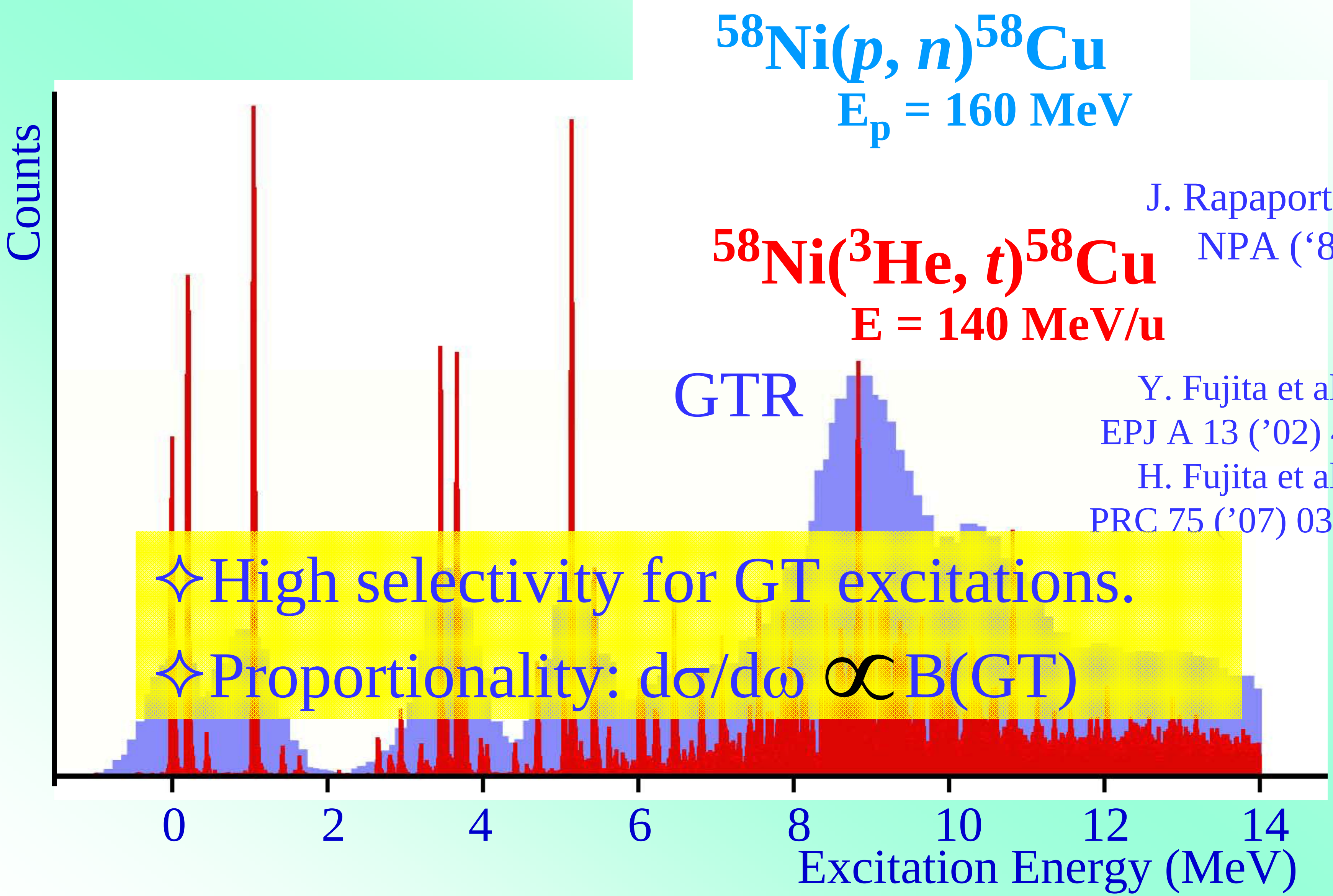

J. Rapaport et al.
NPA ('83)

Y. Fujita et al.,
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PRC 75 ('07) 034310

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

β-decay & Nuclear Reaction

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B(GT) : reduced GT transition strength

$\propto$ (matrix element)^2

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

= reaction mechanism

$\otimes$ operator

$\otimes$ structure

=(matrix element)^2

Study of Weak Response of Nuclei
by means of
Strong Interaction !
using β-decay as a reference

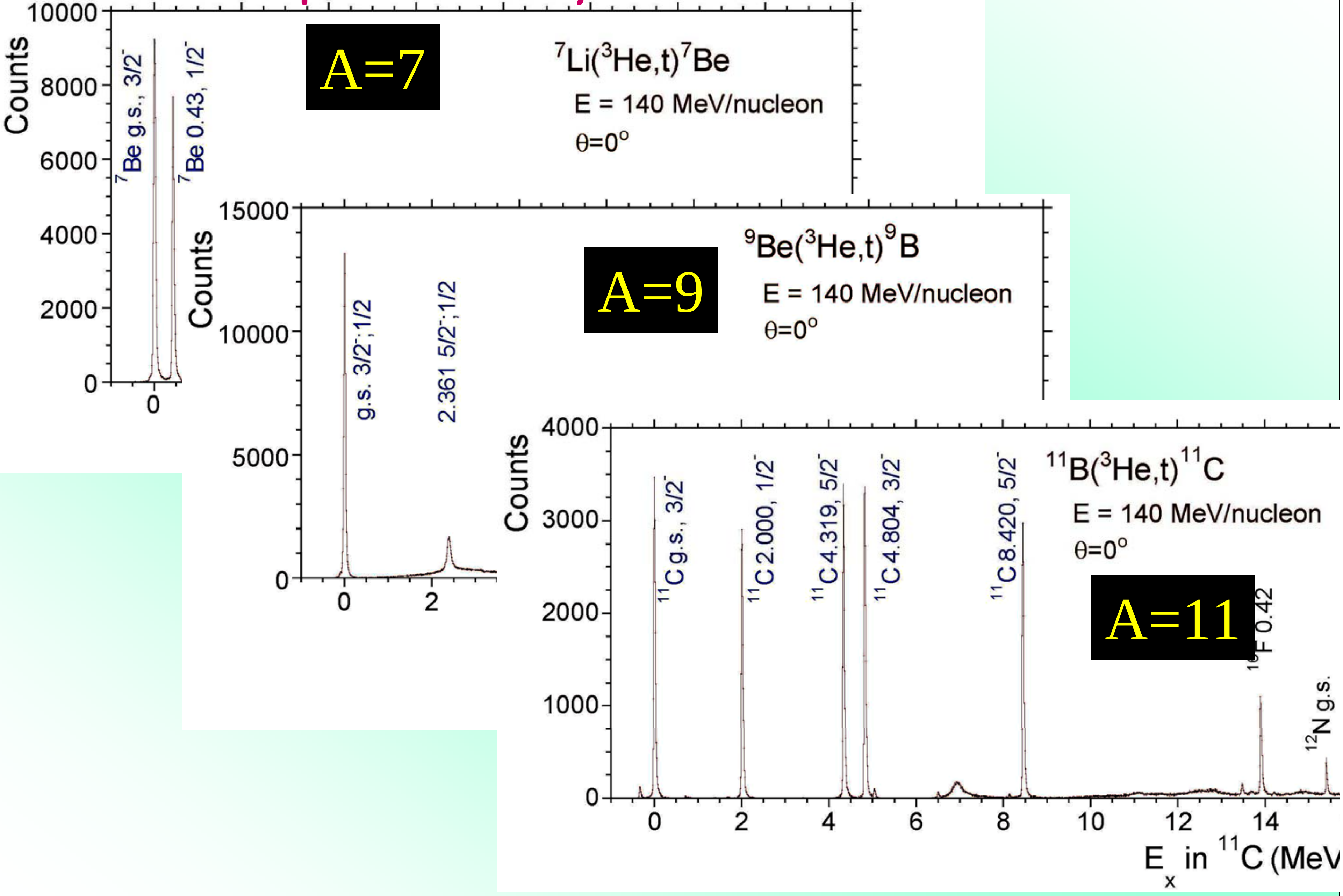
A simple reaction mechanism should be achieved !

→ we have to go to high incoming energy

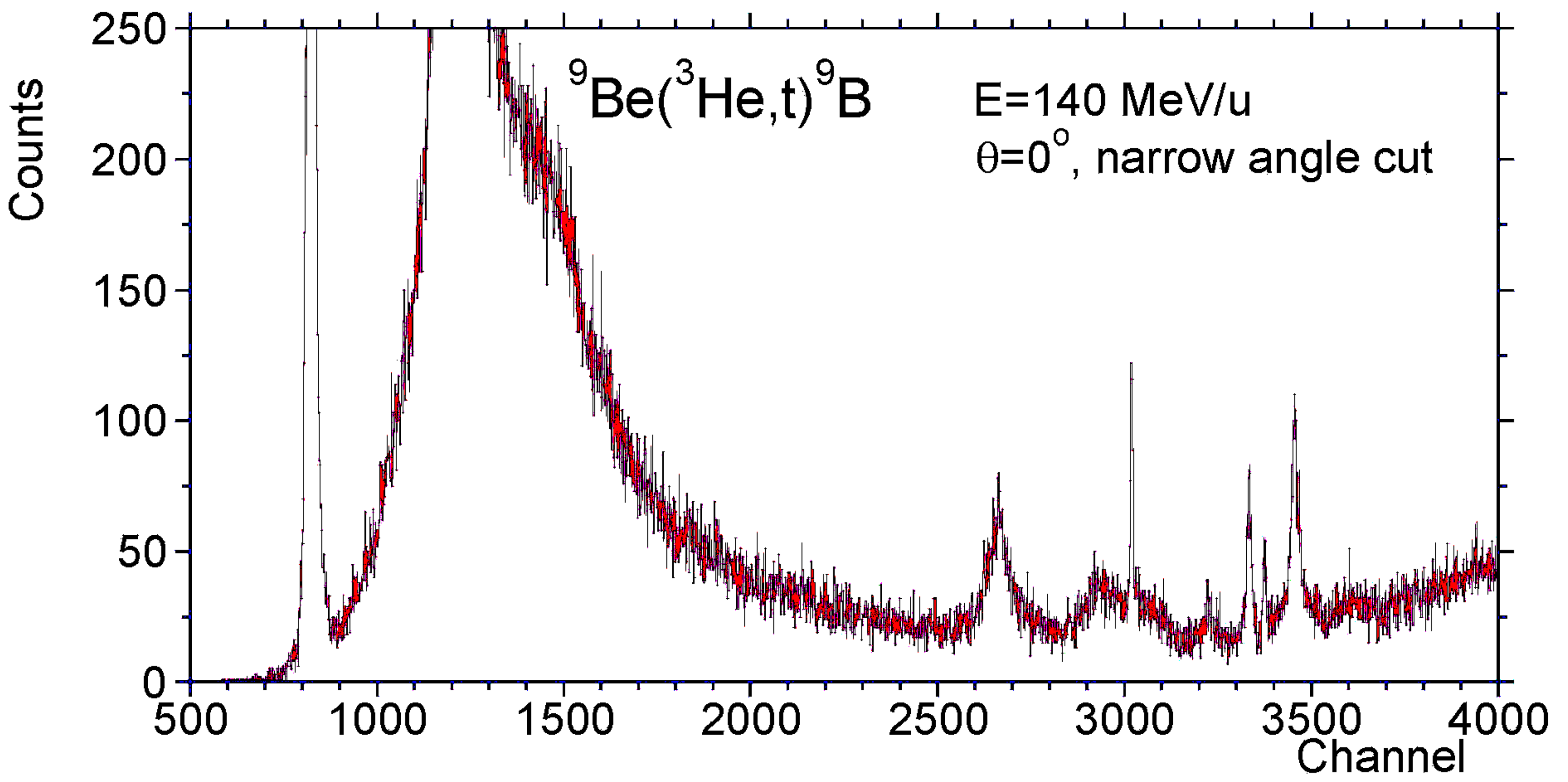
**GT transitions in each nucleus are UNIQUE !

***(^{3}He,t): high resolution and sensitivity !**

Spectra of *p*-shell Tz=1/2 Nuclei



$^{9}Be(^{3}He,t)^{9}B$ spectrum (various scales)



Relationship: Decay and Width

Heisenberg's Uncertainty Priciple

$$\Delta x \cdot \Delta p \approx \hbar$$

$$\boxed{\Delta t \cdot \Delta E \approx \hbar}$$

Width $\Gamma = \Delta E$

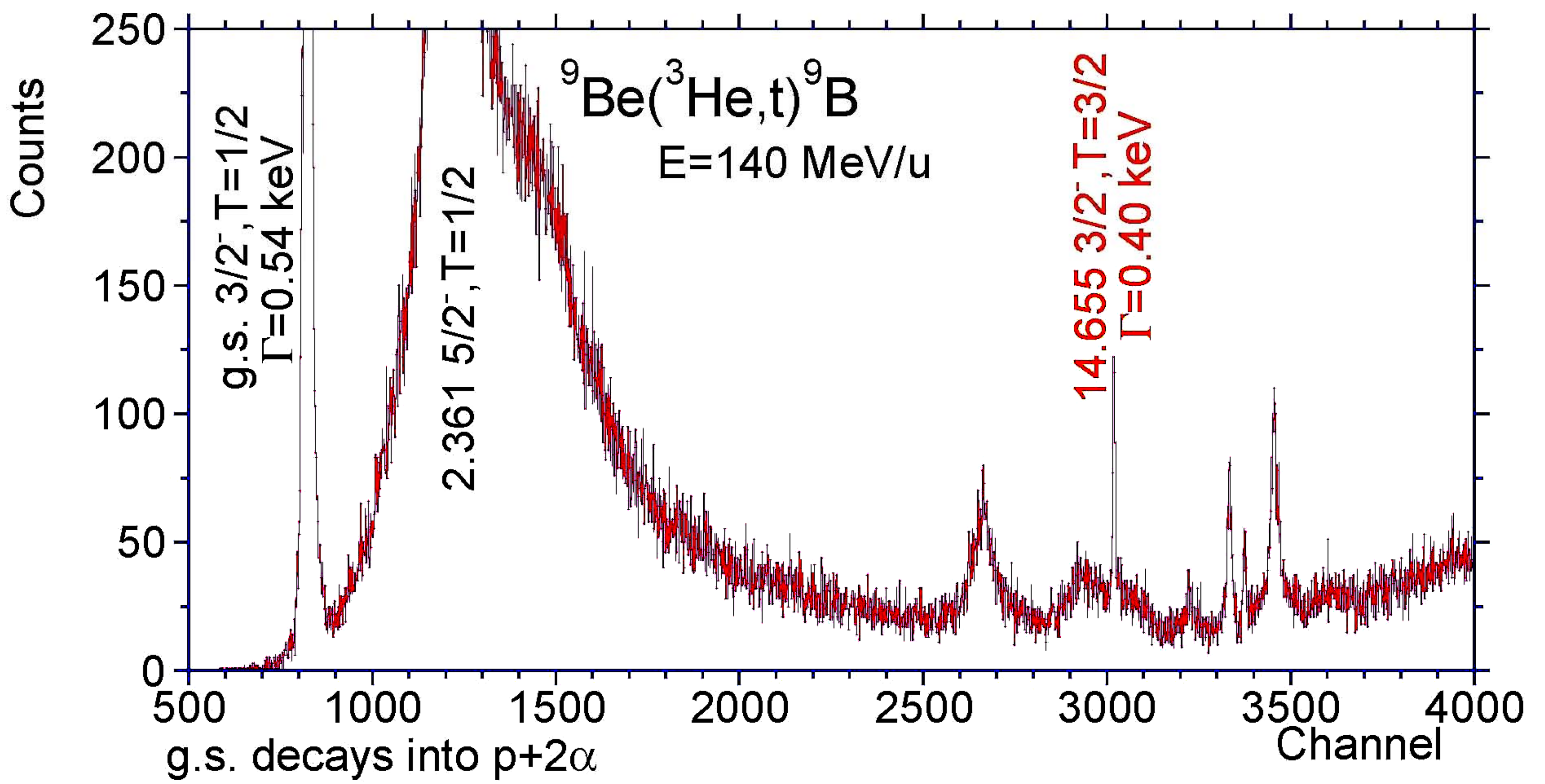
*if: Decay is Fast,

then: Width of a State is Wider !

*if $\Delta t = 10^{-20}$ sec → ΔE ~100 keV (particle decay)

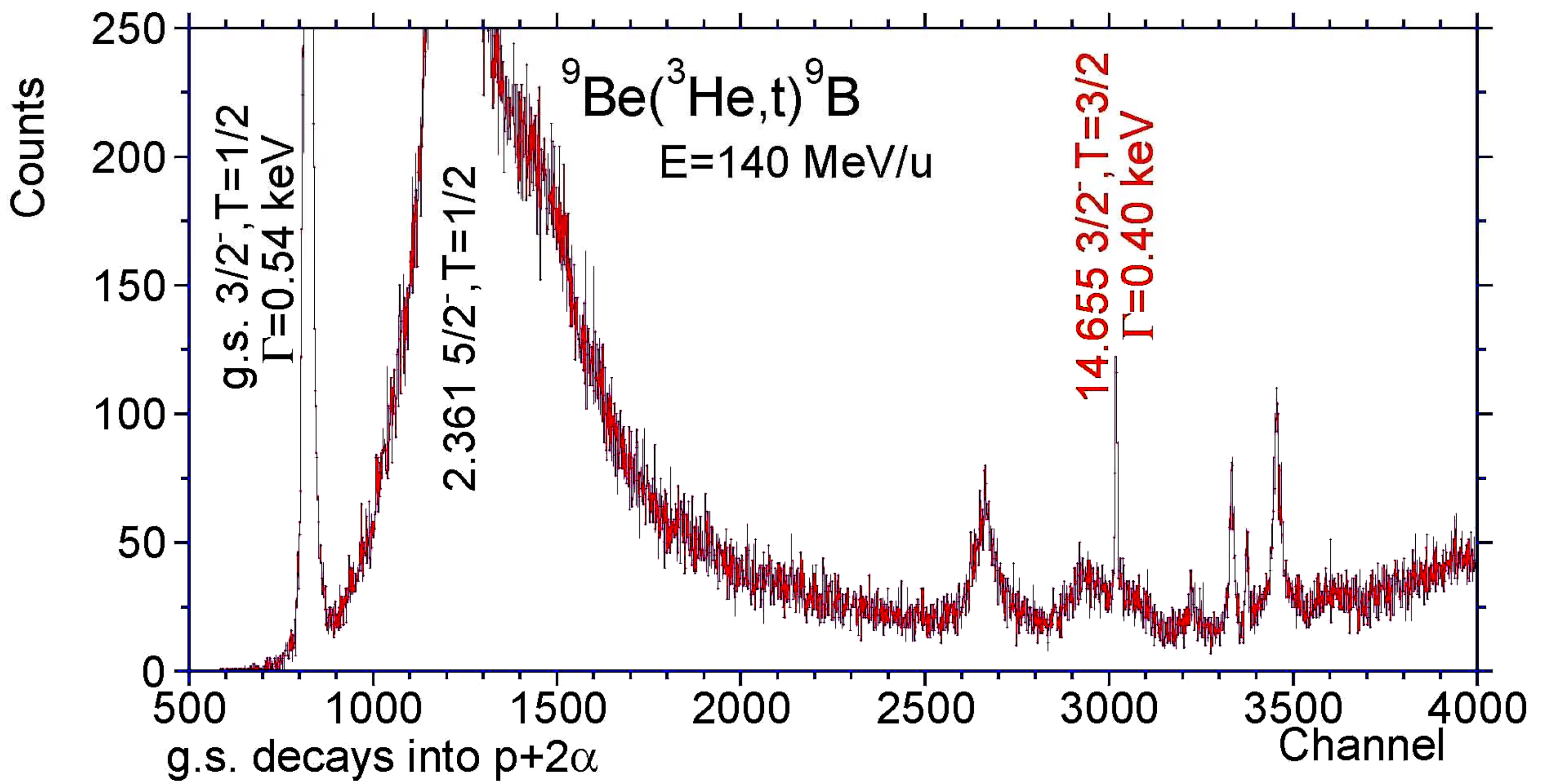
$\Delta t = 10^{-15}$ sec → ΔE ~ 1 eV (fast γ decay)

^{9}Be(^{3}He,t)^{9}B spectrum (II)



Isospin selection rule prohibits
proton decay of **T=3/2** state!

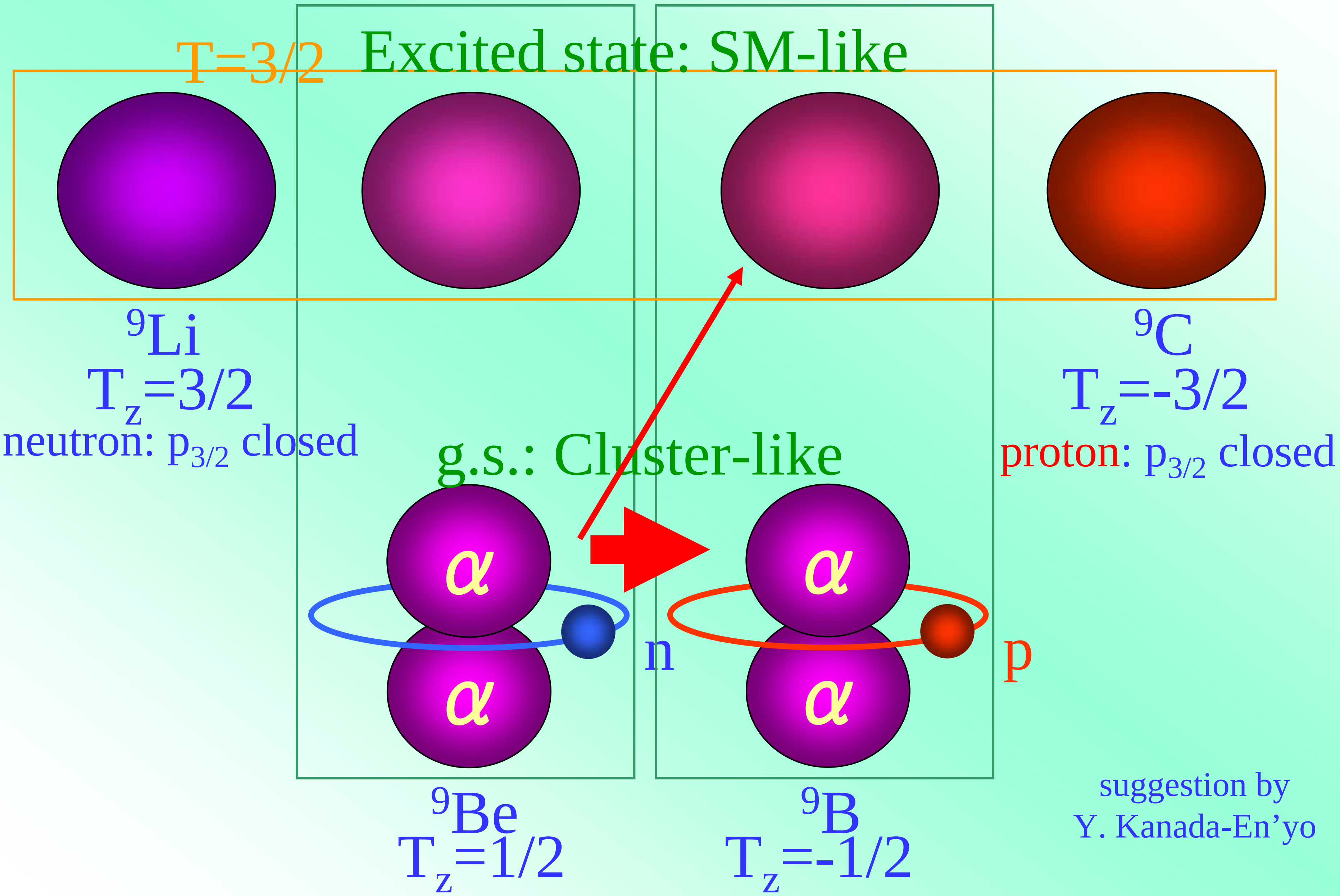
^{9}Be(^{3}He,t)^{9}B spectrum (III)



14.7 MeV T=3/2 state is very weak!

Strength ratio of g.s. & 14.7 MeV 3/2^{-} states: 140:1

Shell Structure and Cluster Structure



T=3/2

Excited state: SM-like

^{9}Li
$T_z=3/2$
neutron: $p_{3/2}$ closed

^{9}C
$T_z=-3/2$
proton: $p_{3/2}$ closed

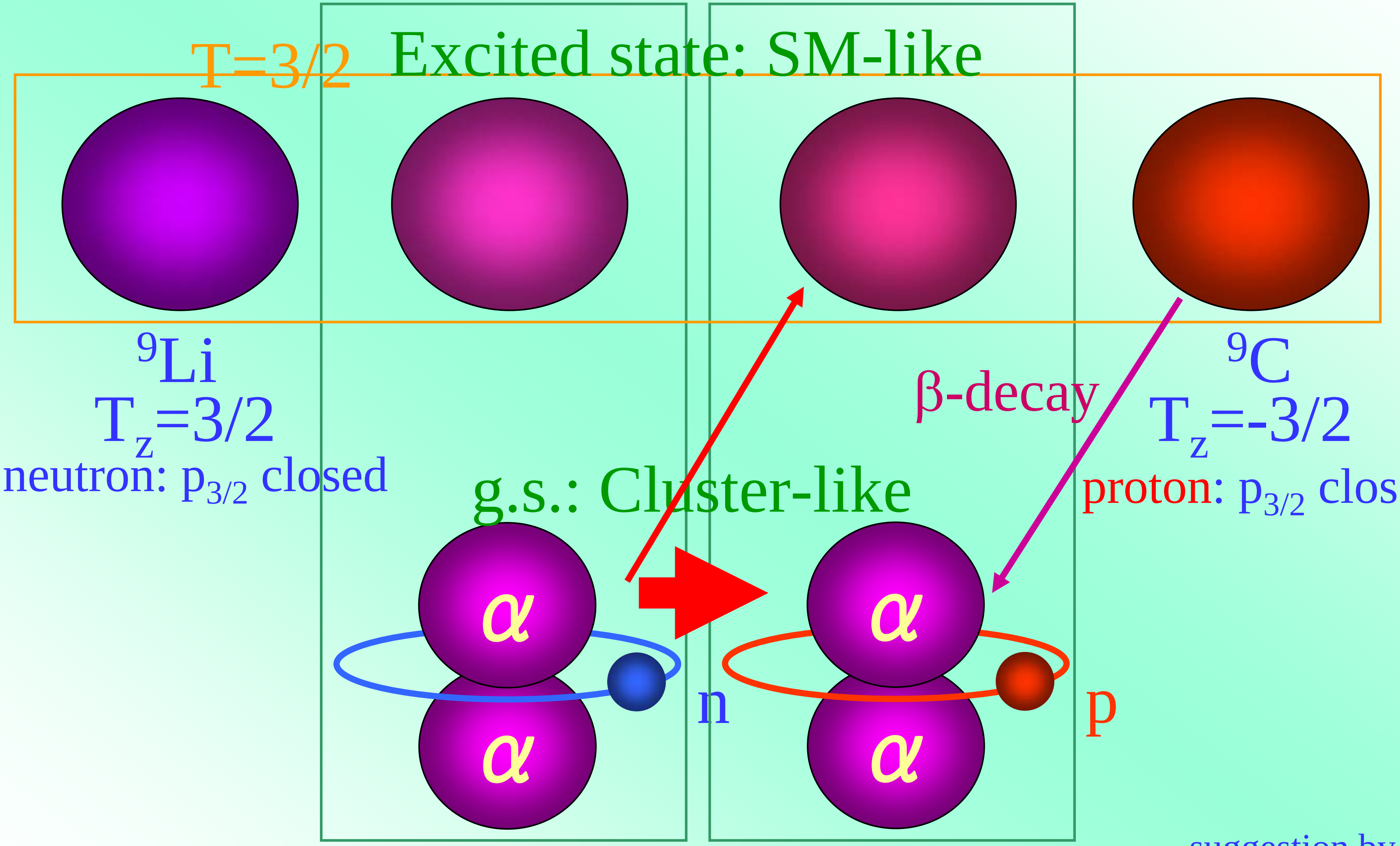
g.s.: Cluster-like

^{9}Be
$T_z=1/2$

^{9}B
$T_z=-1/2$

suggestion by
Y. Kanada-En'yo

Shell Structure and Cluster Structure



T=3/2 Excited state: SM-like

^{9}Li
T_z=3/2
neutron: $p_{3/2}$ closed

β-decay

^{9}C
T_z=-3/2
proton: $p_{3/2}$ closed

g.s.: Cluster-like

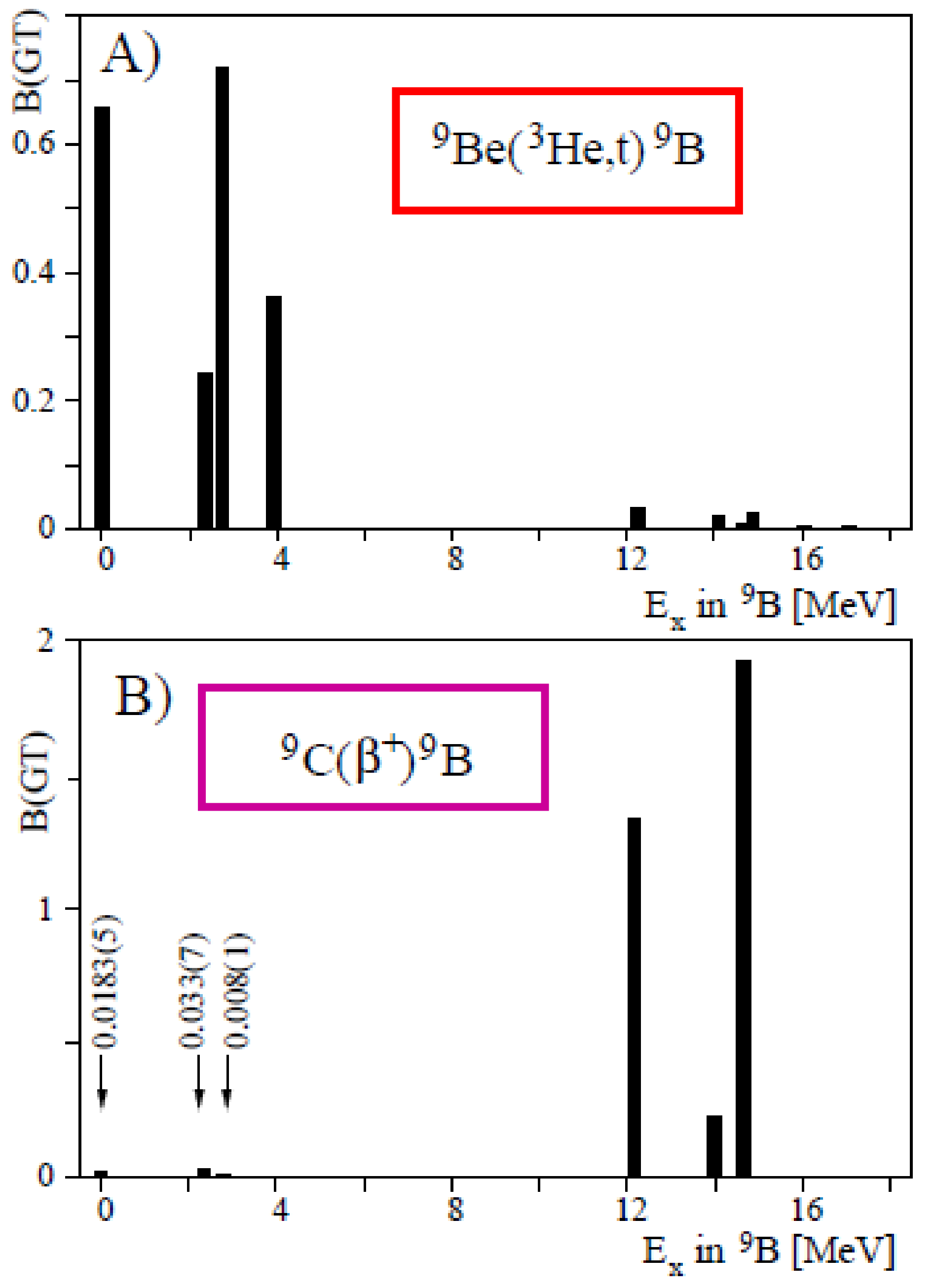
^{9}Be
T_z=1/2

^{9}B
T_z=-1/2

suggestion by
Y. Kanada-En'yo

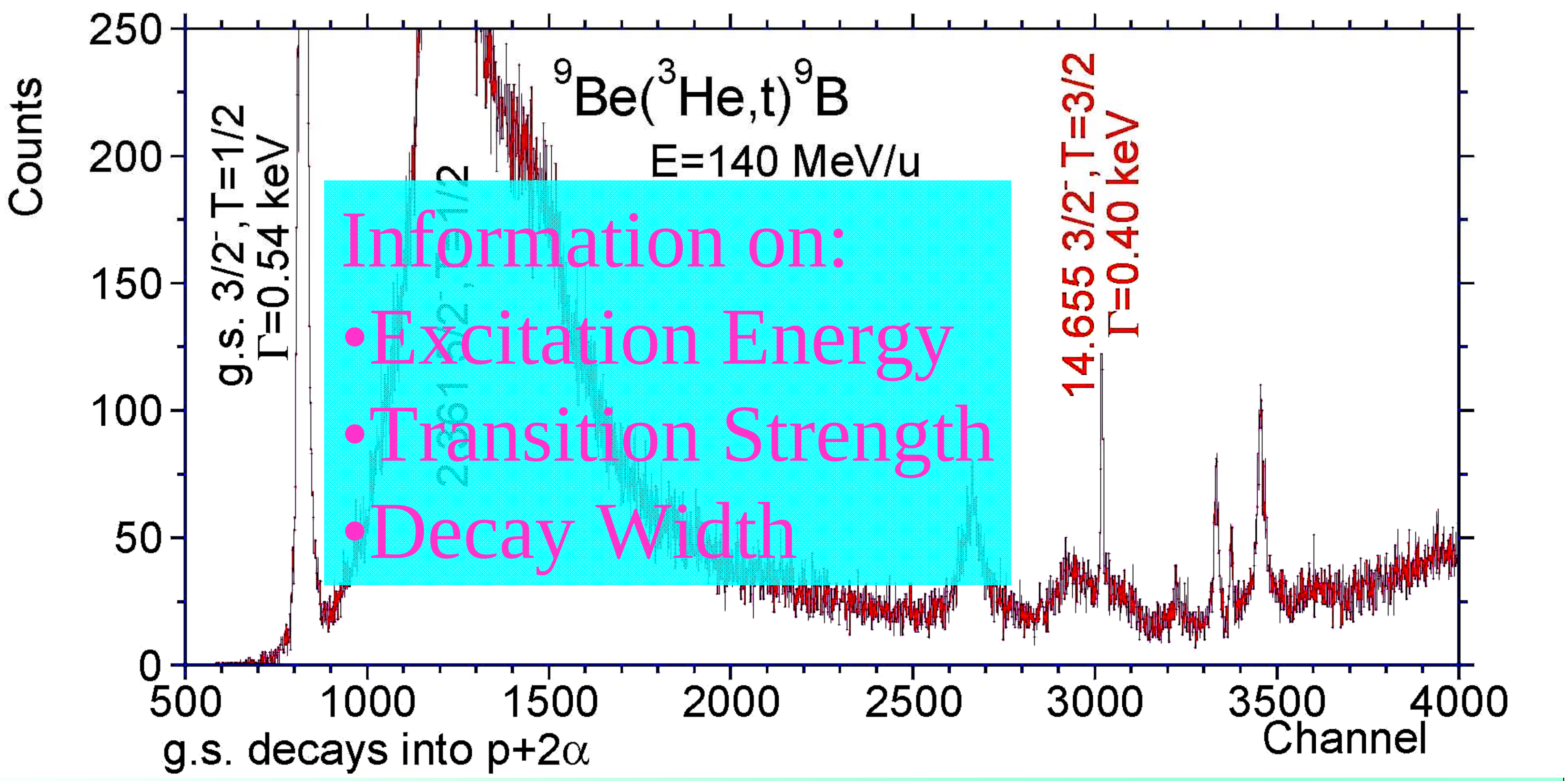
β-decay and (^{3}He,t) results

C. Scholl et al,
PRC 84, 014308 (2011)



L.Buchmann et al.,
PRC 63 (2001) 034303.
U.C.Bergmann et al.,
Nucl. Phys. A 692 (2001) 427.

^{9}Be(^{3}He,t)^{9}B spectrum (III)



Information on:

- Excitation Energy
- Transition Strength
- Decay Width

14.7 MeV T=3/2 state is very weak!

Strength ratio of g.s. & 14.7 MeV 3/2^{-} states: 140:1

Connection between β-decay and (^{3}He,t) reaction

by means of
Isospin Symmetry

***Isospin Symmetry

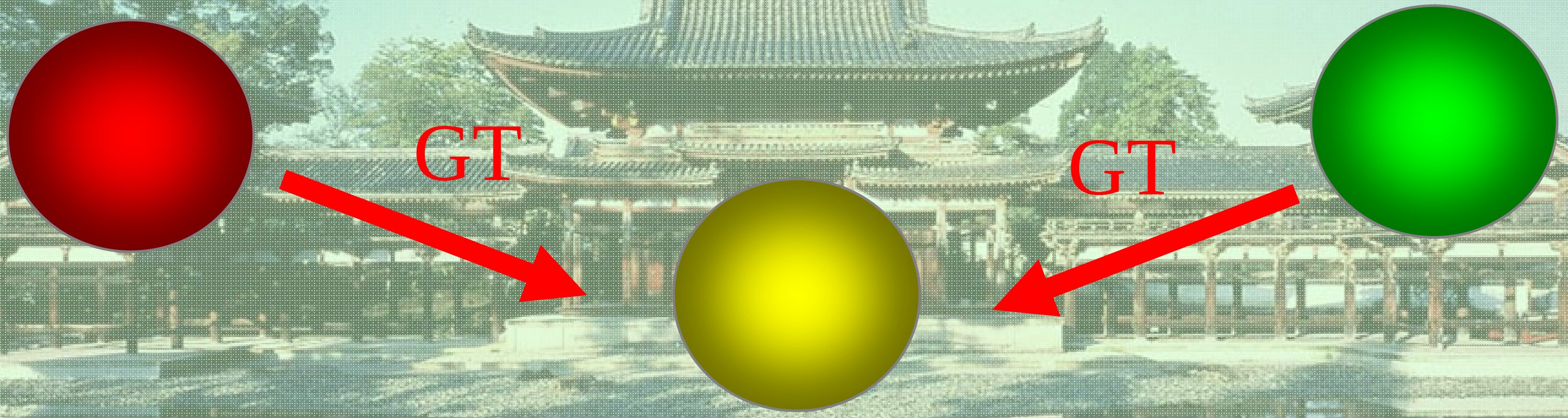
an important idea to see the connection of
decays and excitations caused
by Strong, EM and Weak interactions !

There are many cases that the "operators" are the same
in transitions caused by "strong," "EM" and "weak" int.

T=1 Isospin Symmetry

Byodoin-temple,
Uji, Kyoto

T=1 Isospin Symmetry



$^{26}_{12}Mg_{14}$

$T_z= +1$

$^{26}_{13}Al_{13}$

$T_z= 0$

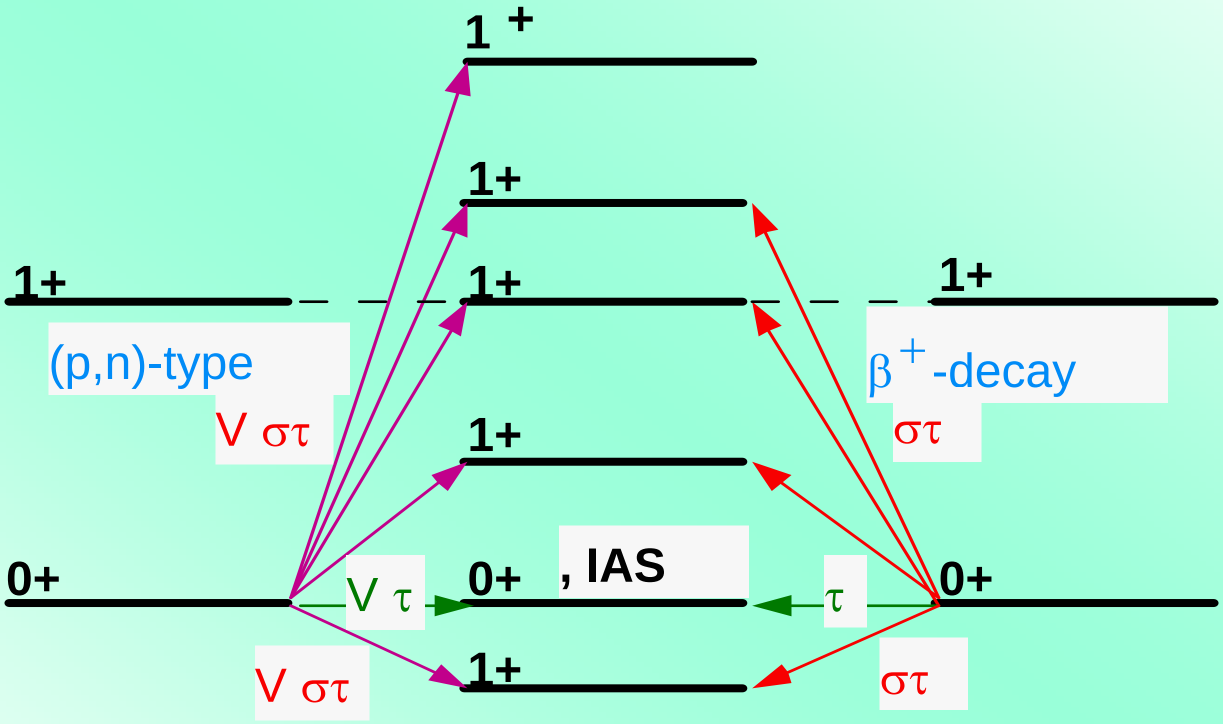
$^{26}_{14}Si_{12}$

$T_z= -1$

T=1 symmetry : Structures & Transitions

T_z=+1 → T_z=0 ← T_z=-1

(in isospin symmetry space*)



1 +

1+

1+ 1+ 1+

(p,n)-type

V στ

β^+-decay

στ

1+

0+ V τ 0+ , IAS τ 0+

1+

V στ

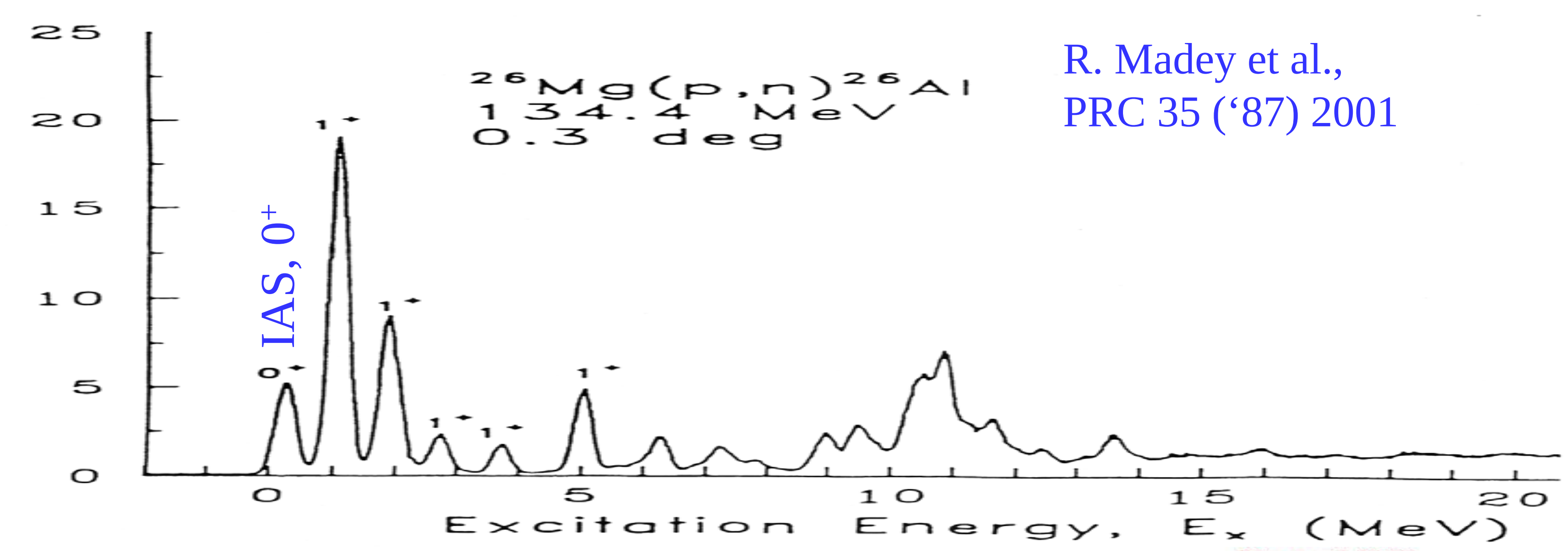
στ

T_z=+1 T_z=0 T_z=-1

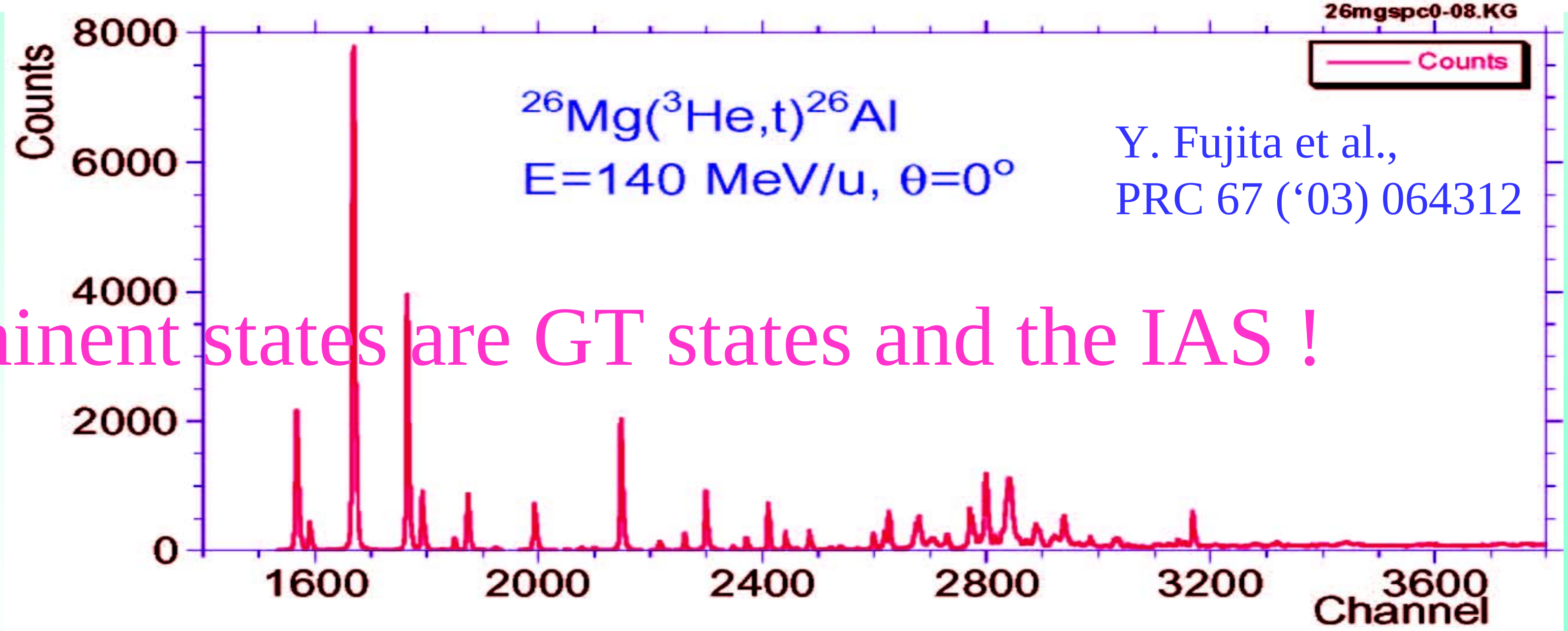
^{26}Mg ^{26}Al ^{26}Si

Z=12, N=14 Z=13, N=13 Z=14, N=12

^{26}Mg(p, n)^{26}Al & ^{26}Mg(^{3}He,t)^{26}Al spectra



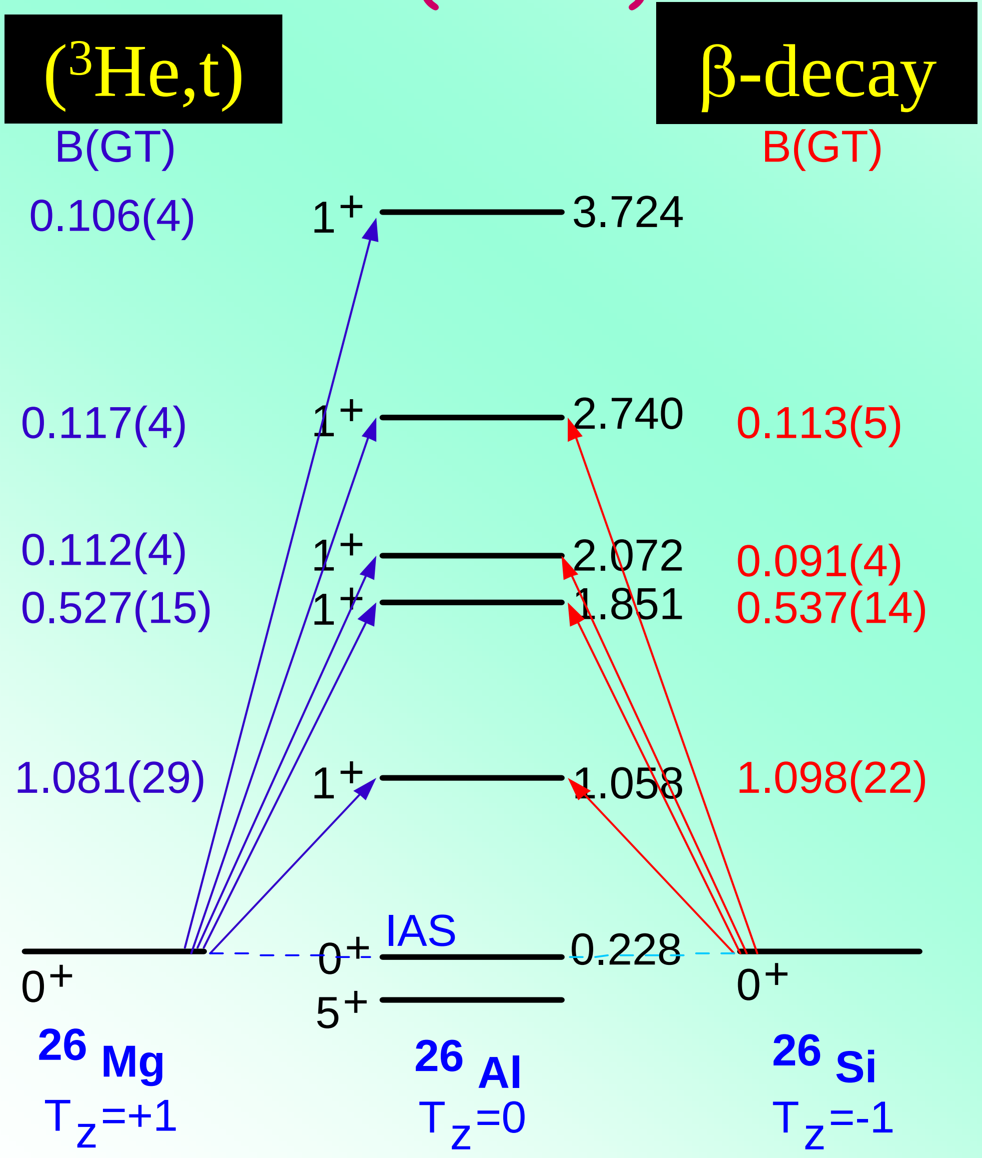
R. Madey et al.,
PRC 35 (‘87) 2001



Y. Fujita et al.,
PRC 67 (‘03) 064312

Prominent states are GT states and the IAS !

B(GT) values from Symmetry Transitions (A=26)



(^{3}He,t)

β-decay

B(GT)

B(GT)

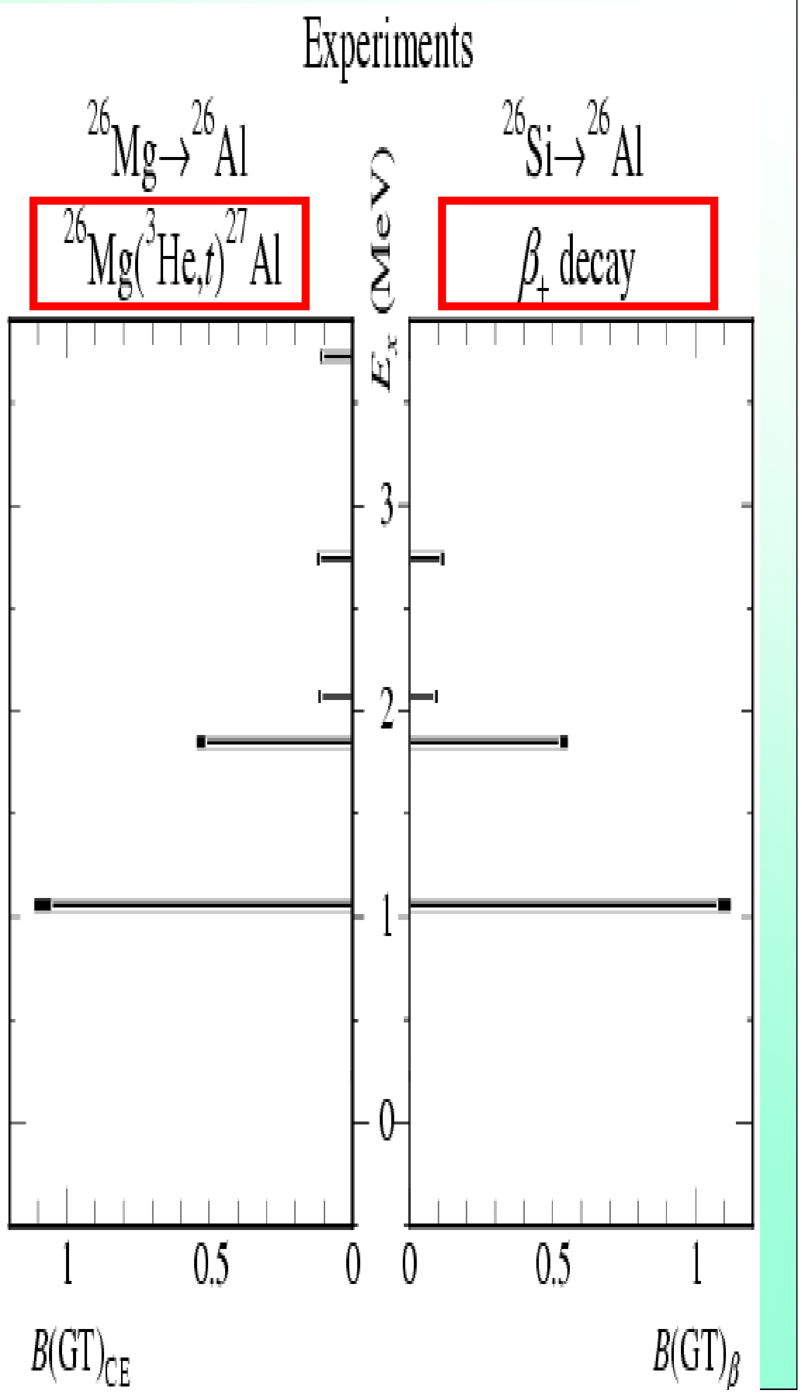
B(GT) (^{3}He,t)	J^π	E_x	B(GT) β-decay
0.106(4)	1^+	3.724	
0.117(4)	1^+	2.740	0.113(5)
0.112(4)	1^+	2.072	0.091(4)
0.527(15)	1^+	1.851	0.537(14)
1.081(29)	1^+	1.058	1.098(22)
	0^+ IAS	0.228	
	5^+		

0^+ **26 Mg** T_z=+1

26 Al T_z=0

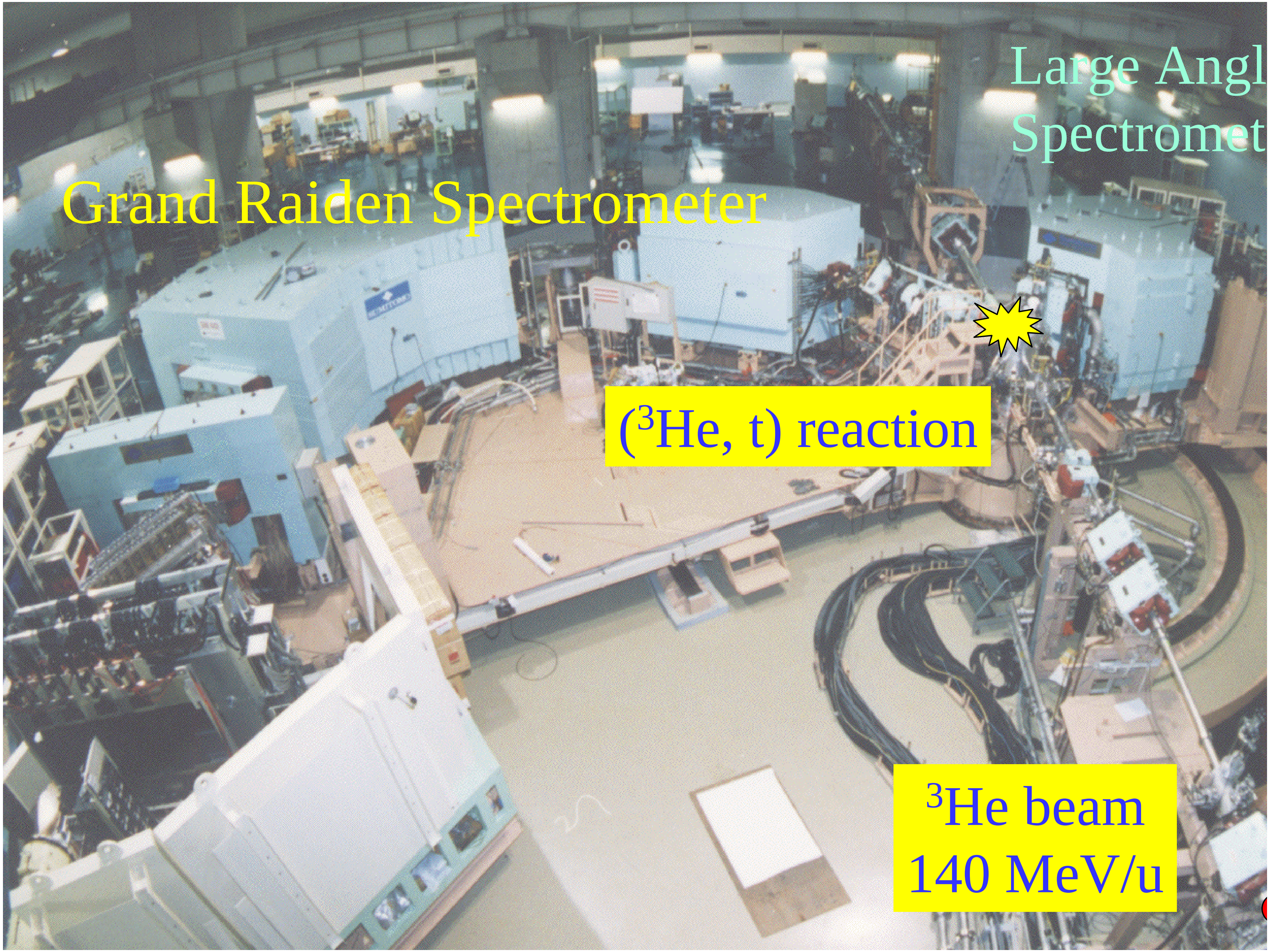
0^+ **26 Si** T_z=-1

Y. Fujita et al., PRC 67 (‘03) 064312



RCNP (Osaka) Ring Cyclotron

Good quality ^{3}He beam (140 MeV/nucleon)



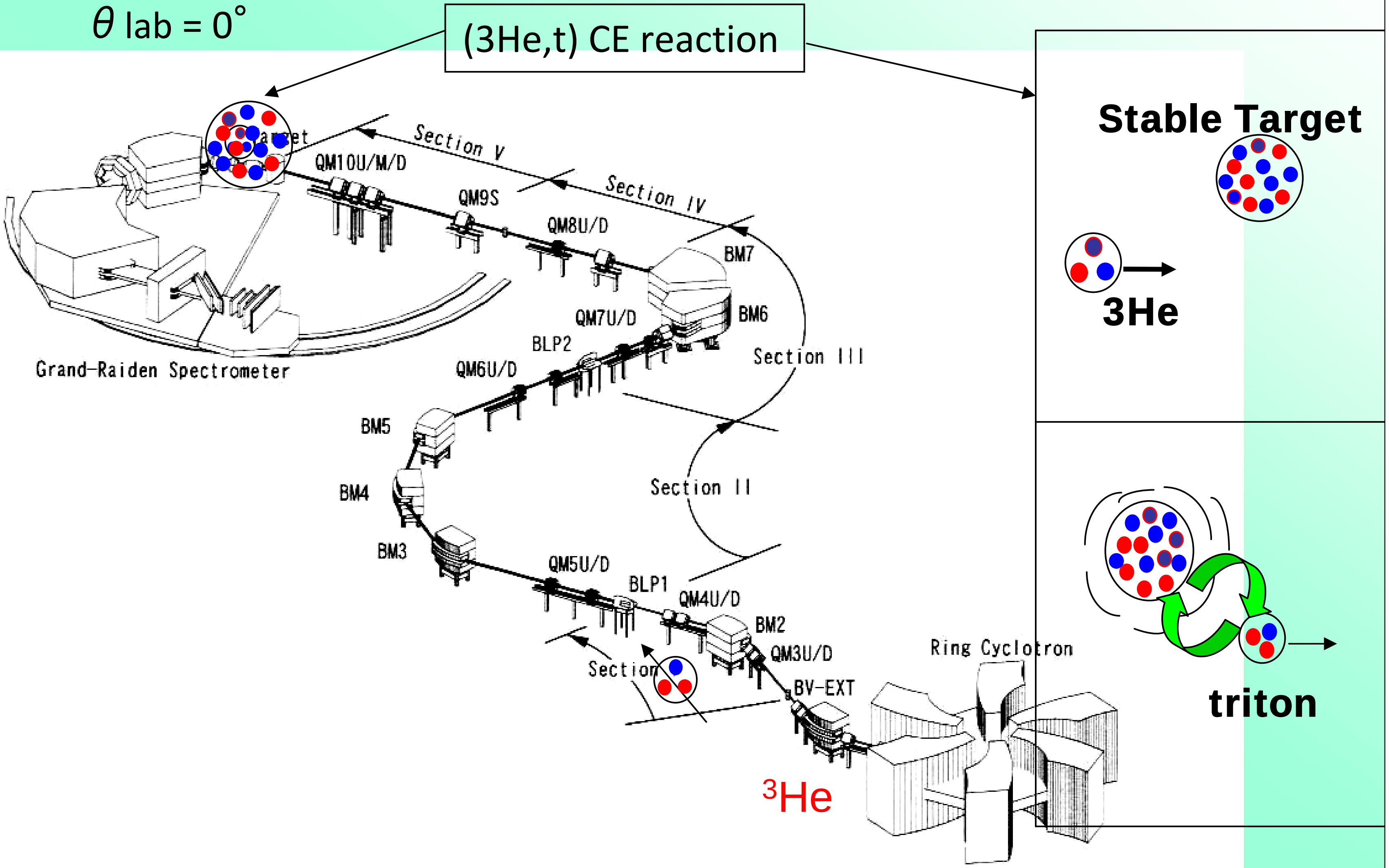
Grand Raiden Spectrometer

Large Angl
Spectromet

(^{3}He, t) reaction

^{3}He beam
140 MeV/u

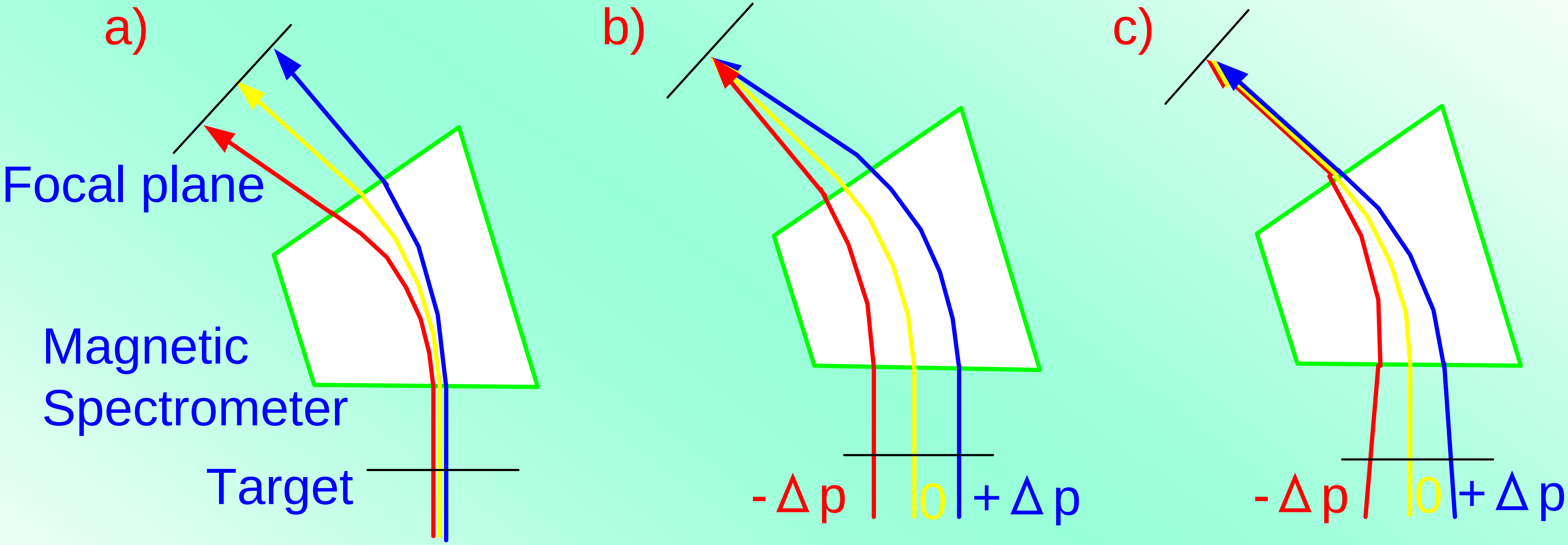
(^{3}He,t) CE Reactions @ RCNP (Osaka)



Matching Techniques

Y. Fujita et al., N.I.M. B 126 (1997) 274.

H. Fujita et al., N.I.M. A 484 (2002) 17.



Achromatic beam transportation

$\Delta E \sim 200$ keV
for 140MeV/u ^{3}He beam

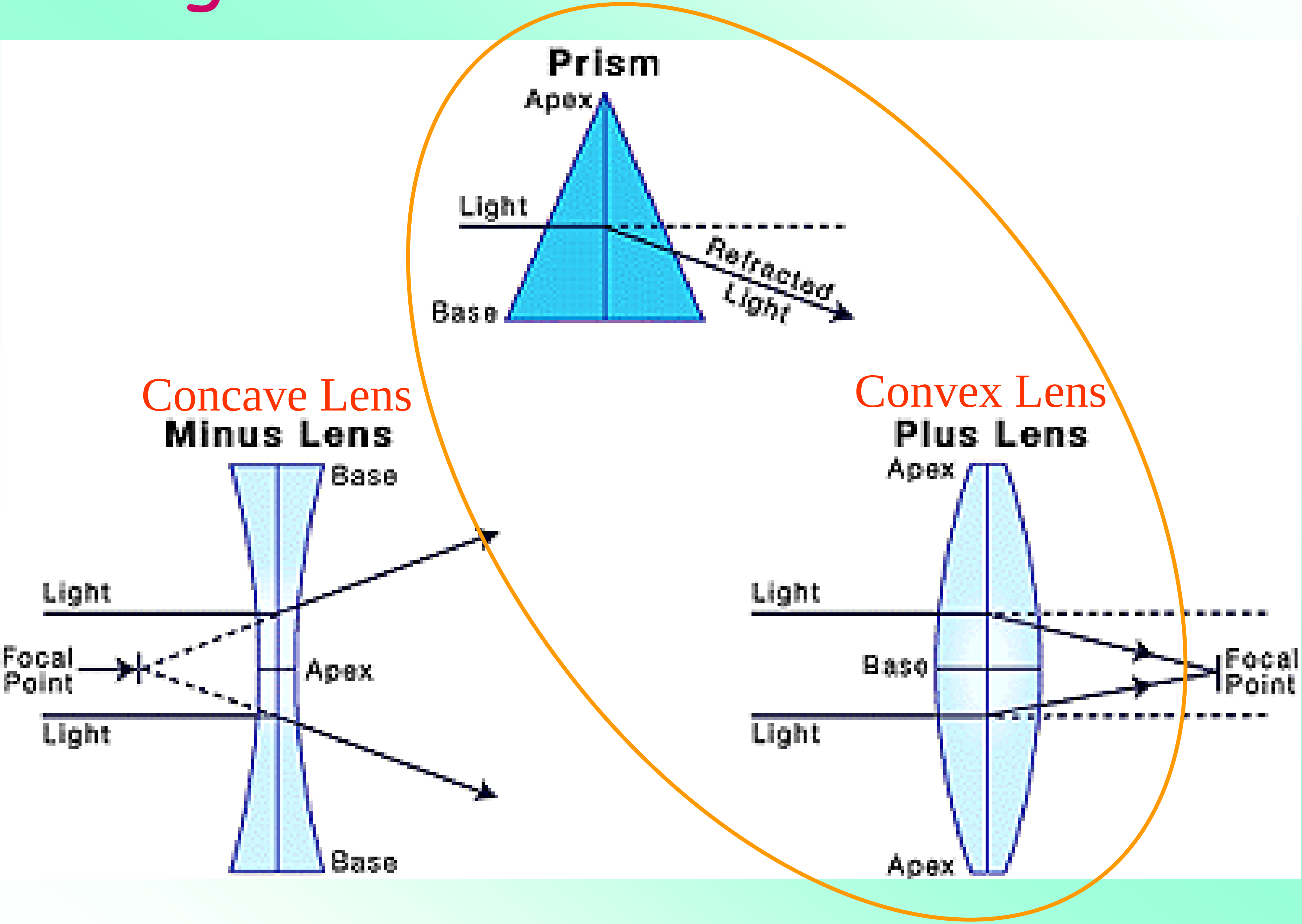
Lateral dispersion matching

$\Delta E \sim 35$ keV
Horiz. angle resolution
$\Delta\theta_{sc} > 15$mrad

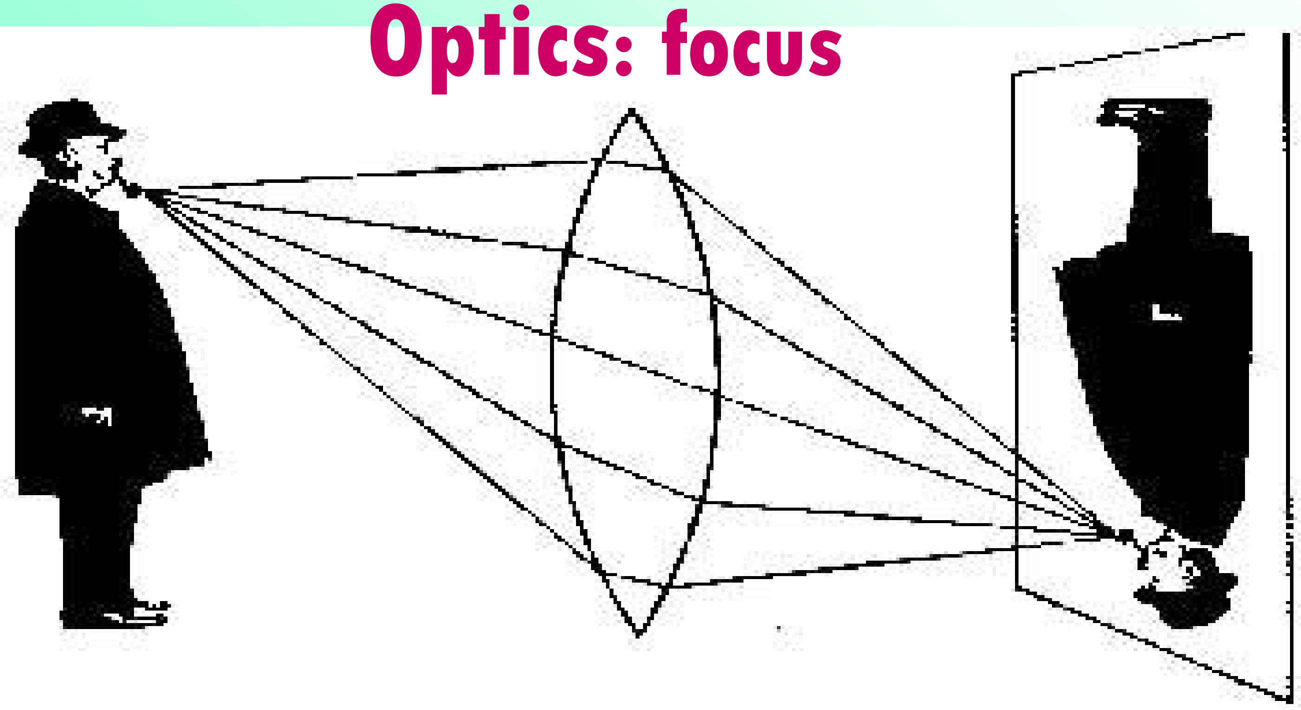
Angular dispersion matching

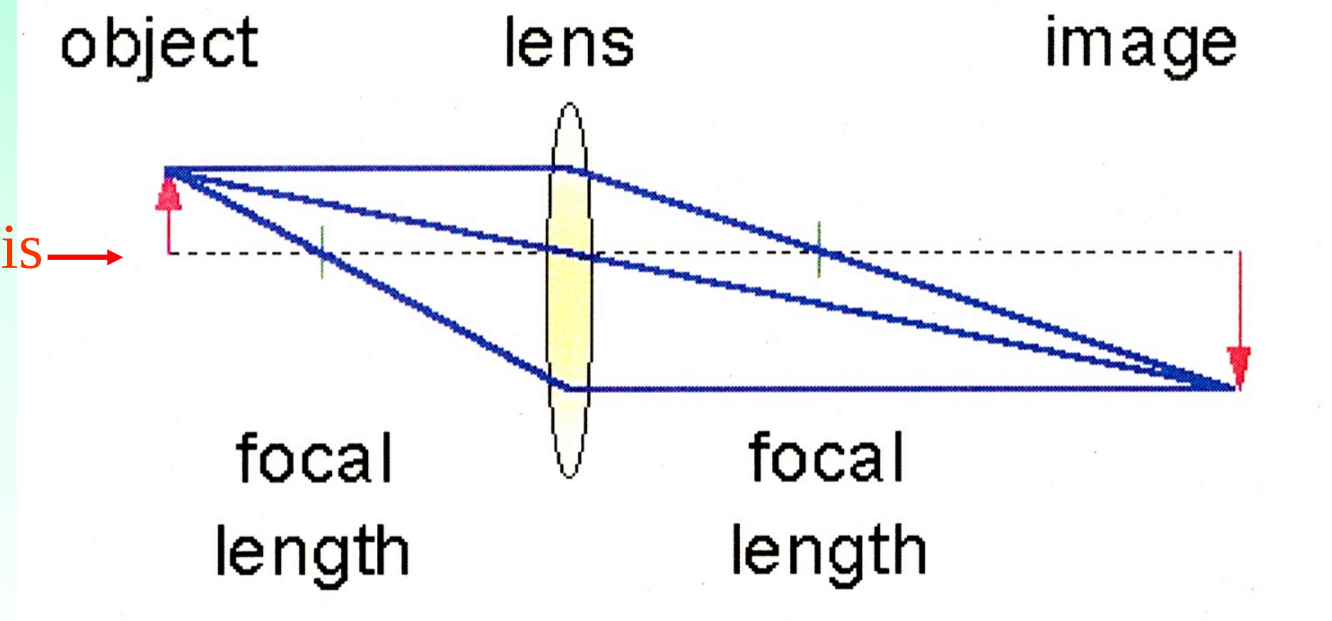
$\Delta\theta_{sc} \sim 5$mrad

Magnet= Convex Lens + Prism



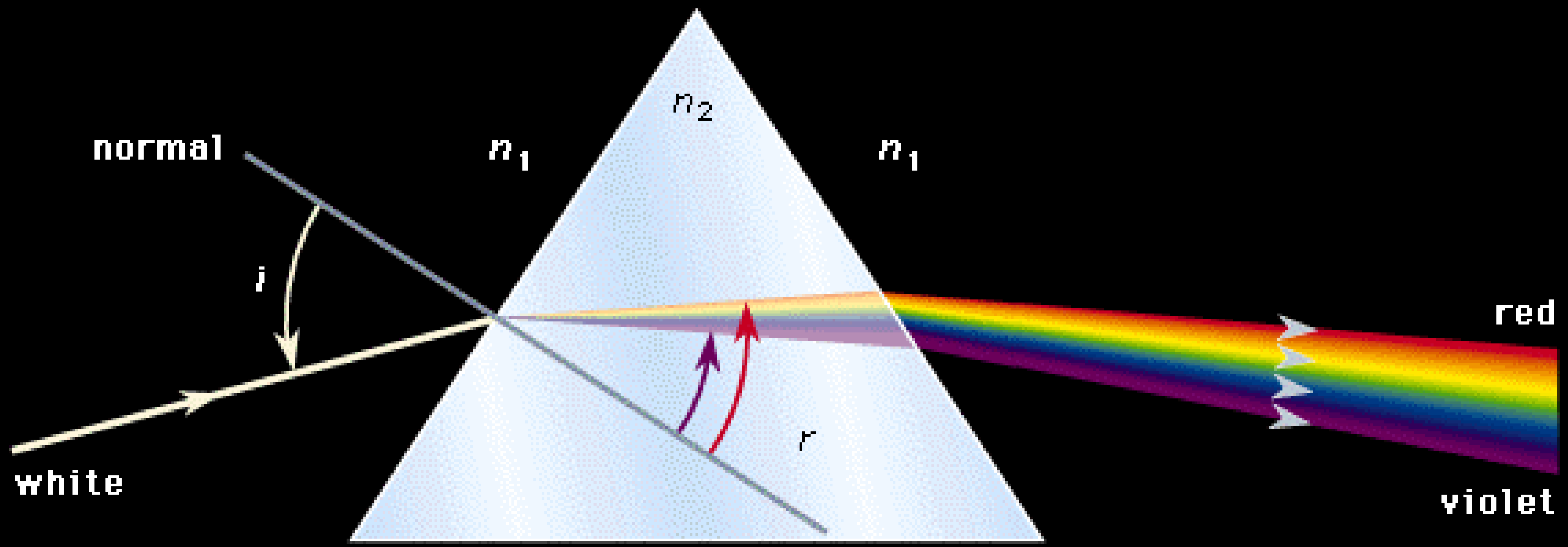
Optics: focus





lens axis→

Prism

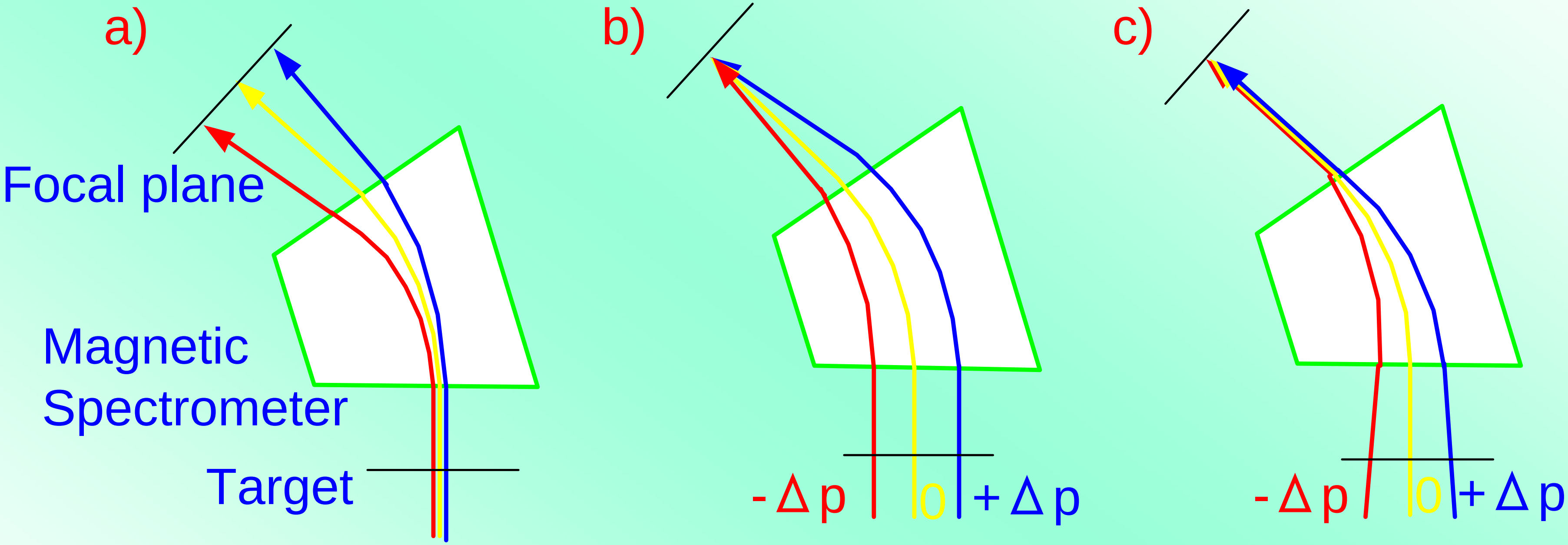


The angles i and r that the rays make with the normal are the angles of incidence and refraction. Because n_2 depends upon wavelength, the incident white ray separates into its constituent colours upon refraction, with deviation of the red ray the least and the violet ray the most.

Matching Techniques

Y. Fujita et al., N.I.M. B 126 (1997) 274.

H. Fujita et al., N.I.M. A 484 (2002) 17.



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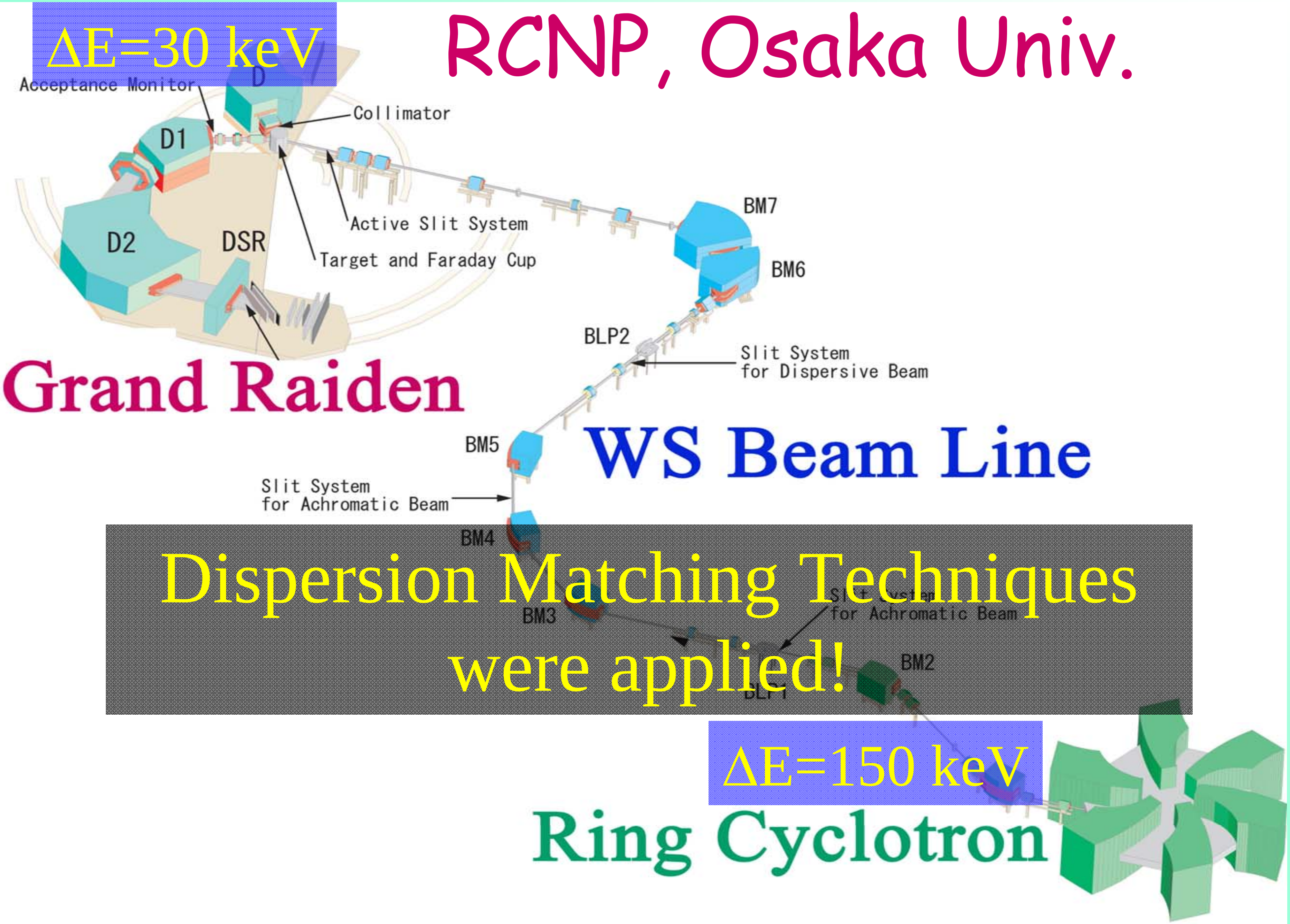
RCNP, Osaka Univ.

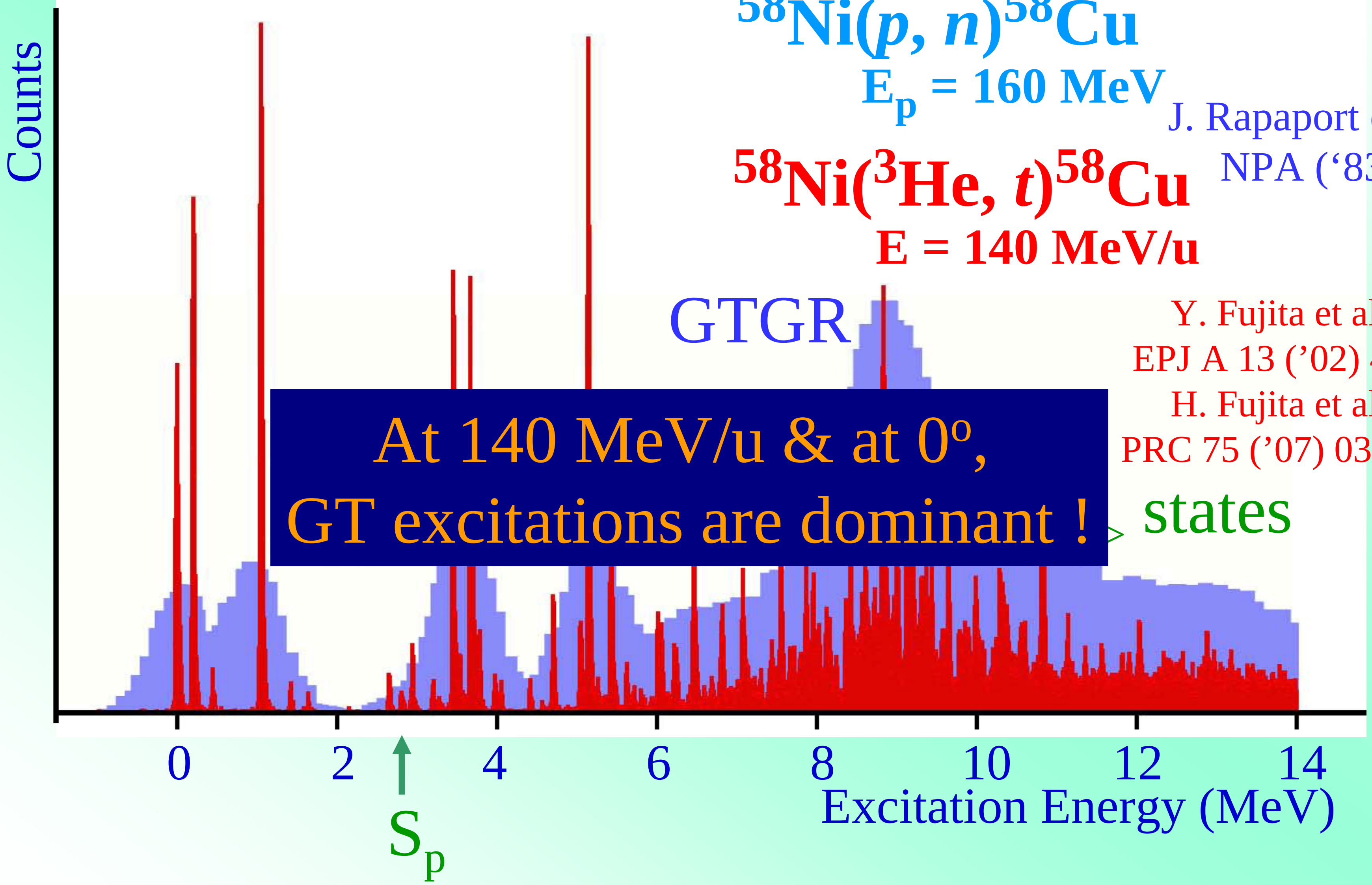


ΔE=30 keV

Dispersion Matching Techniques
were applied!

ΔE=150 keV

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



^{58}Ni(*p*, *n*)^{58}Cu
E_p = 160 MeV

J. Rapaport et al.
NPA (‘83)

^{58}Ni(^{3}He, *t*)^{58}Cu
E = 140 MeV/u

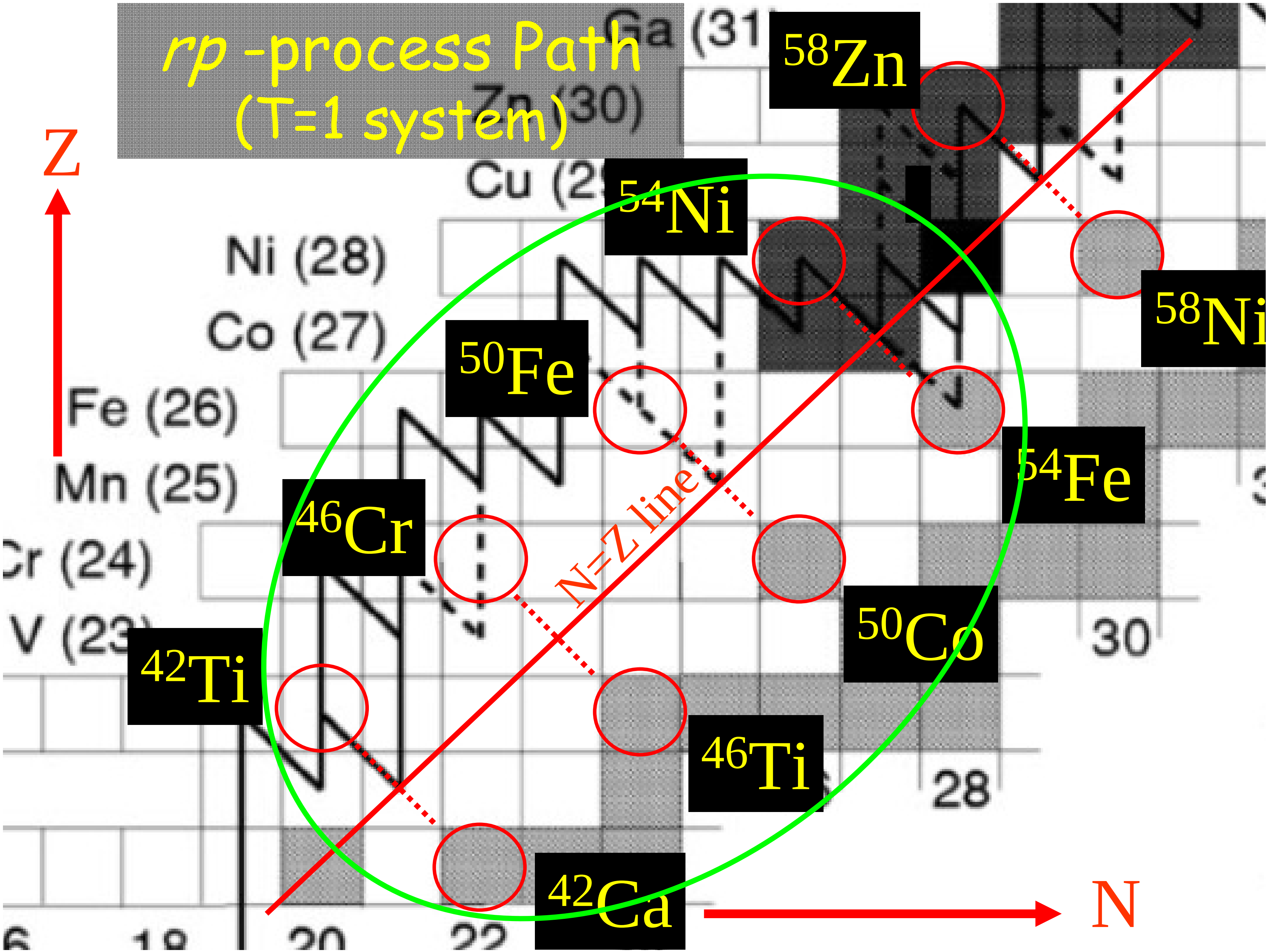
Y. Fujita et al.,
EPJ A 13 (’02) 411.
H. Fujita et al.,
PRC 75 (’07) 034310

At 140 MeV/u & at 0°,
GT excitations are dominant !

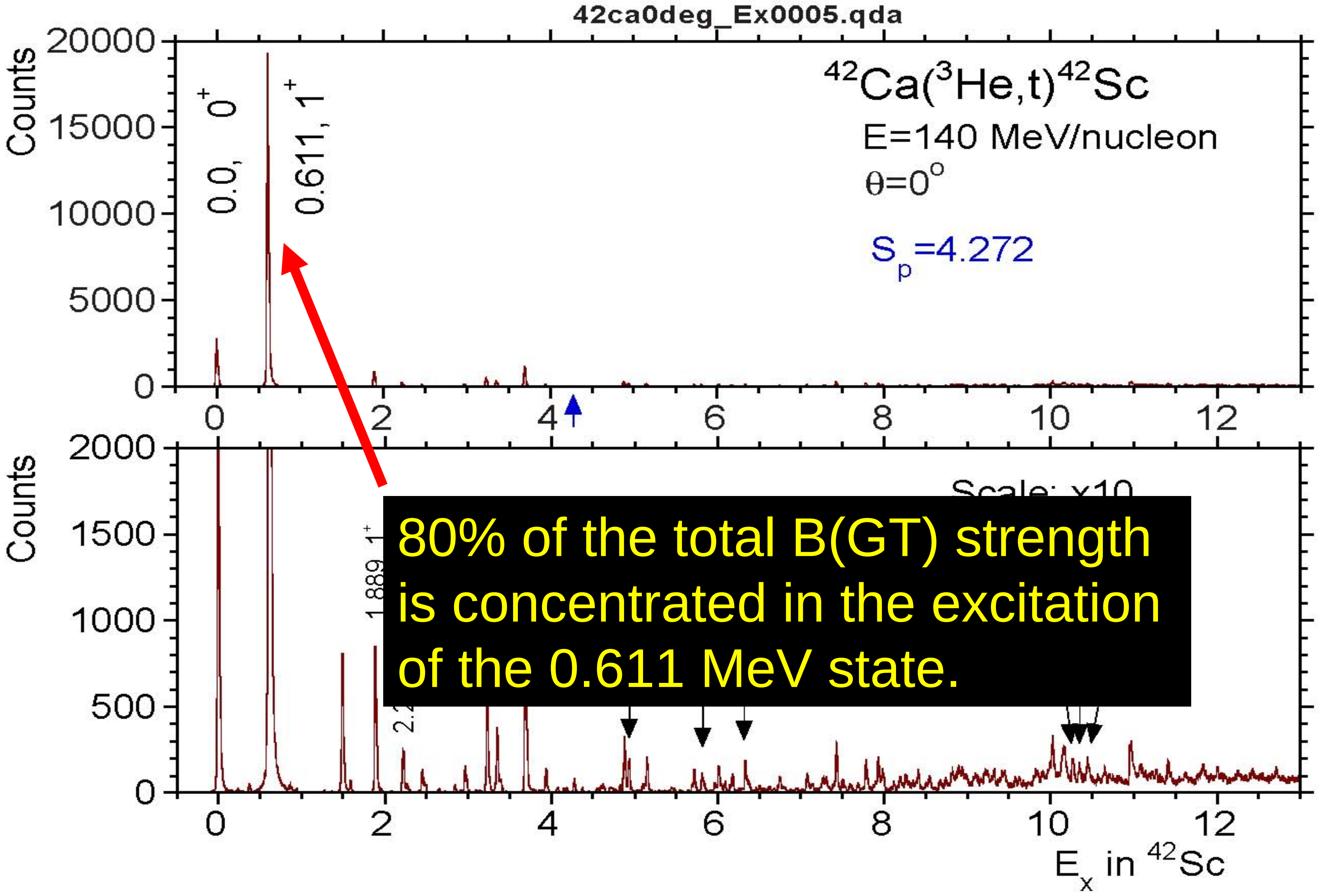
**GT transitions in each nucleus are UNIQUE !

- *pf*-shell nuclei -

rp -process Path (T=1 system)

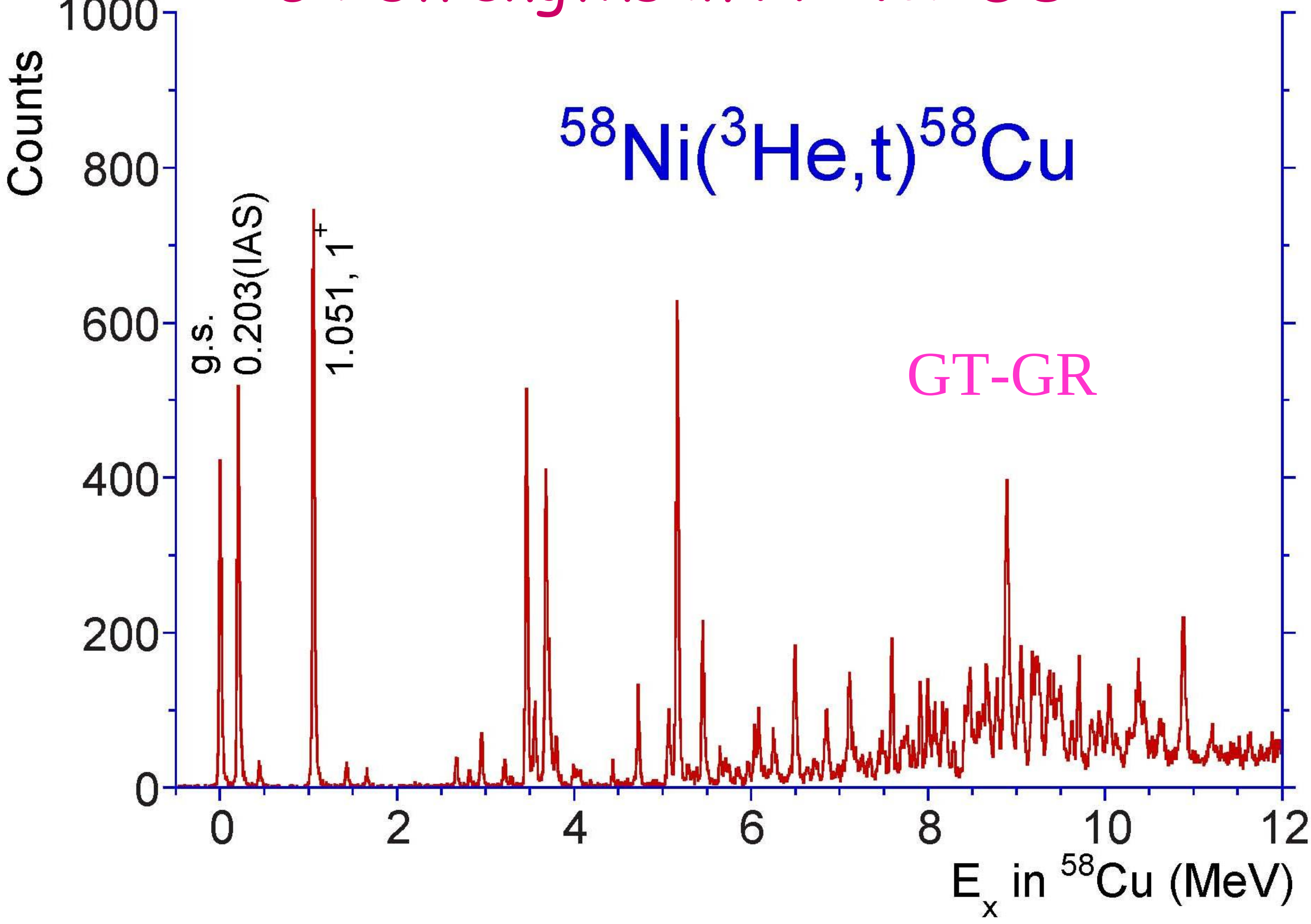


$^{42}Ca(^3He,t)^{42}Sc$ in 2 scales



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

GT strengths in *A*=42-58

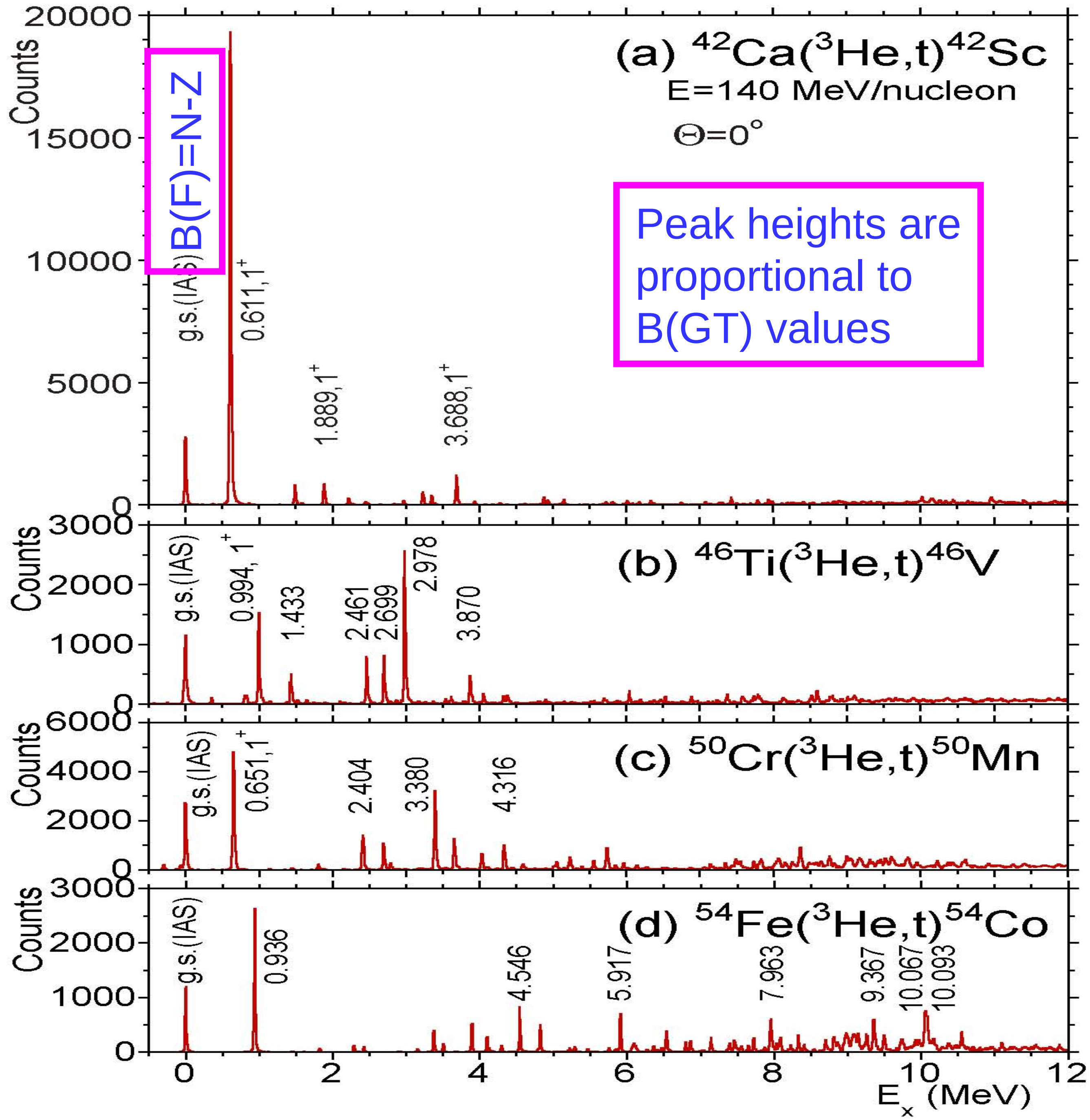


GT states in A=42-54 T_z=0 nuclei

T. Adachi et al.
PRC '06

Y. Fujita et al.
PRL '05

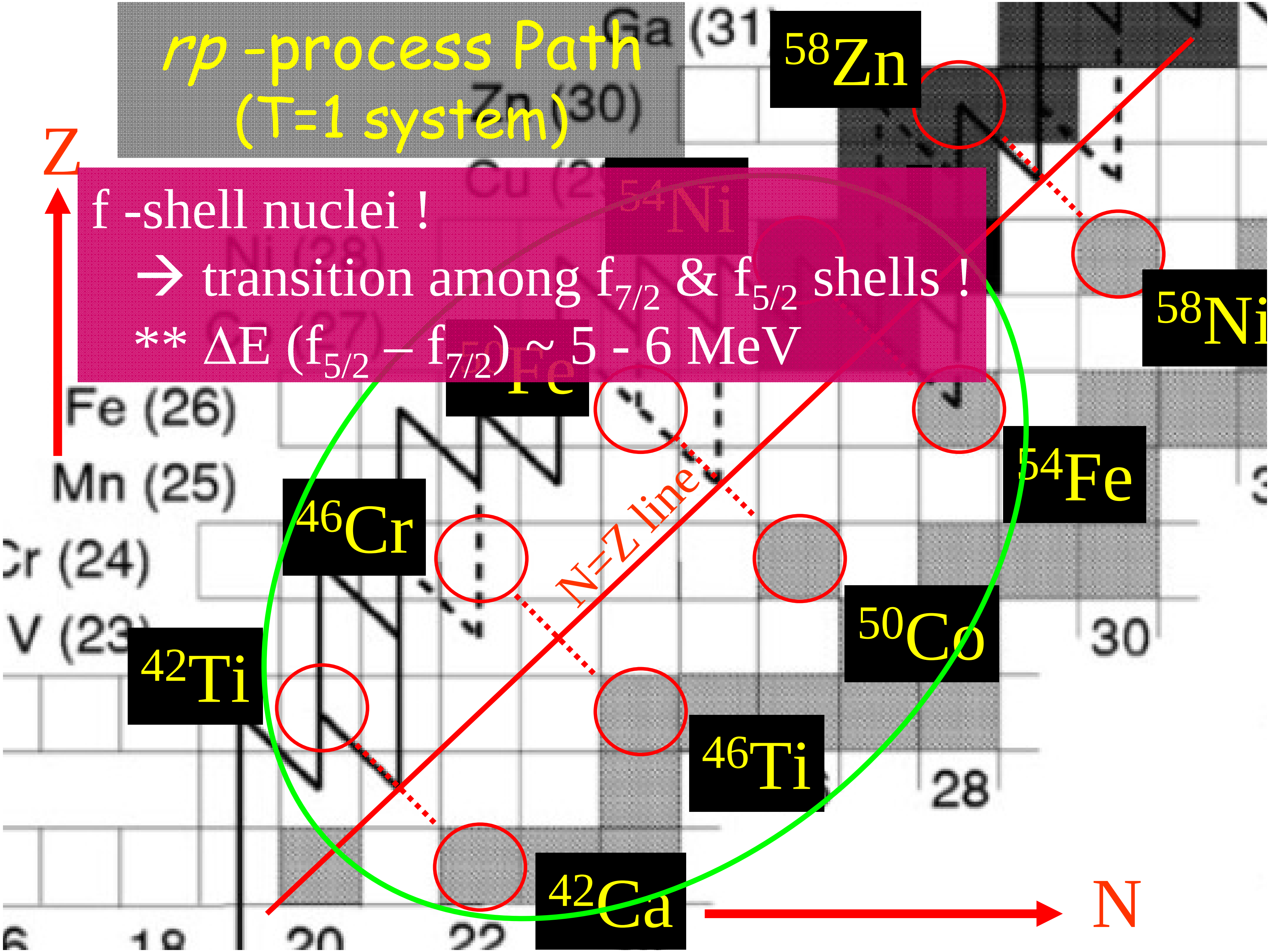
T. Adachi et al.
PRC '12



B(F)=N-Z

Peak heights are proportional to B(GT) values

rp -process Path (T=1 system)

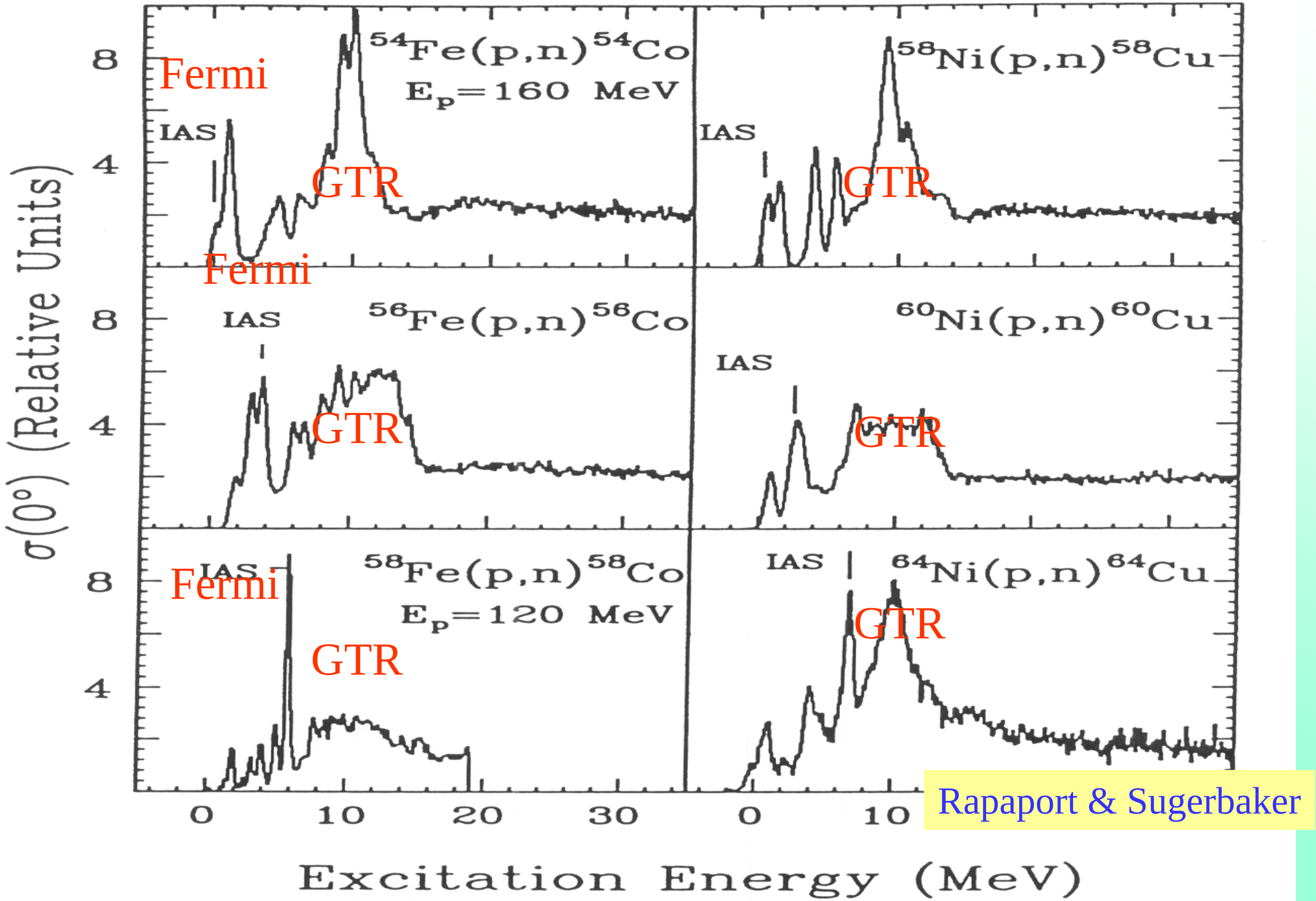


f -shell nuclei !

→ transition among $f_{7/2}$ & $f_{5/2}$ shells !

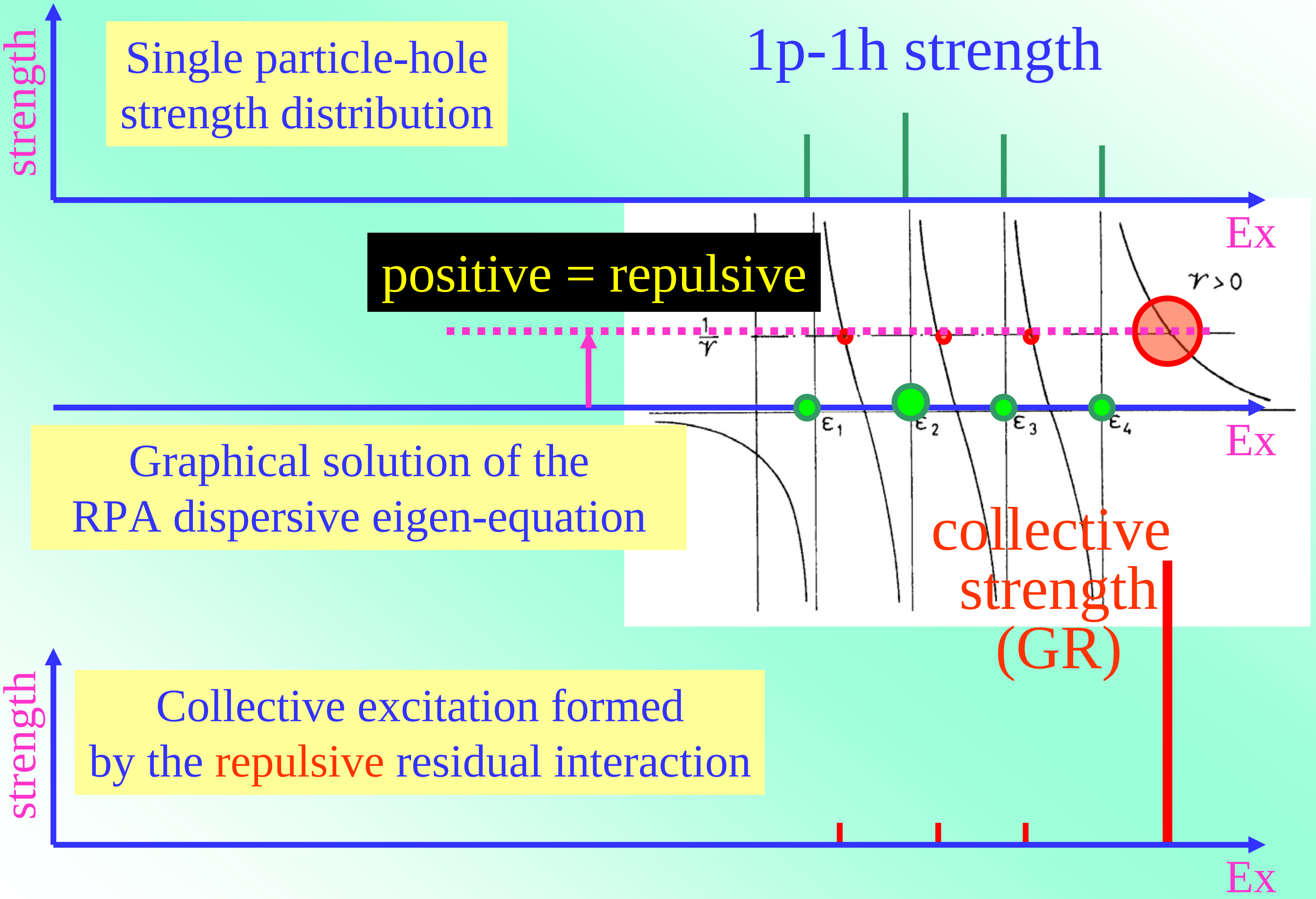
** ΔE ($f_{5/2}$ – $f_{7/2}$) ~ 5 - 6 MeV

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



Rapaport & Sugerbaker

Role of Residual Int. (repulsive)



Single particle-hole strength distribution

1p-1h strength

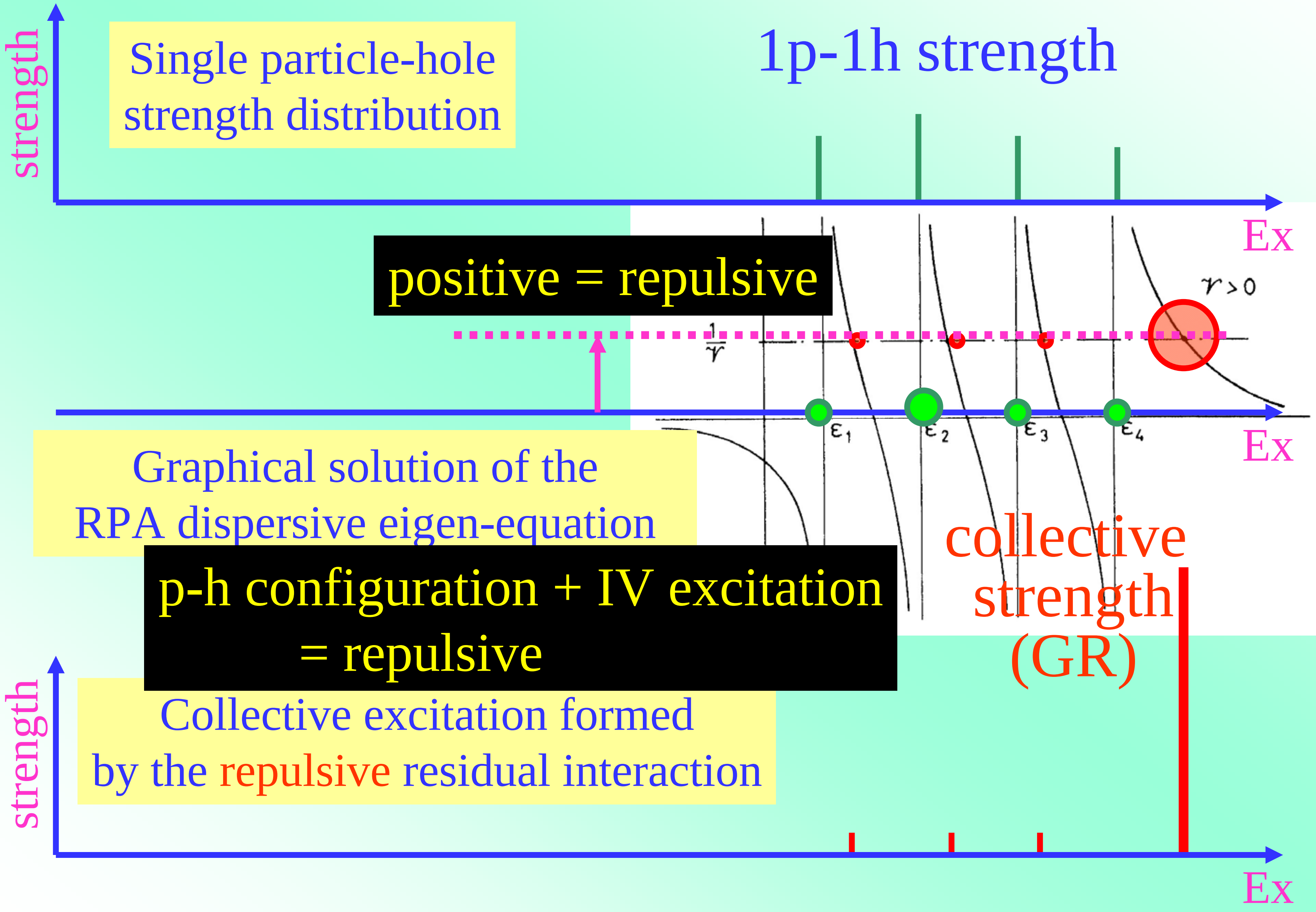
positive = repulsive

Graphical solution of the RPA dispersive eigen-equation

collective strength (GR)

Collective excitation formed by the repulsive residual interaction

Role of Residual Int. (repulsive)



Single particle-hole strength distribution

1p-1h strength

positive = repulsive

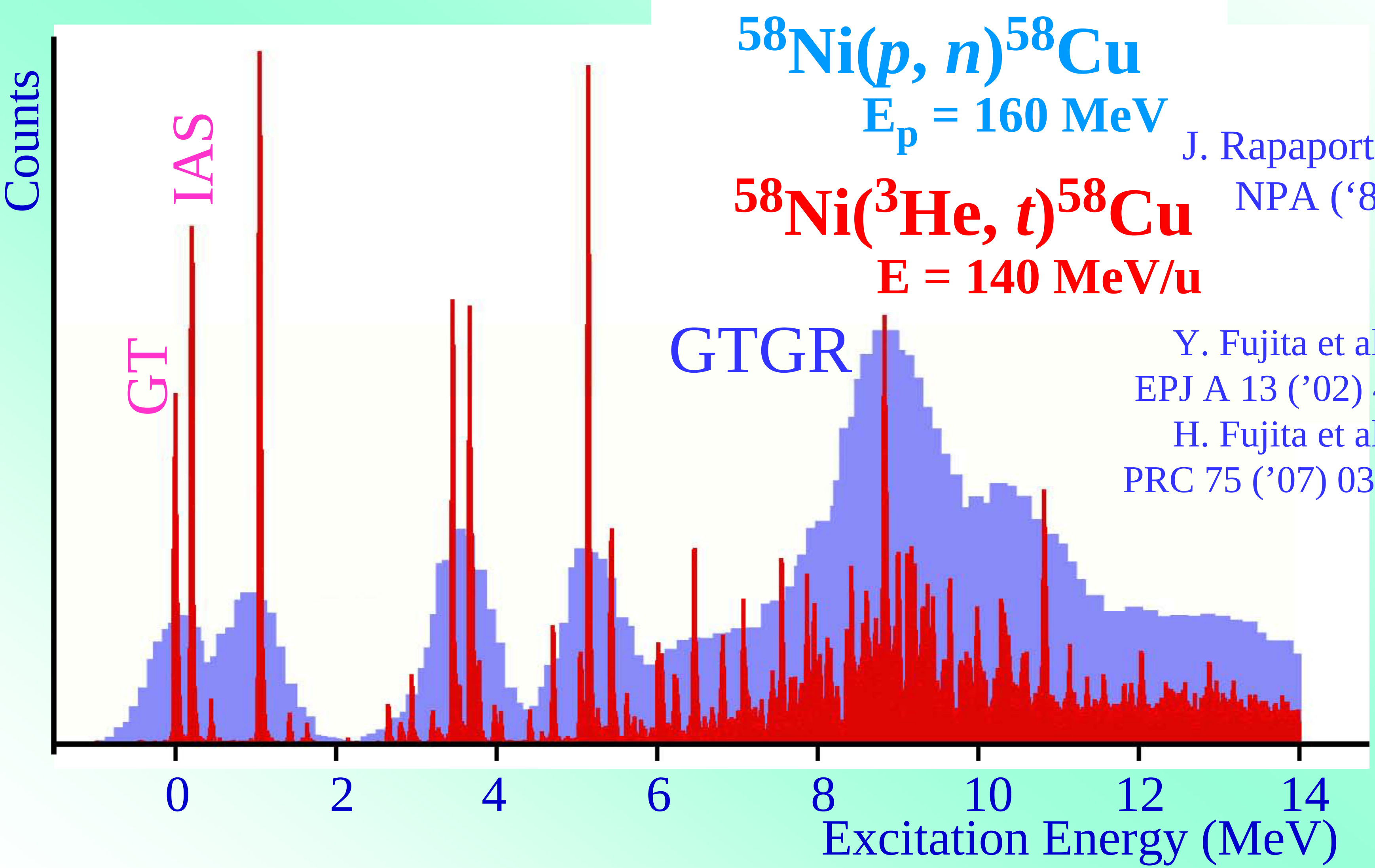
Graphical solution of the RPA dispersive eigen-equation

collective strength (GR)

p-h configuration + IV excitation = repulsive

Collective excitation formed by the repulsive residual interaction

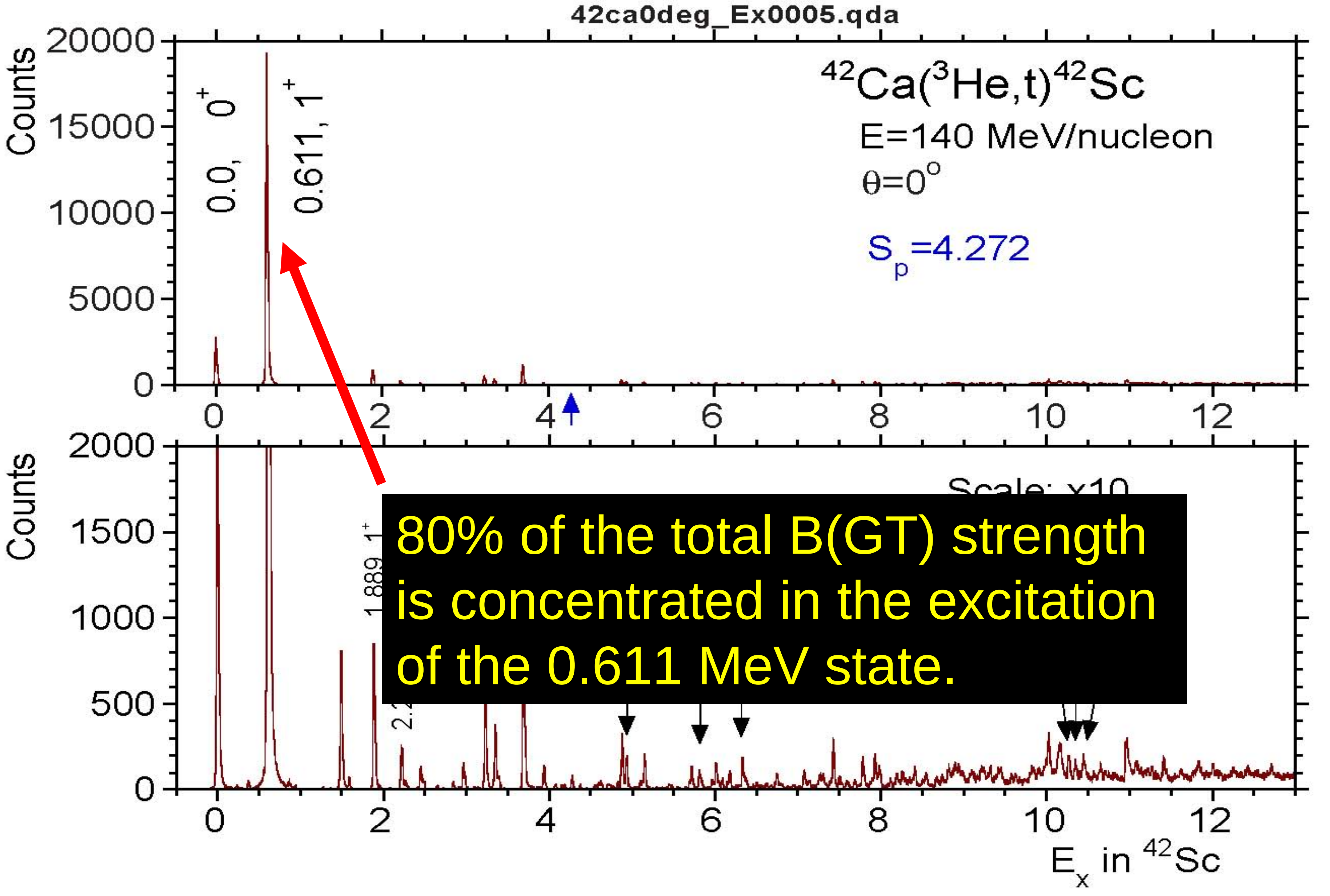
Comparison of (p, n) and (^{3}He,t) 0° spectra



J. Rapaport et al. NPA (‘83)

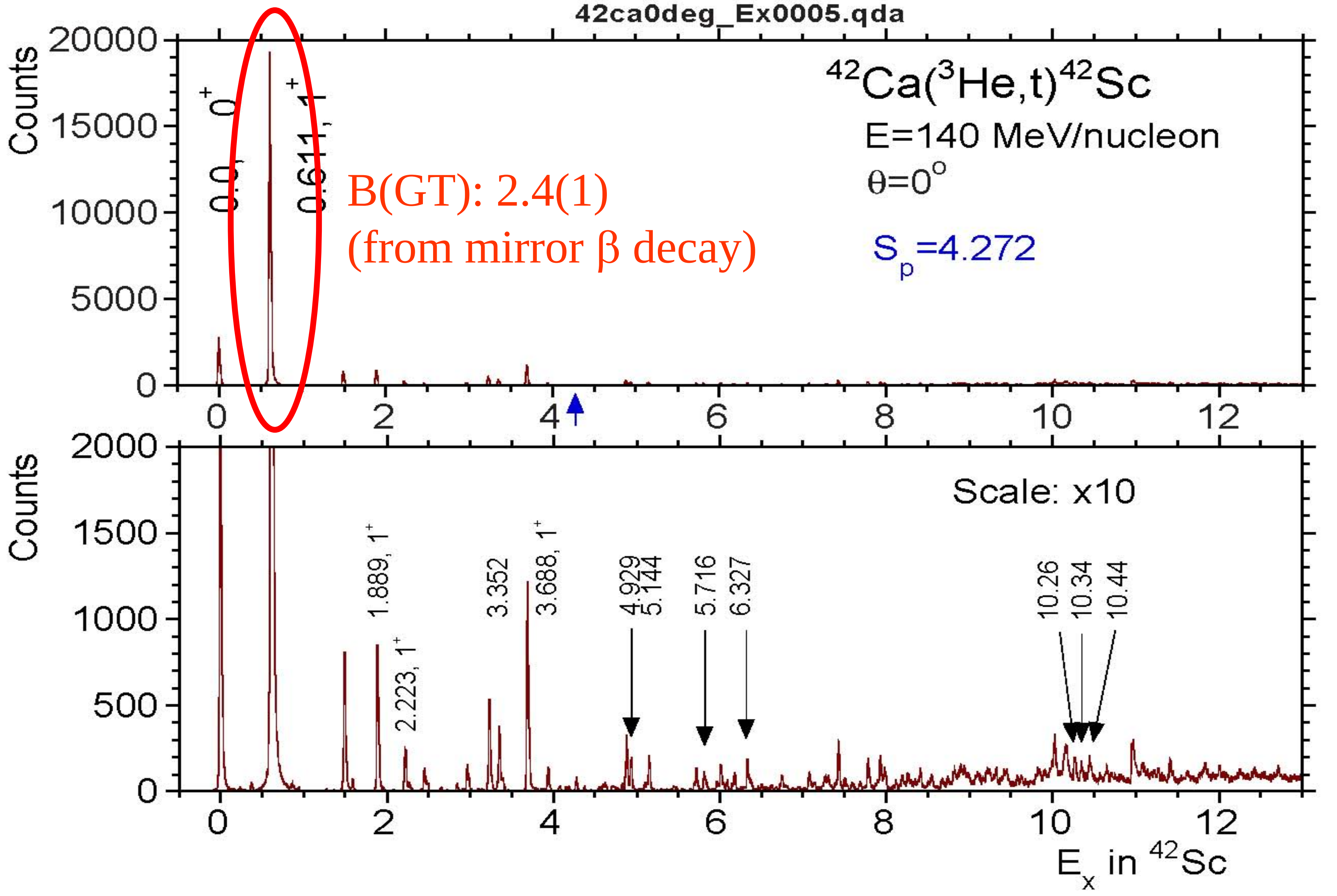
Y. Fujita et al., EPJ A 13 (’02) 411.
H. Fujita et al., PRC 75 (’07) 034310

^{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.

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

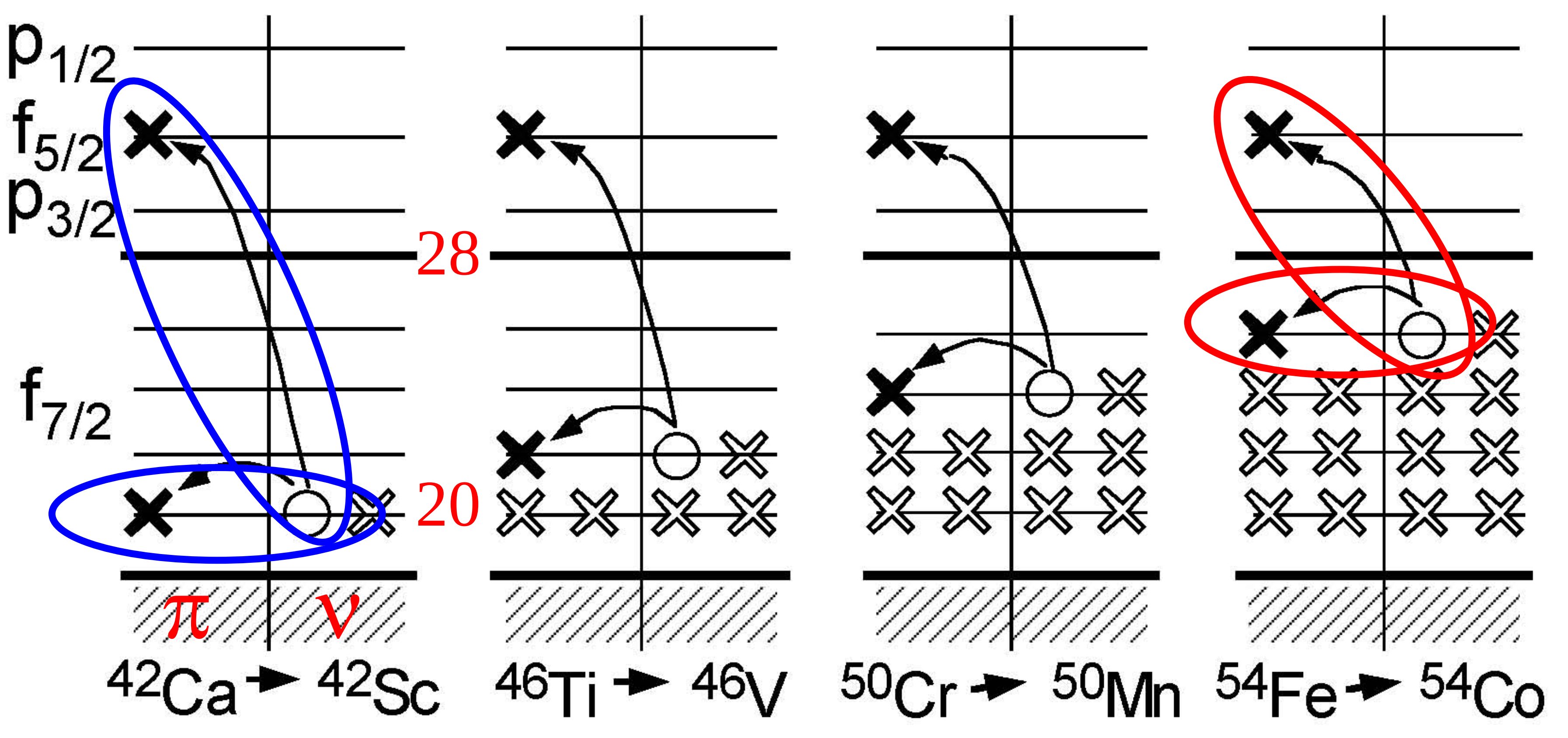

B(GT): 2.4(1)
(from mirror β decay)

**Residual Interaction

- poor man’s understanding! -

coupled pendulum

SM Configurations of GT transitions



Target nuclei: $N = Z + 2$ ($T_z = +1$)

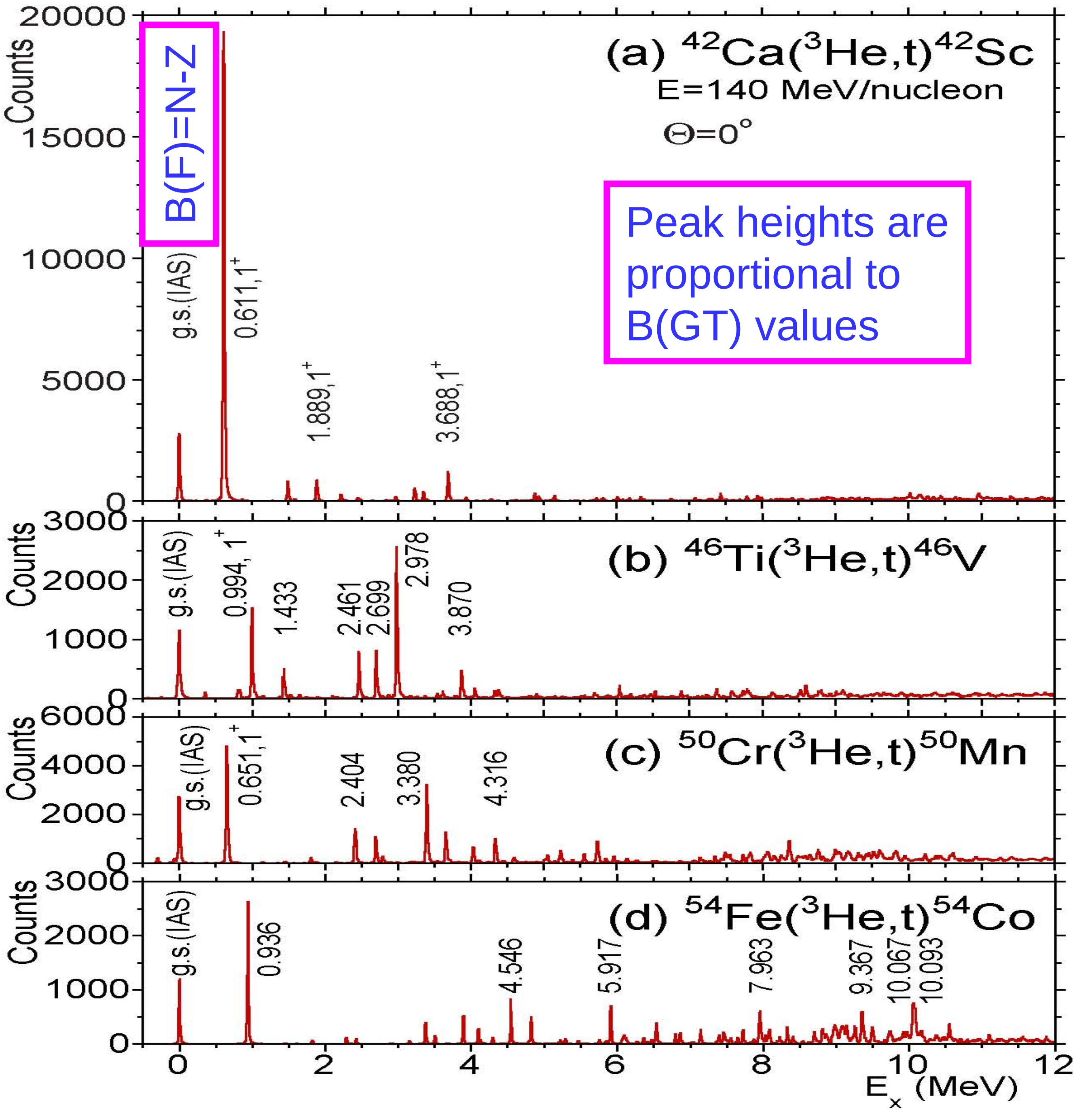
Final nuclei : $N = Z$ ($T_z = 0$)

GT states in A=42-54 T_z=0 nuclei

T. Adachi et al.
PRC '06

Y. Fujita et al.
PRL '05

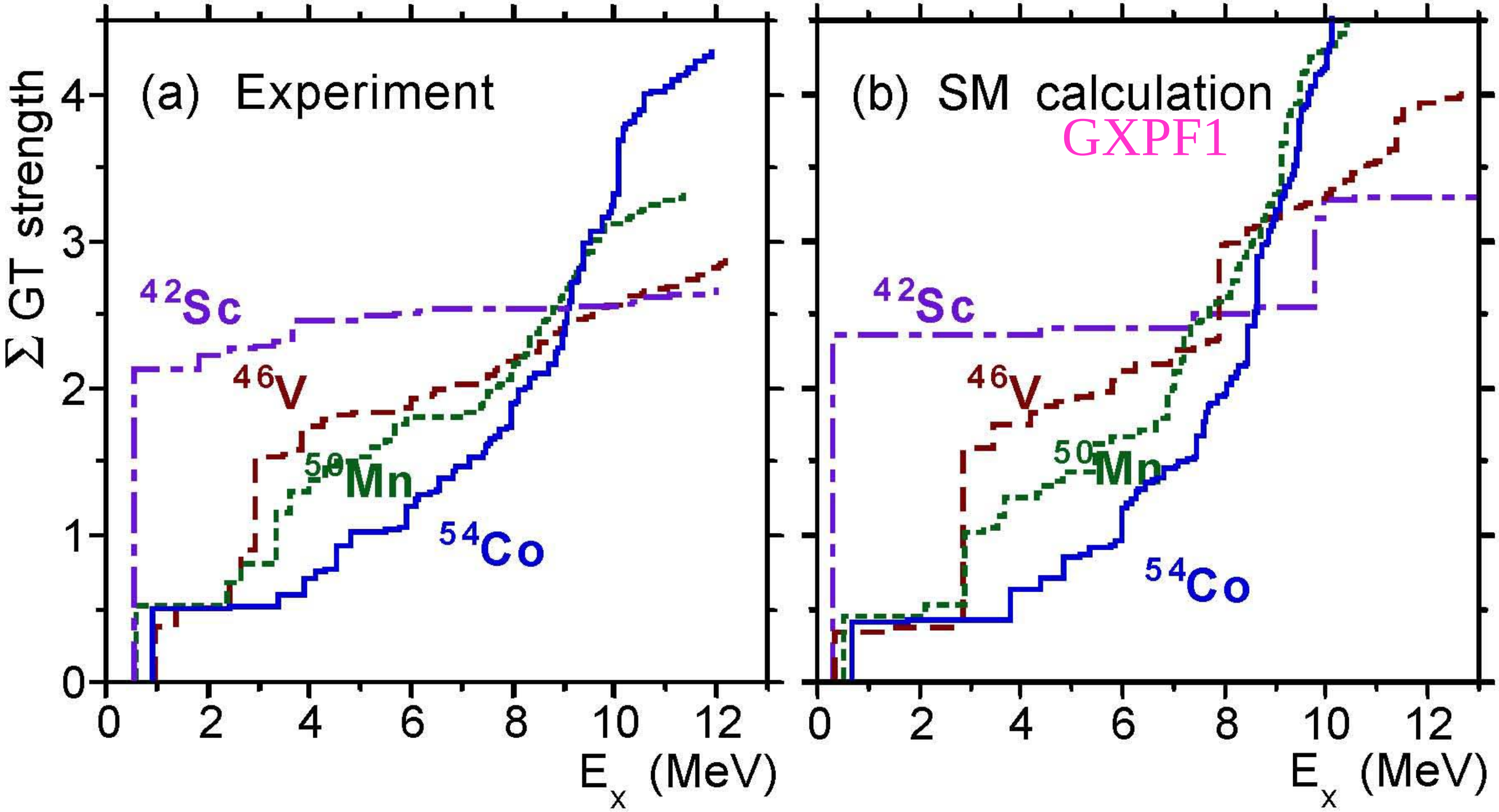
T. Adachi et al.
PRC '12



B(F)=N-Z

Peak heights are proportional to B(GT) values

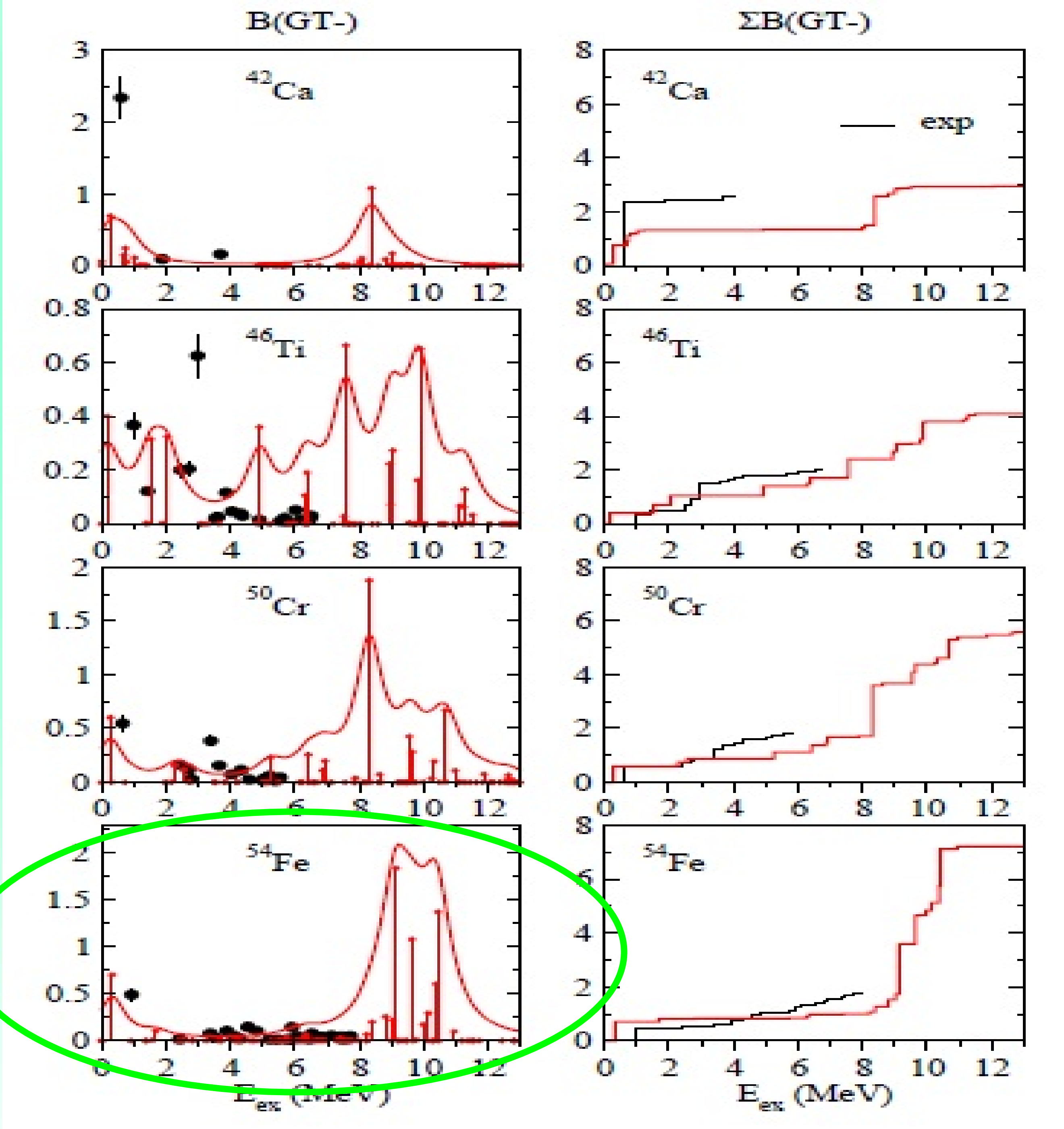
GT-strength: Cumulative Sum



M. Homma et al.

QRPA calculations

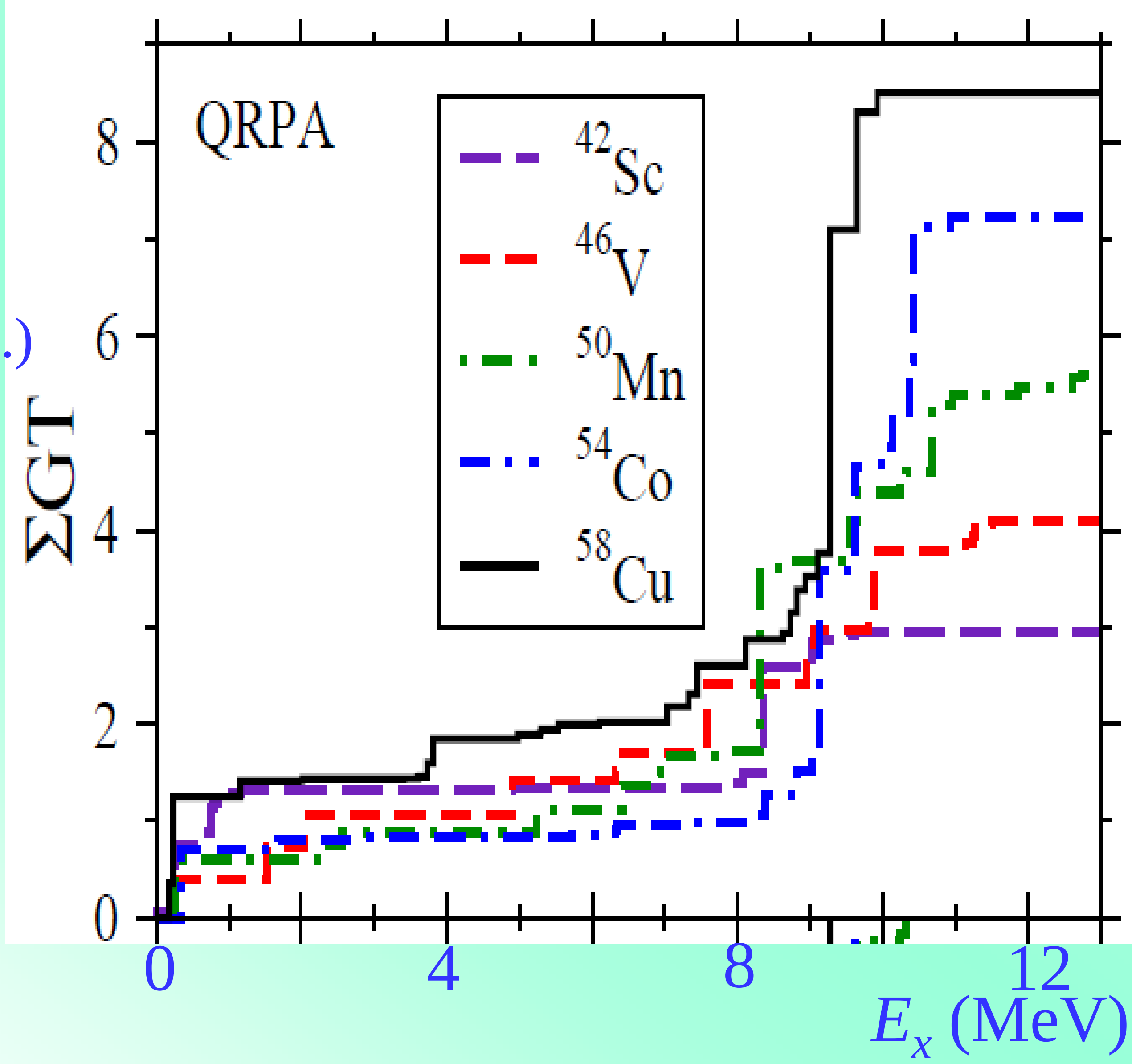
using Skyrme int. SG1
(with IV pairing corr.)



Calculation by
P. Sarrigren,
CSIC, Madrid

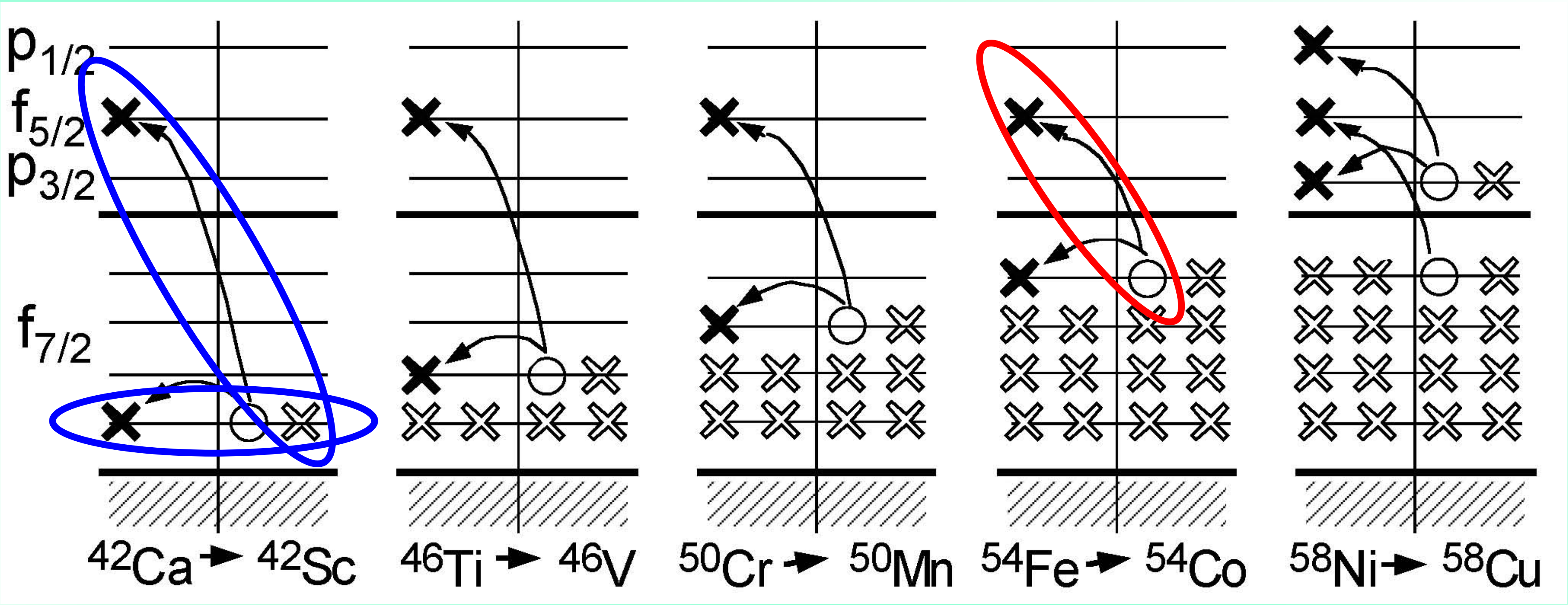
QRPA calculations

using Skyrme int.
(with IV pairing corr.)



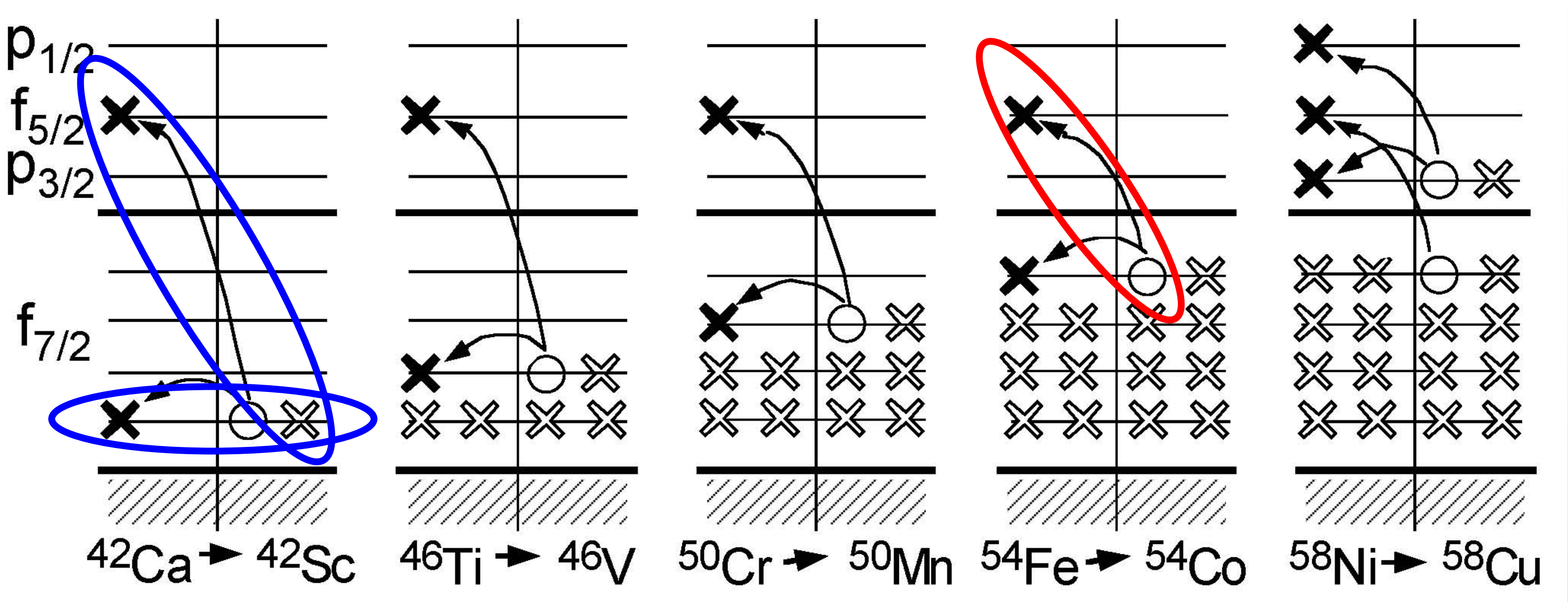
Calculation by
P. Sarrigren,
CSIC, Madrid

SM Configurations of GT transitions



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

SM Configurations of GT transitions

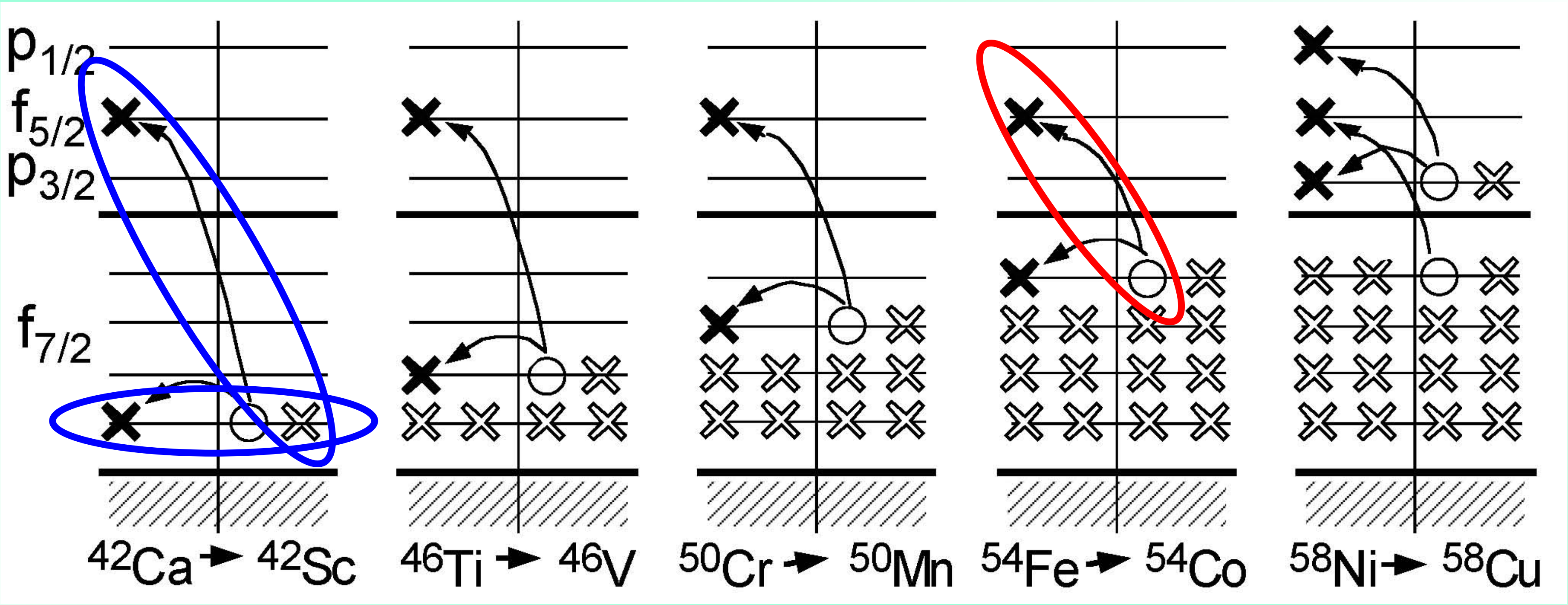


π-p - ν-p configurations
sensitive to IS pairing int.
and
it is attractive
(spin-triplet, IS int. is stronger
than spin-singlet, IV int.)

particle-hole configurations
+
IV-type excitation (στ)
→repulsive

by Engel, Bertsch, Macchiavelli

SM Configurations of GT transitions



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

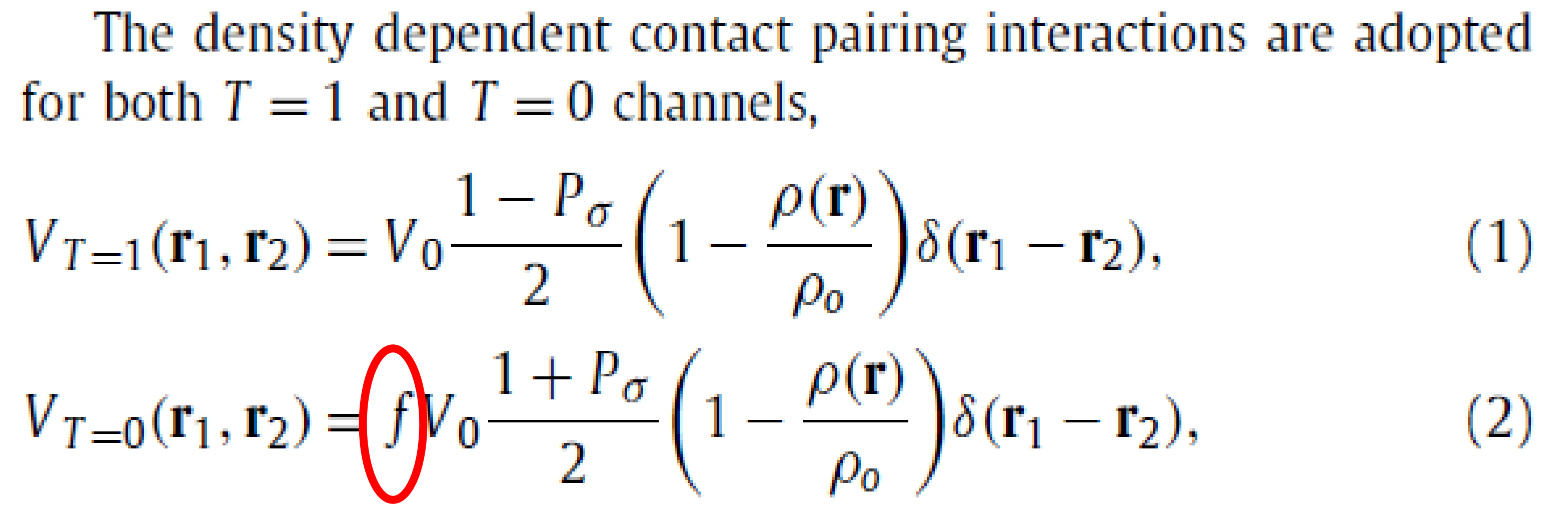
(T=0, IS p-n int. is attractive)

Isoscalar interaction
can play Important roles !

Cooperative with the repulsive
nature of στ int. !

GT strength Calculations: HFB+QRPA + pairing int.

C.L. Bai, H. Sagawa et al., PL B 719 (2013) 116



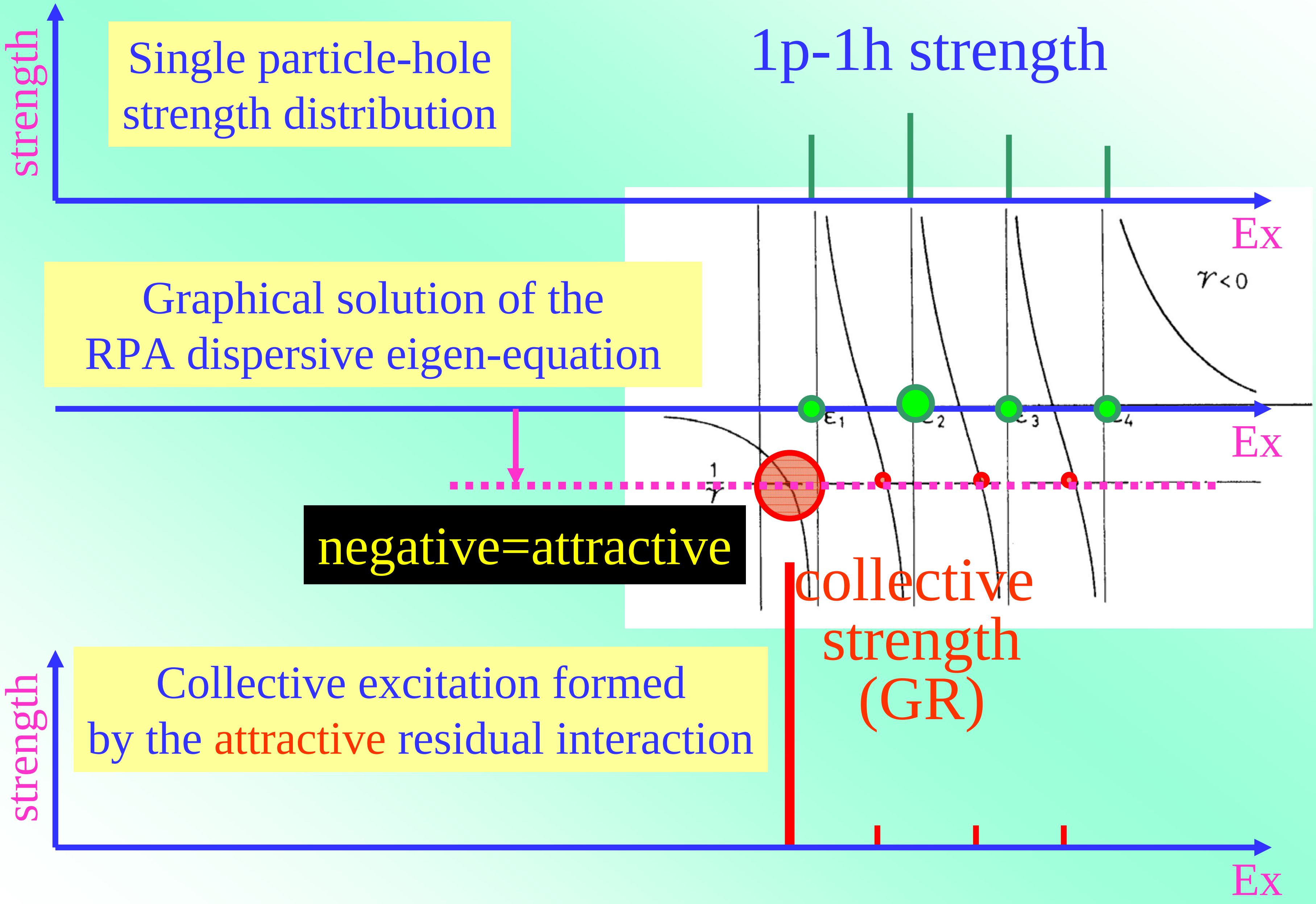
The density dependent contact pairing interactions are adopted for both $T = 1$ and $T = 0$ channels,

IV $$V_{T=1}(\mathbf{r}_1, \mathbf{r}_2) = V_0 \frac{1 - P_\sigma}{2} \left(1 - \frac{\rho(\mathbf{r})}{\rho_0}\right) \delta(\mathbf{r}_1 - \mathbf{r}_2), \qquad (1)$$

IS $$V_{T=0}(\mathbf{r}_1, \mathbf{r}_2) = \boxed{f} V_0 \frac{1 + P_\sigma}{2} \left(1 - \frac{\rho(\mathbf{r})}{\rho_0}\right) \delta(\mathbf{r}_1 - \mathbf{r}_2), \qquad (2)$$

Results (using Skyrme int. SGII)
at *f* =0: there is little strength in the lower energy part,
at *f* =1.0~1.7: coherent low-energy strength develops!

Role of Residual Int. (attractive)



Single particle-hole strength distribution

1p-1h strength

Graphical solution of the RPA dispersive eigen-equation

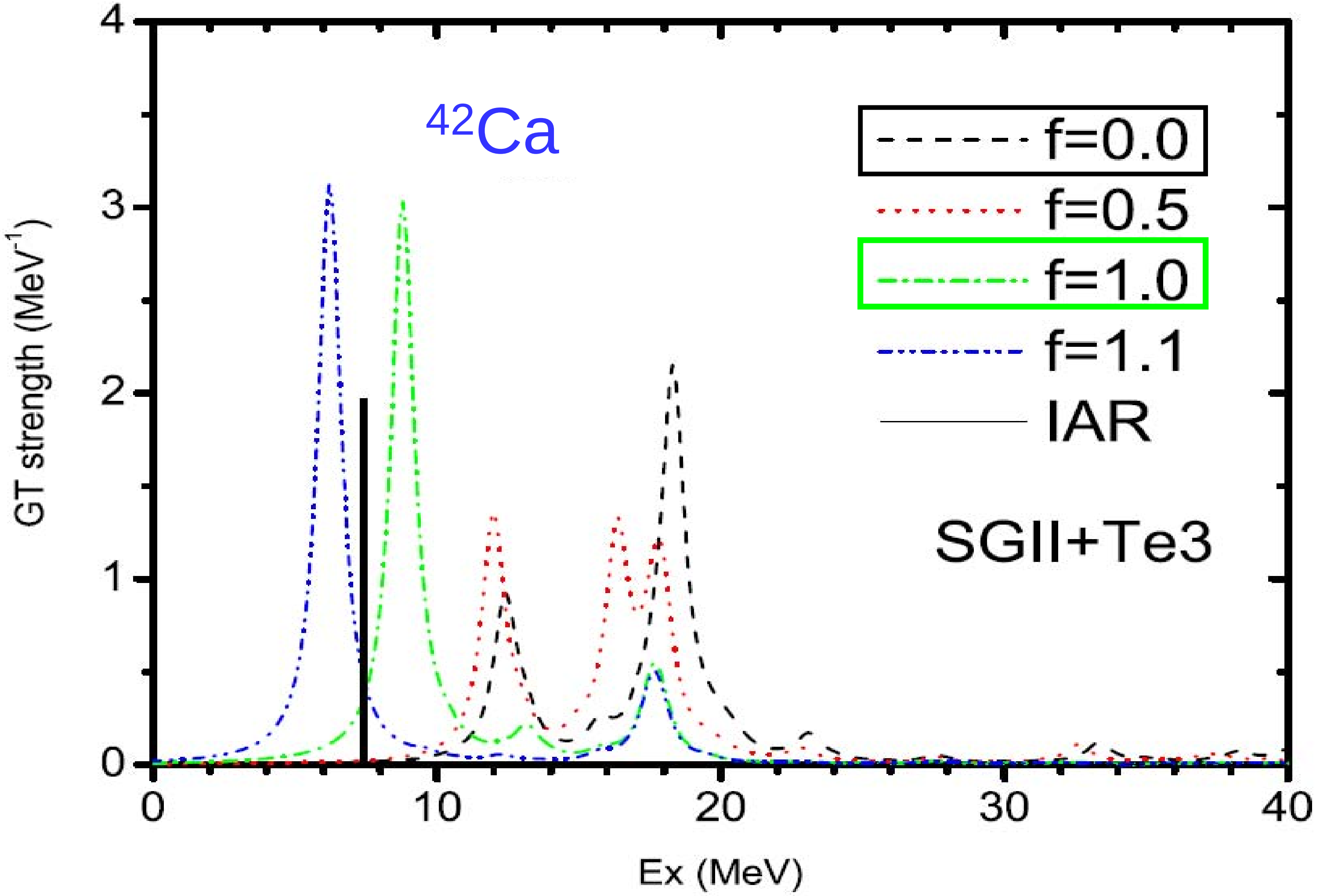
negative=attractive

collective strength (GR)

Collective excitation formed by the attractive residual interaction

QRPA-cal. GT-strength (with IS-int.)

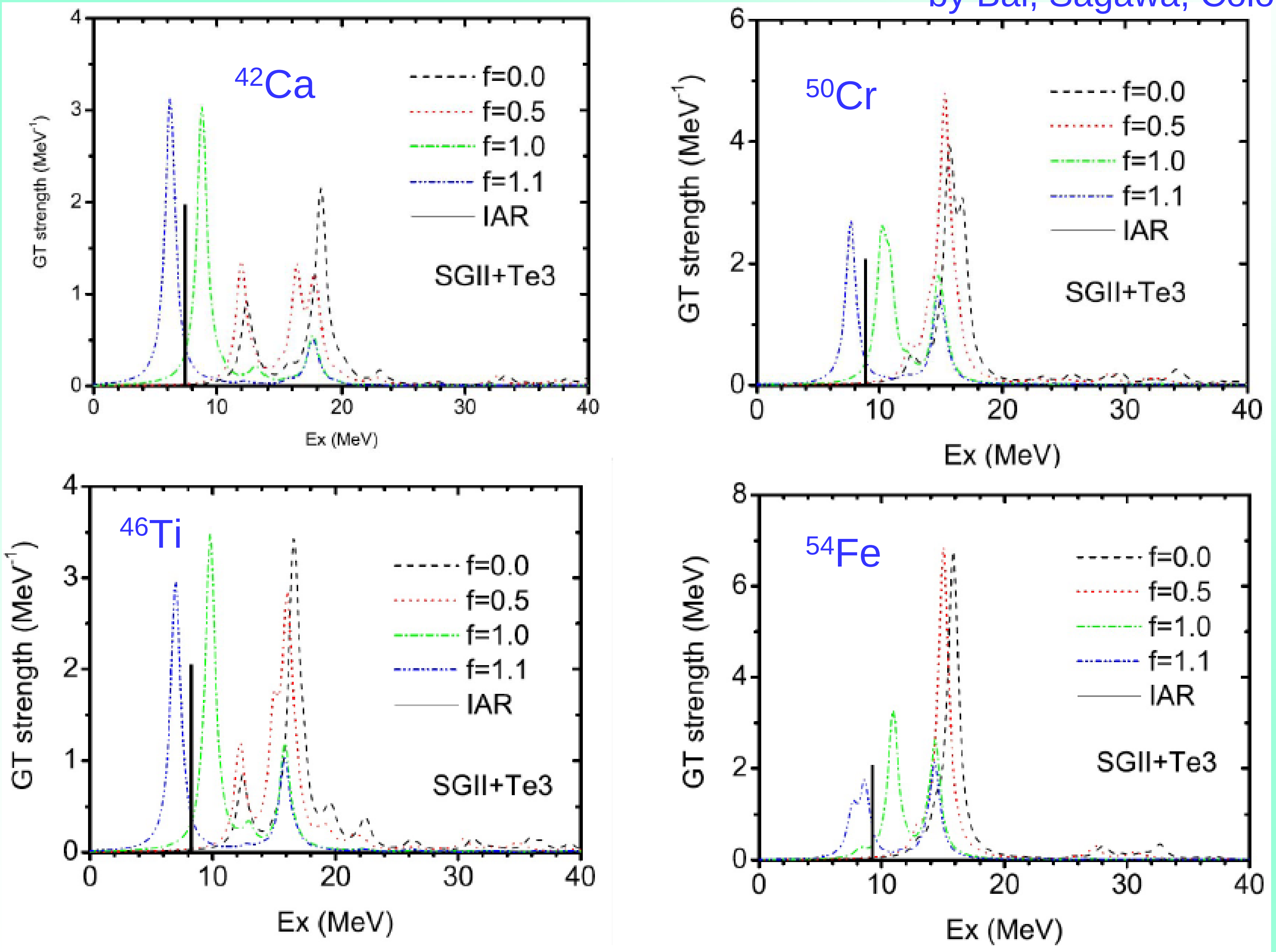
by Bai Sagawa Colo



^{42}Ca→^{42}Sc (Q-value)

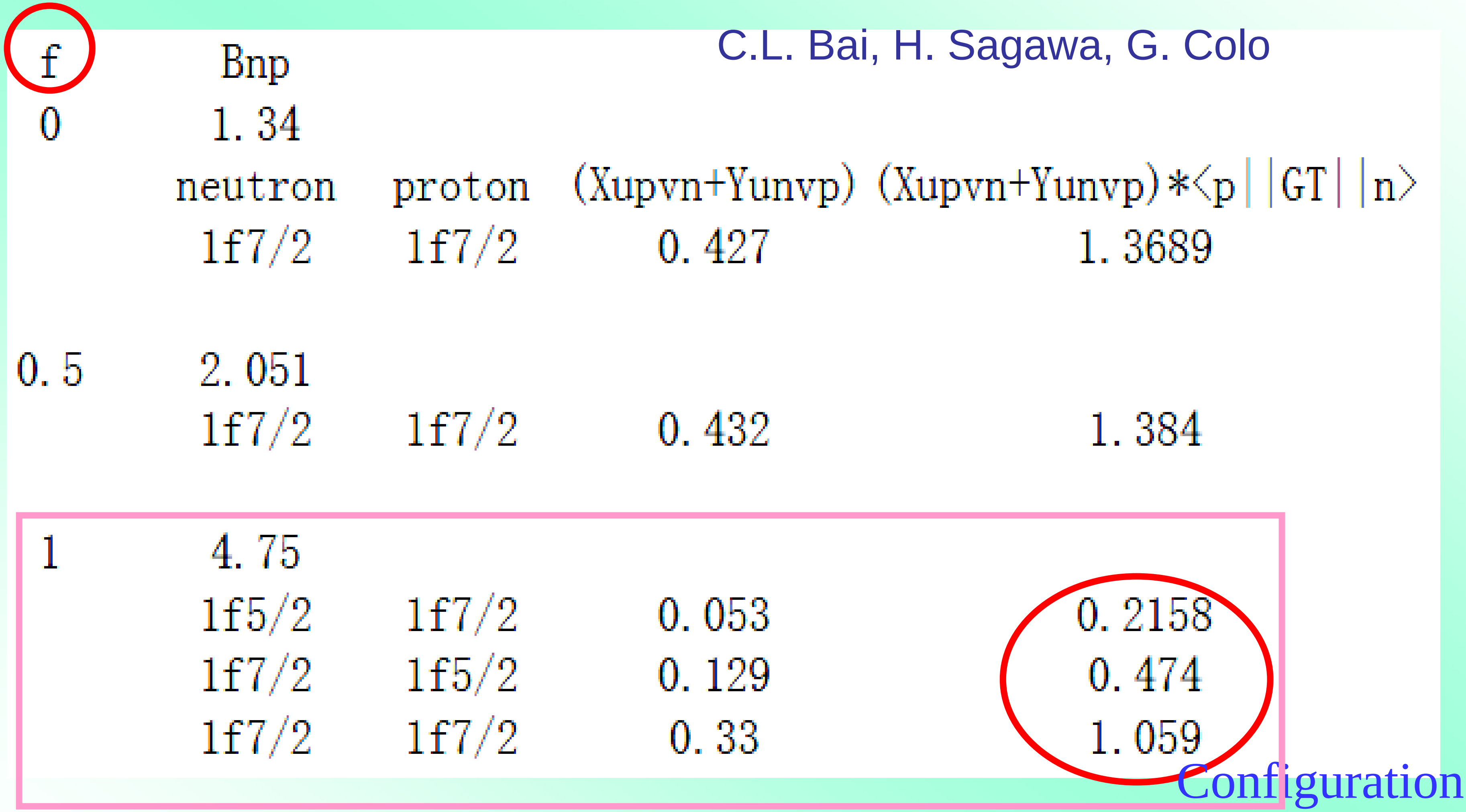
QRPA-cal. GT-strength (with IS-int.)

by Bai, Sagawa, Colo



QRPA cal. including IS int.

C.L. Bai, H. Sagawa, G. Colo



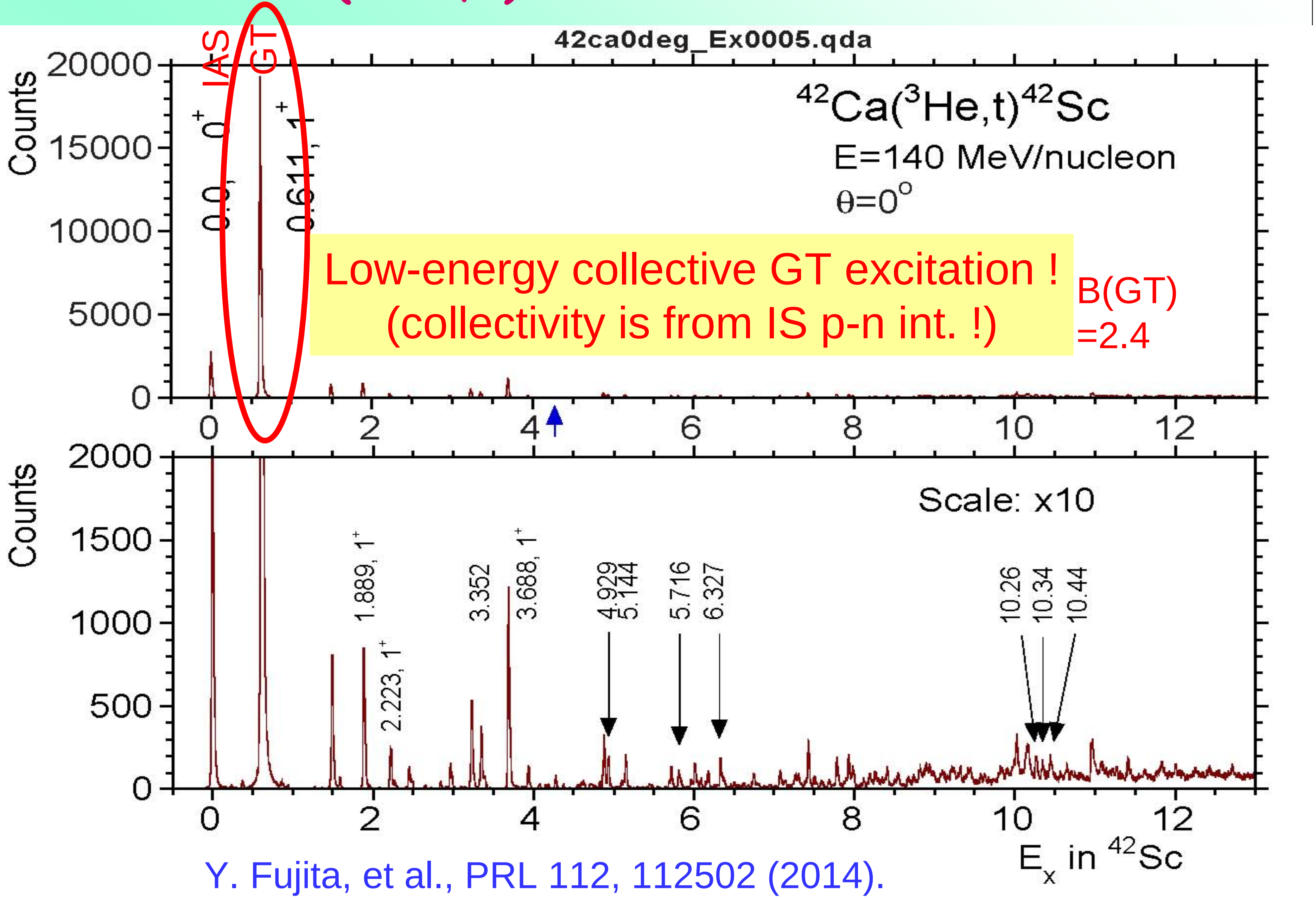
```
f        Bnp
0        1.34
       neutron    proton   (Xupvn+Yunvp) (Xupvn+Yunvp)*<p||GT||n>
        1f7/2      1f7/2       0.427            1.3689

0.5      2.051
        1f7/2      1f7/2       0.432            1.384

1        4.75
        1f5/2      1f7/2       0.053            0.2158
        1f7/2      1f5/2       0.129            0.474
        1f7/2      1f7/2       0.33             1.059
```

Configurations
are in phase!

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

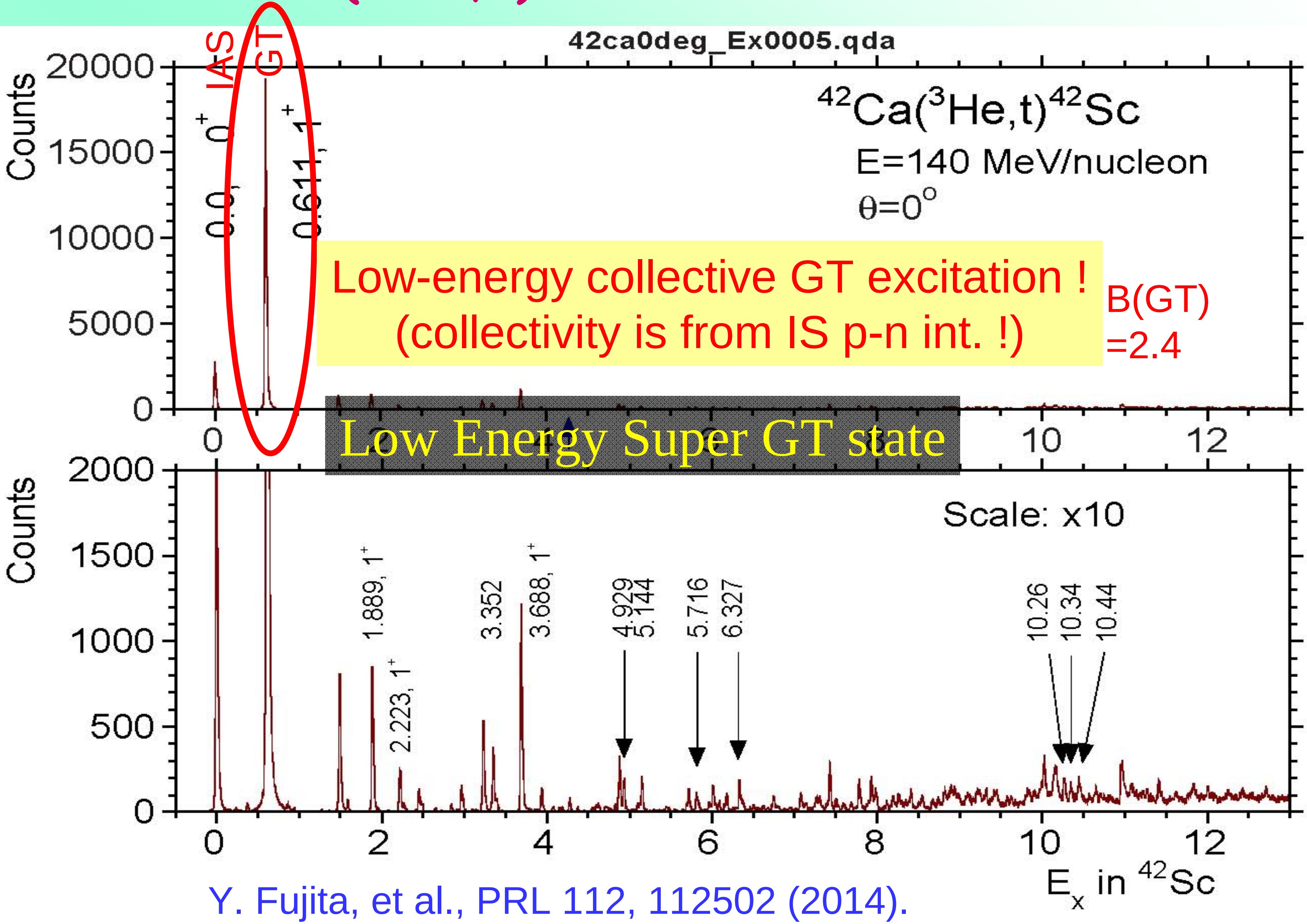


Low-energy collective GT excitation !
(collectivity is from IS p-n int. !)

B(GT)
=2.4

Y. Fujita, et al., PRL 112, 112502 (2014).

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



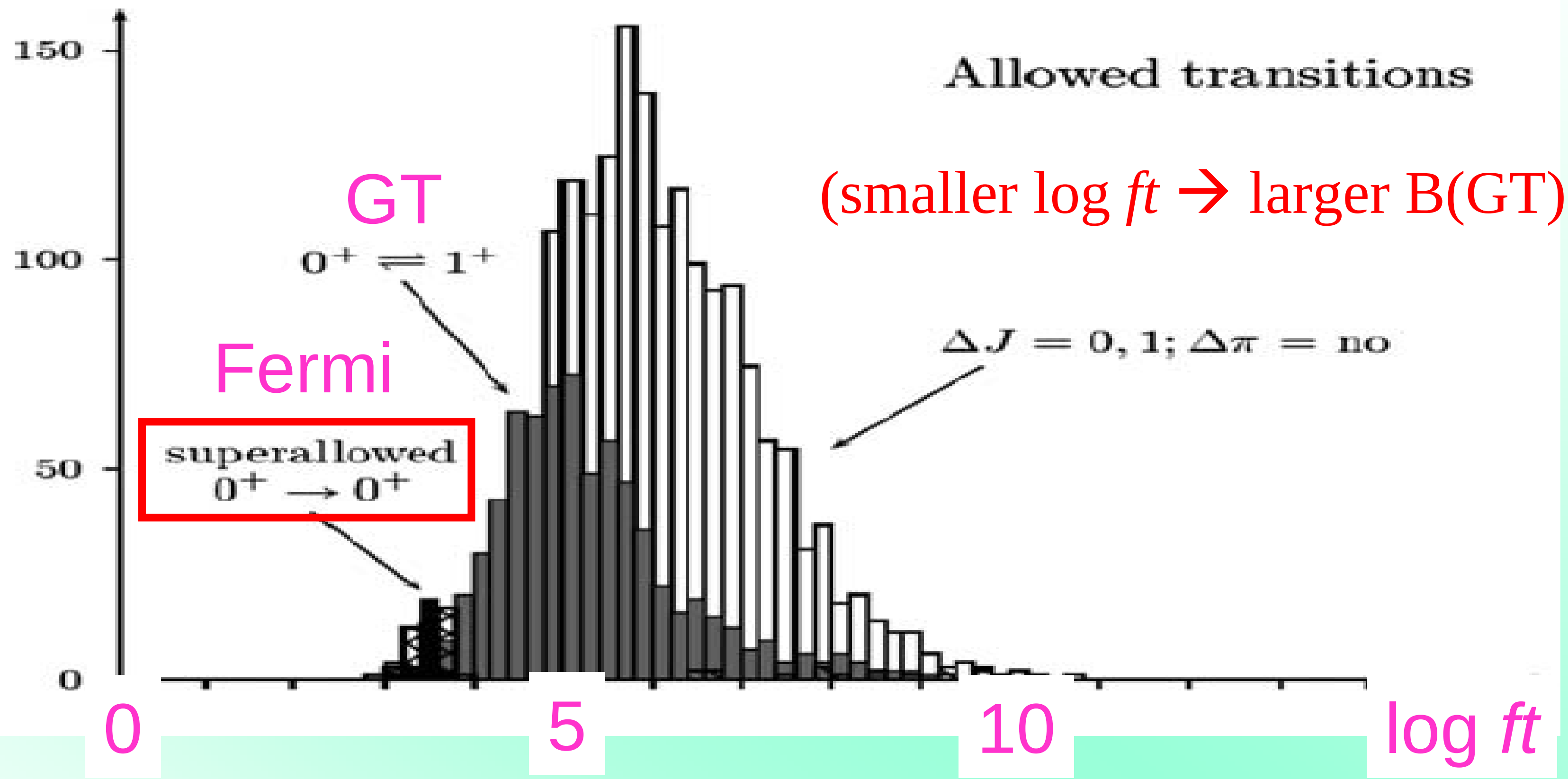
Low-energy collective GT excitation !
(collectivity is from IS p-n int. !)

B(GT)
=2.4

Low Energy Super GT state

Y. Fujita, et al., PRL 112, 112502 (2014).

Super-allowed GT transitions in β decay



(smaller log *ft* → larger B(GT))

^{6}He, $0^+ \rightarrow$ ^{6}Li, 1^+ log *ft* = 2.9
^{18}Ne, $0^+ \rightarrow$ ^{18}F, 1^+ log *ft* = 3.1
^{42}Ti, $0^+ \rightarrow$ ^{42}Sc, 1^+ log *ft* = 3.2

Super-allowed GT transitions

Super-Multiplet State

*proposed by Wigner (1937)

In the limit of null $L \cdot S$ force, SU(4) symmetry exists.

We expect:

a) GT excitation strength is concentrated
in a low-energy GT state.

b) excitation energies of
both the IAS and the GT state are identical.

→ *Super-Multiplet State*

In ^{54}Co, we see a broken SU(4) symmetry.

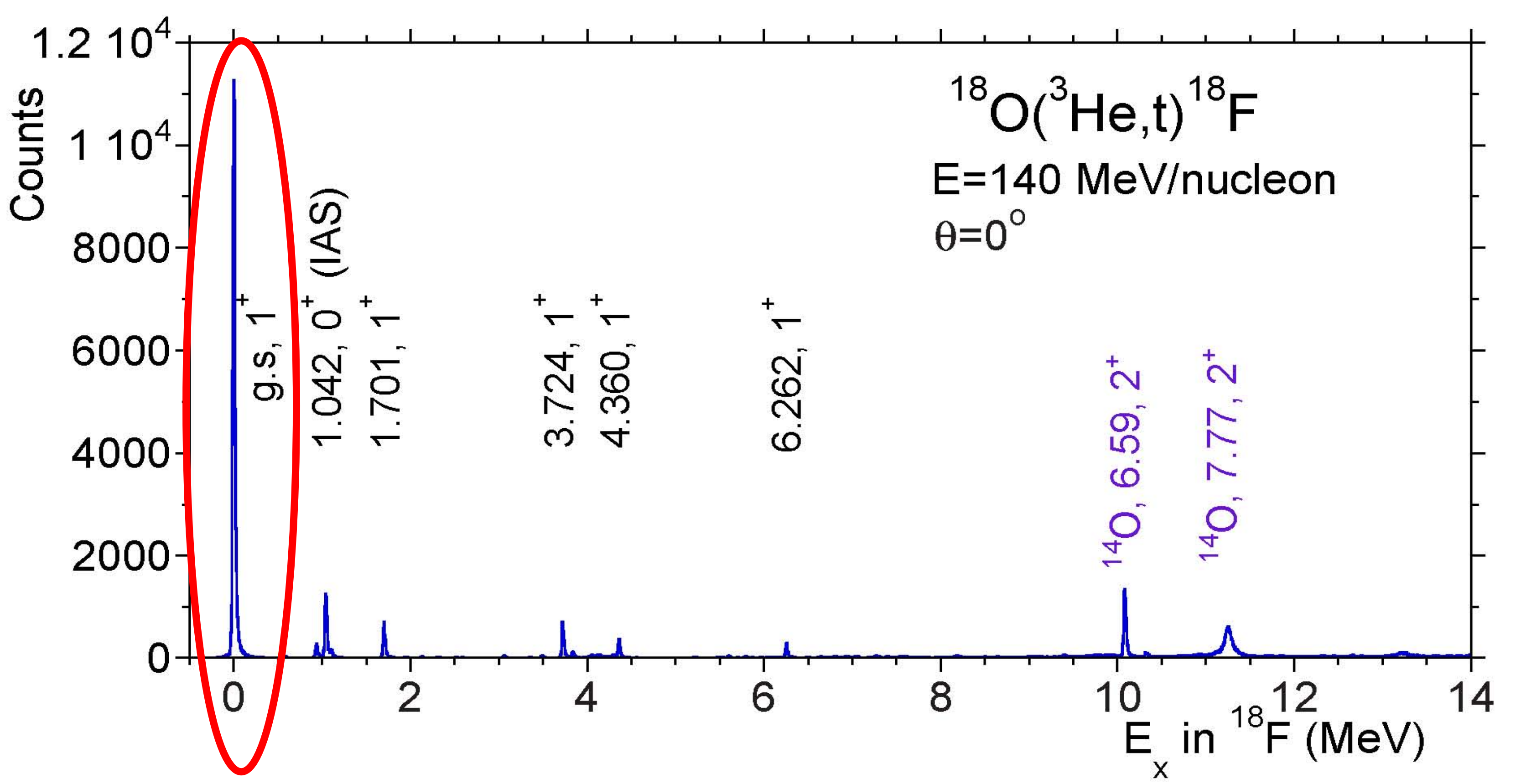
In ^{42}Sc, we see a good SU(4) symmetry.

→ attractive IS residual int. restores the symmetry !

→ 0.611 MeV state in ^{42}Sc has a character close to
Super-Multiplet State !

We call this state the
Low-energy Super GT state !

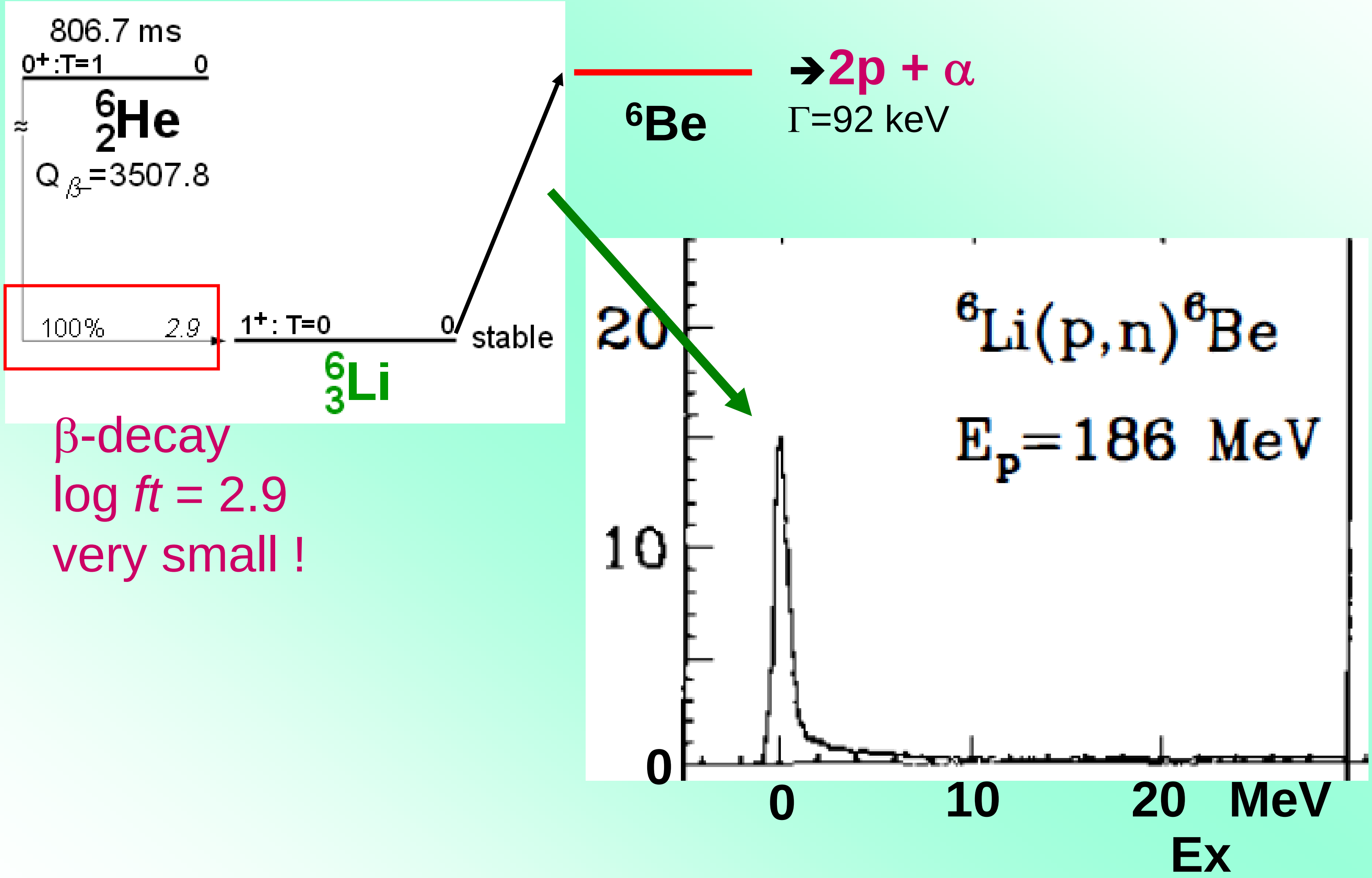
$^{18}O(^{3}He,t)^{18}F$ at 0°



Low-energy collective GT excitation: B(GT)=3.1

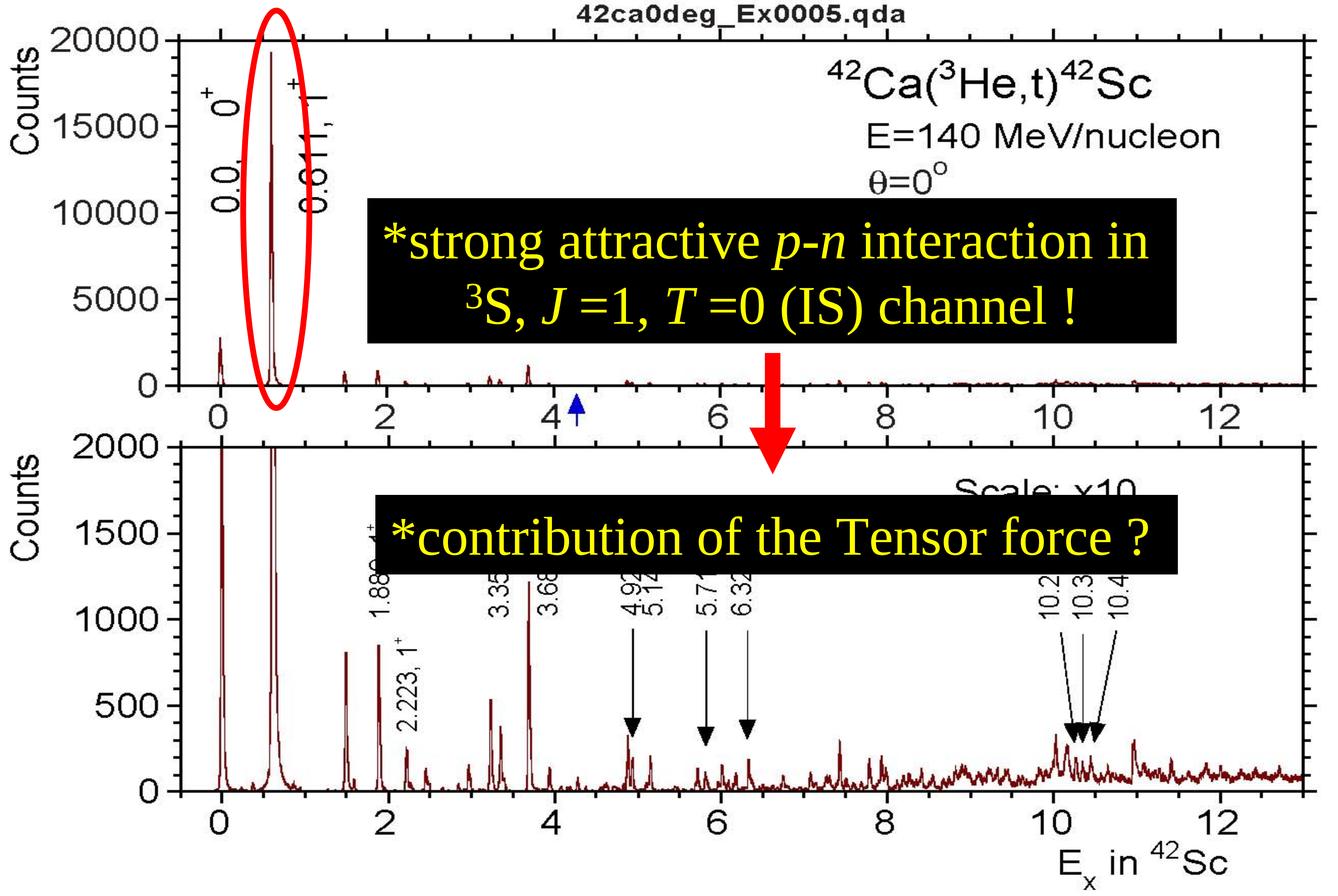
Low Energy Super GT state

^{6}He β-decay & ^{6}Li(pn)^{6}Be



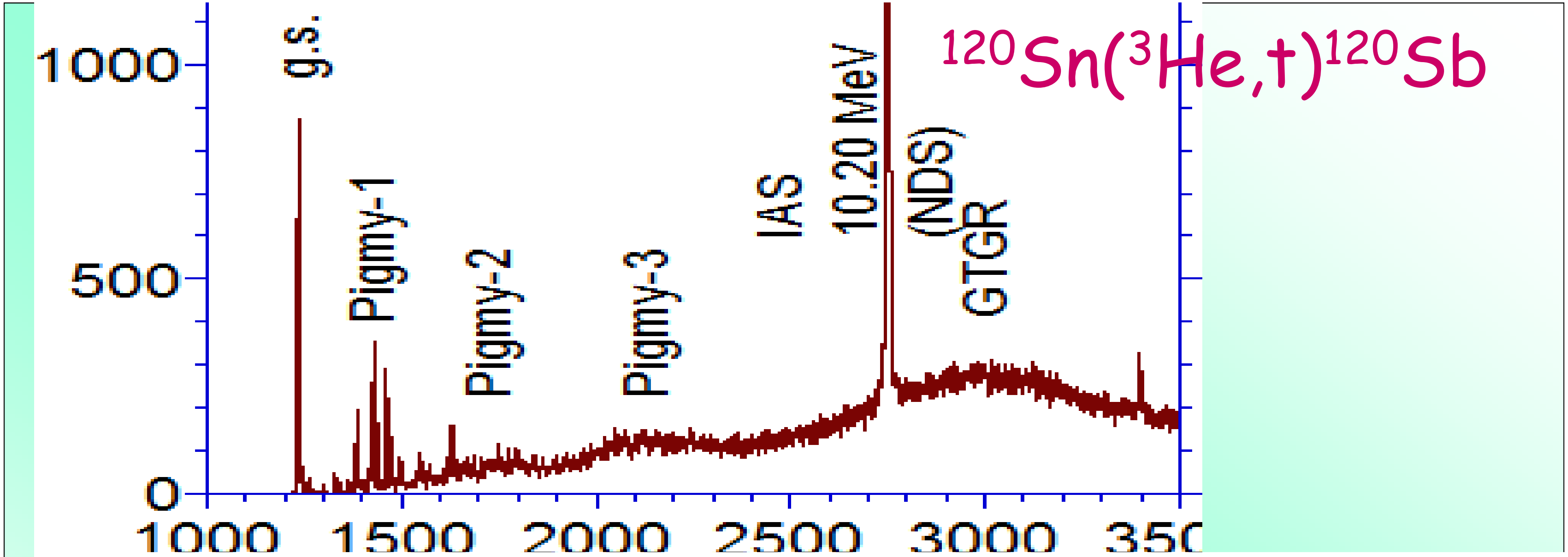
β-decay
log *ft* = 2.9
very small !

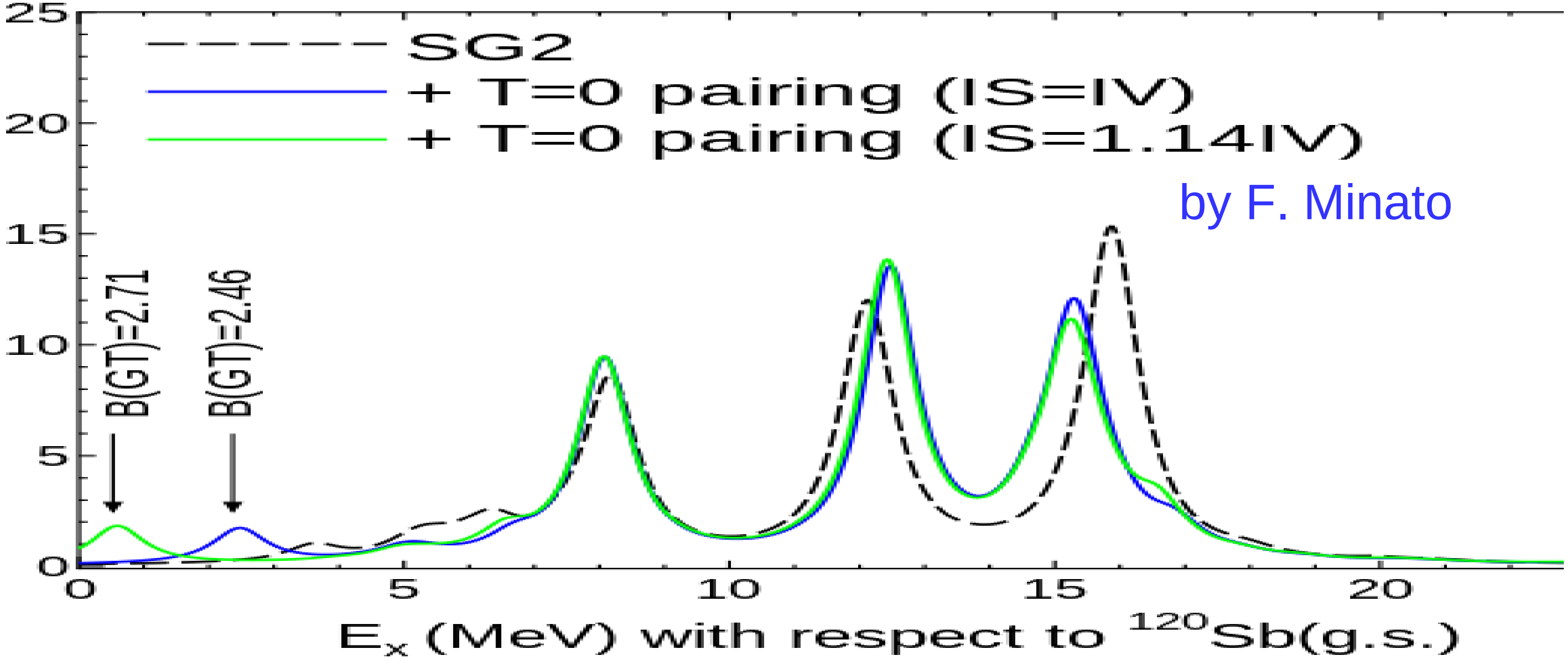
$^{42}Ca(^{3}He,t)^{42}Sc$ in 2 scales



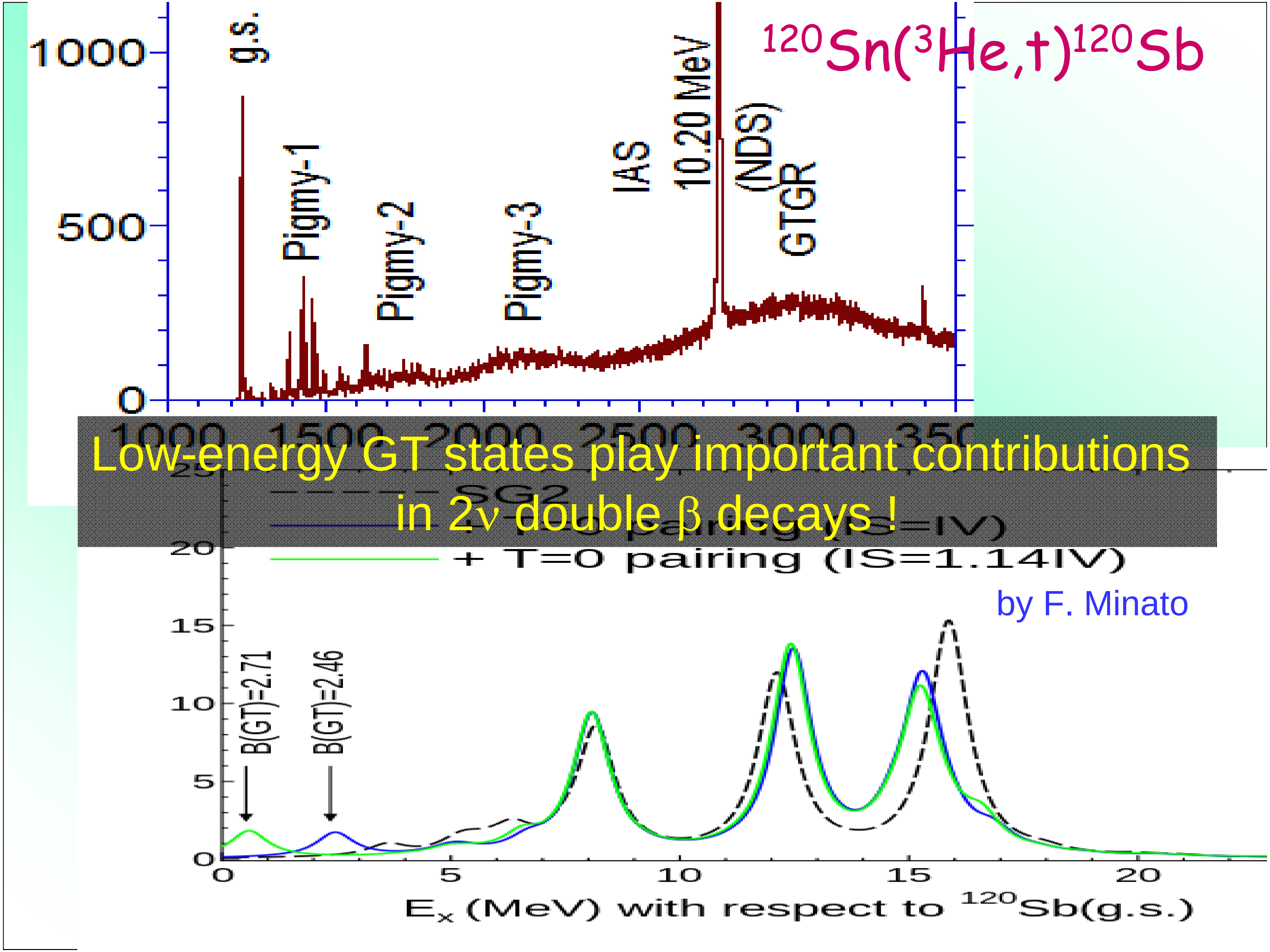
*strong attractive *p-n* interaction in ^{3}S, *J* =1, *T* =0 (IS) channel !

*contribution of the Tensor force ?


$^{120}Sn(^3He,t)^{120}Sb$
1000
500
0
1000
1500
2000
2500
3000
350
g.s.
Pigmy-1
Pigmy-2
Pigmy-3
IAS
10.20 MeV
(NDS)
GTGR


25
20
15
10
5
0
0
5
10
15
20
SG2
+ T=0 pairing (IS=IV)
+ T=0 pairing (IS=1.14IV)
B(GT)=2.71
B(GT)=2.46
E_x (MeV) with respect to ^{120}Sb(g.s.)

by F. Minato



^{120}Sn(^{3}He,t)^{120}Sb

Low-energy GT states play important contributions in 2ν double β decays !

by F. Minato

List of double β-decay nuclei

$^{48}\mathrm{Ca}$	**CANDLES**
$^{64}\mathrm{Zn}$	**COBRA**
$^{76}\mathrm{Ge}$	**GERDA**
$^{82}\mathrm{Se}$	**NEMO**
$^{96}\mathrm{Zr}$	**NEMO**
$^{100}\mathrm{Mo}$	**MOON/NEMO**
$^{116}\mathrm{Cd}$	**COBRA**
$^{128/130}\mathrm{Te}$	**CUORE**
$^{136}\mathrm{Xe}$	**EXO, KamLAND-ZEN**
$^{150}\mathrm{Nd}$	**SNO+**

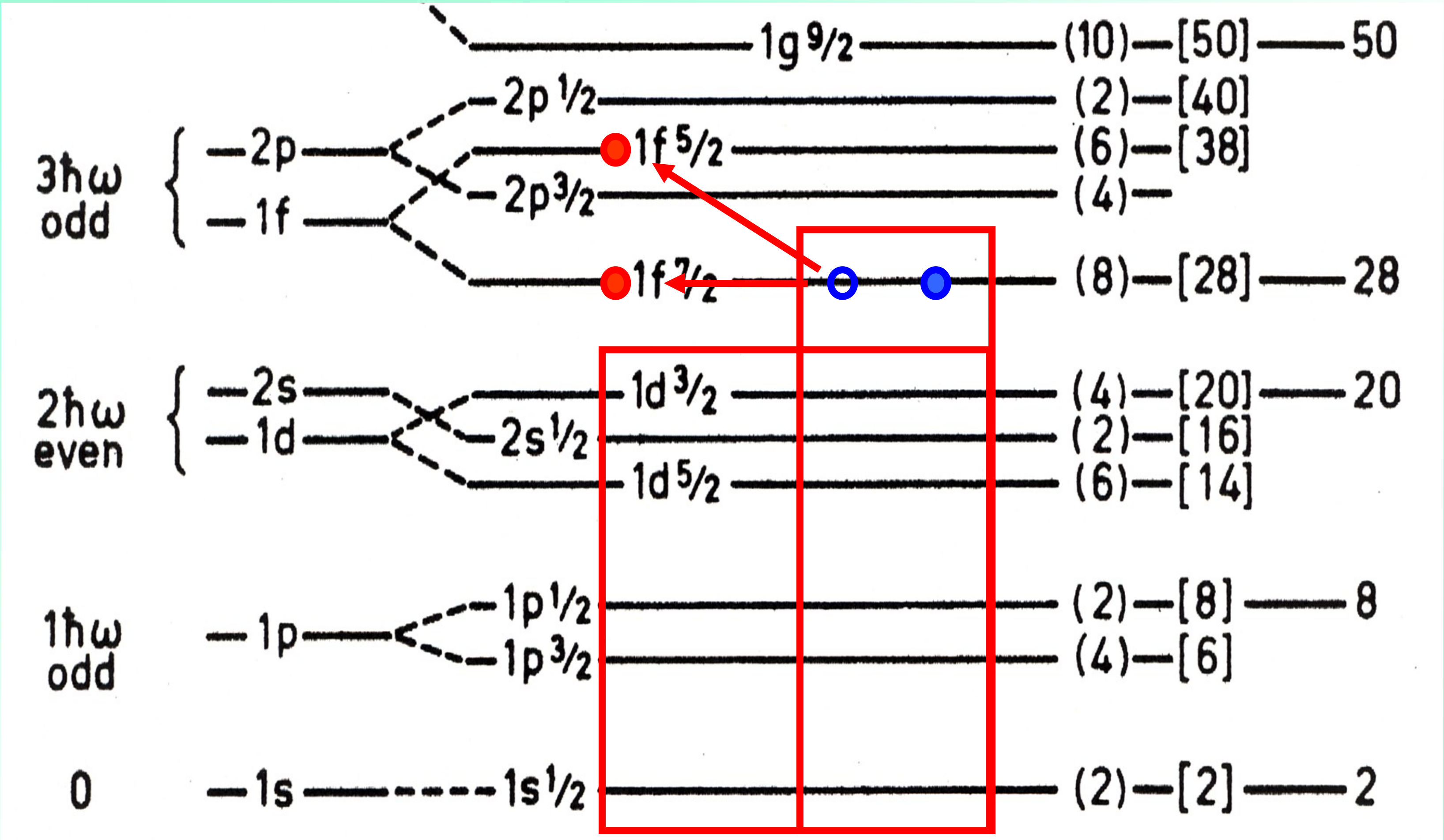
All of these nuclei have N > Z !

$B(GT)^-$ & $B(GT)^+$ strengths from Ca isotopes

Ikeda Sum Rule

$$\Sigma\, B(GT)\beta^- - \Sigma\, B(GT)\beta^+ = 3(N-Z)$$

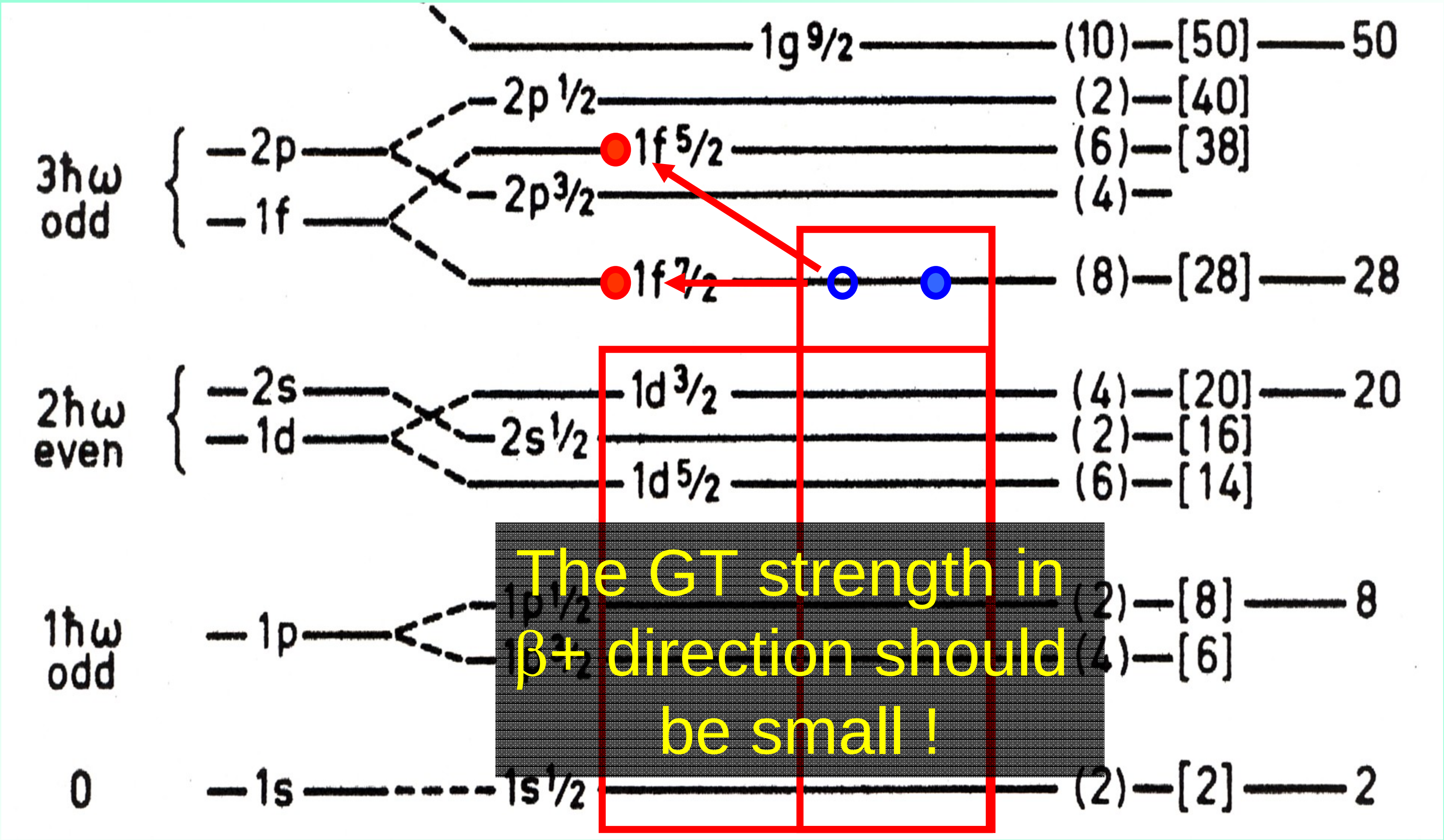
B(GT)$^-$ & B(GT)$^+$ strengths from Ca isotopes



neutron: $f_{7/2} \rightarrow$ proton $f_{7/2}$

neutron: $f_{7/2} \rightarrow$ proton $f_{5/2}$

B(GT)$^-$ & B(GT)$^+$ strengths from Ca isotopes

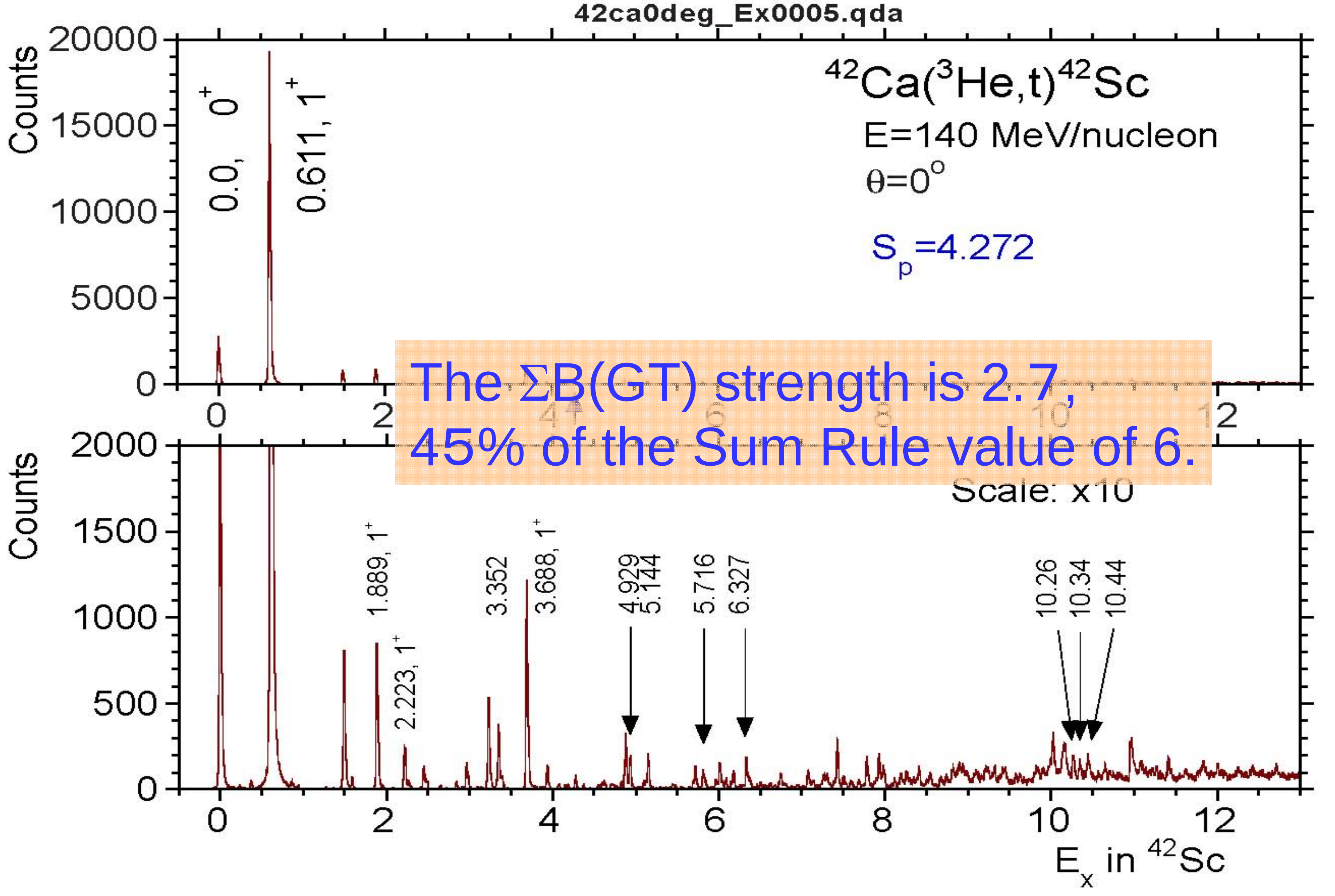


The GT strength in β+ direction should be small !

neutron: $f_{7/2} \rightarrow$ proton $f_{7/2}$

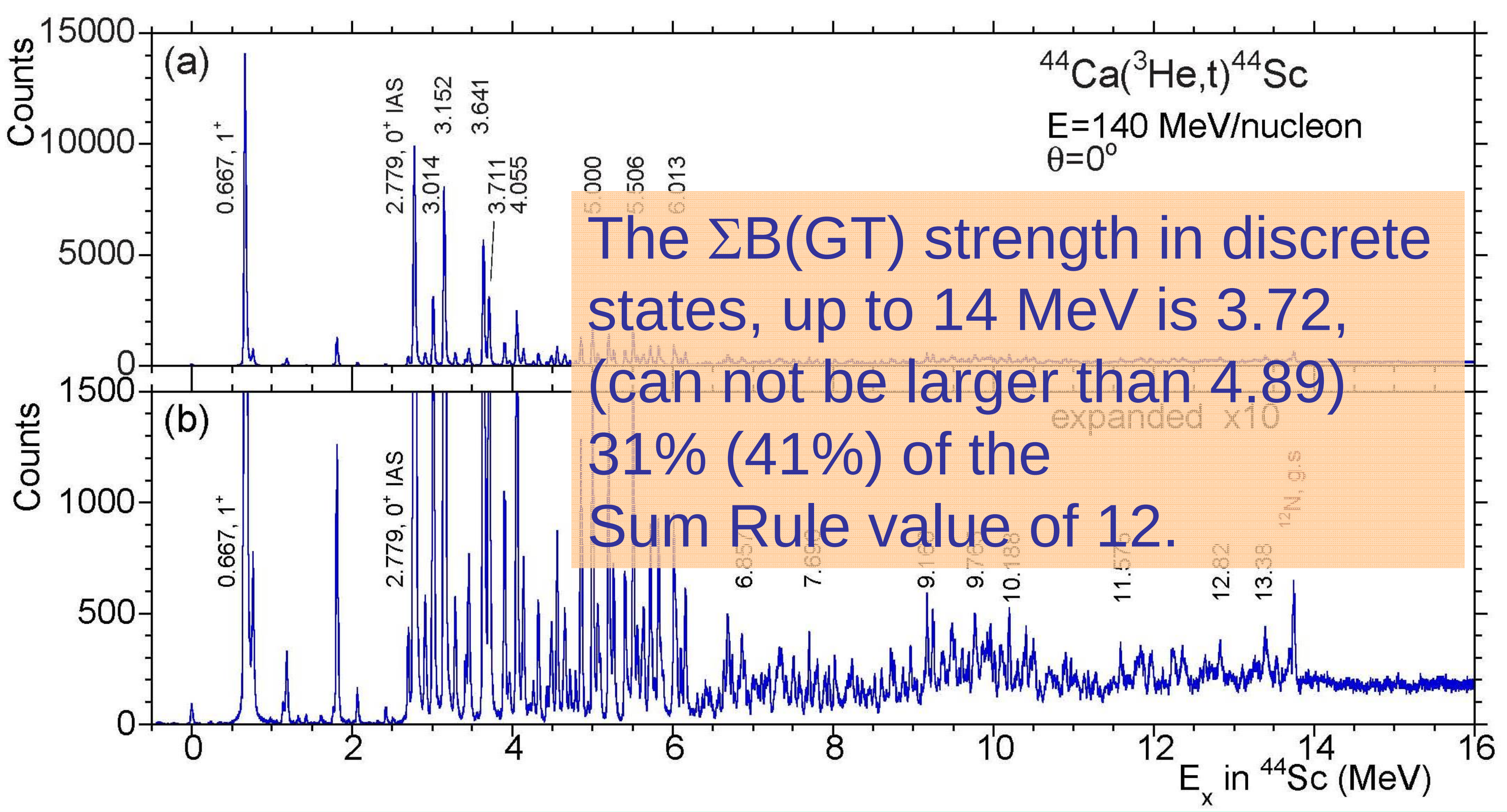
neutron: $f_{7/2} \rightarrow$ proton $f_{5/2}$

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



The ΣB(GT) strength is 2.7,
45% of the Sum Rule value of 6.

$^{44}Ca(^{3}He,t)^{44}Sc$ in 2 scales



The ΣB(GT) strength in discrete states, up to 14 MeV is 3.72, (can not be larger than 4.89) 31% (41%) of the Sum Rule value of 12.

Y. Fujita et al., PRC in press

ΣB(GT) in ^{48}Ca(p,n)^{48}Sc

In E_x < 30 MeV,
ΣB(GT+IVSD =ΔL=0)
is 15.3,
which is 64(9)% of the
Ikeda Sum Rule value
of 3(N-Z) =24

K. Yako et al.,
PRL103 (2009)

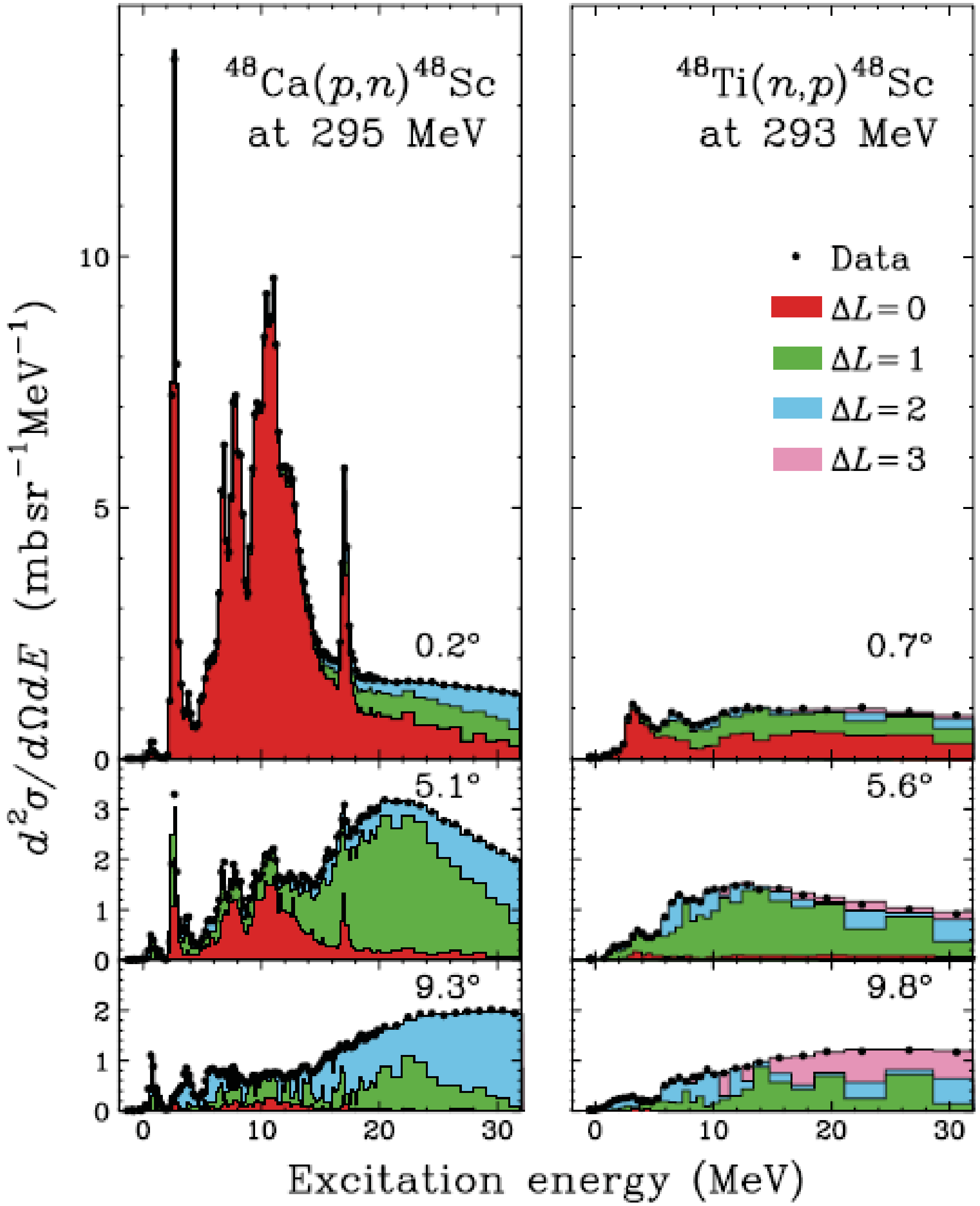


FIG. 1 (color). Double-differential cross sections for the ^{48}Ca(p, n)^{48}Sc (left-hand panel) and ^{48}Ti(n, p)^{48}Sc (right-hand panel) reactions. The histograms show the MD analysis results.

Summary

GT ($\sigma\tau$) operator : a simple operator !

* GT transitions: sensitive to the structure of |i> and |f>

High resolution of the (^{3}He,t) reaction

* Fine structures of GT transitions

(Precise comparison with mirror β-decay results)

➔ Low-energy Super GT state (LESGT state)

➔ Sum Rule values in Ca isotopes?

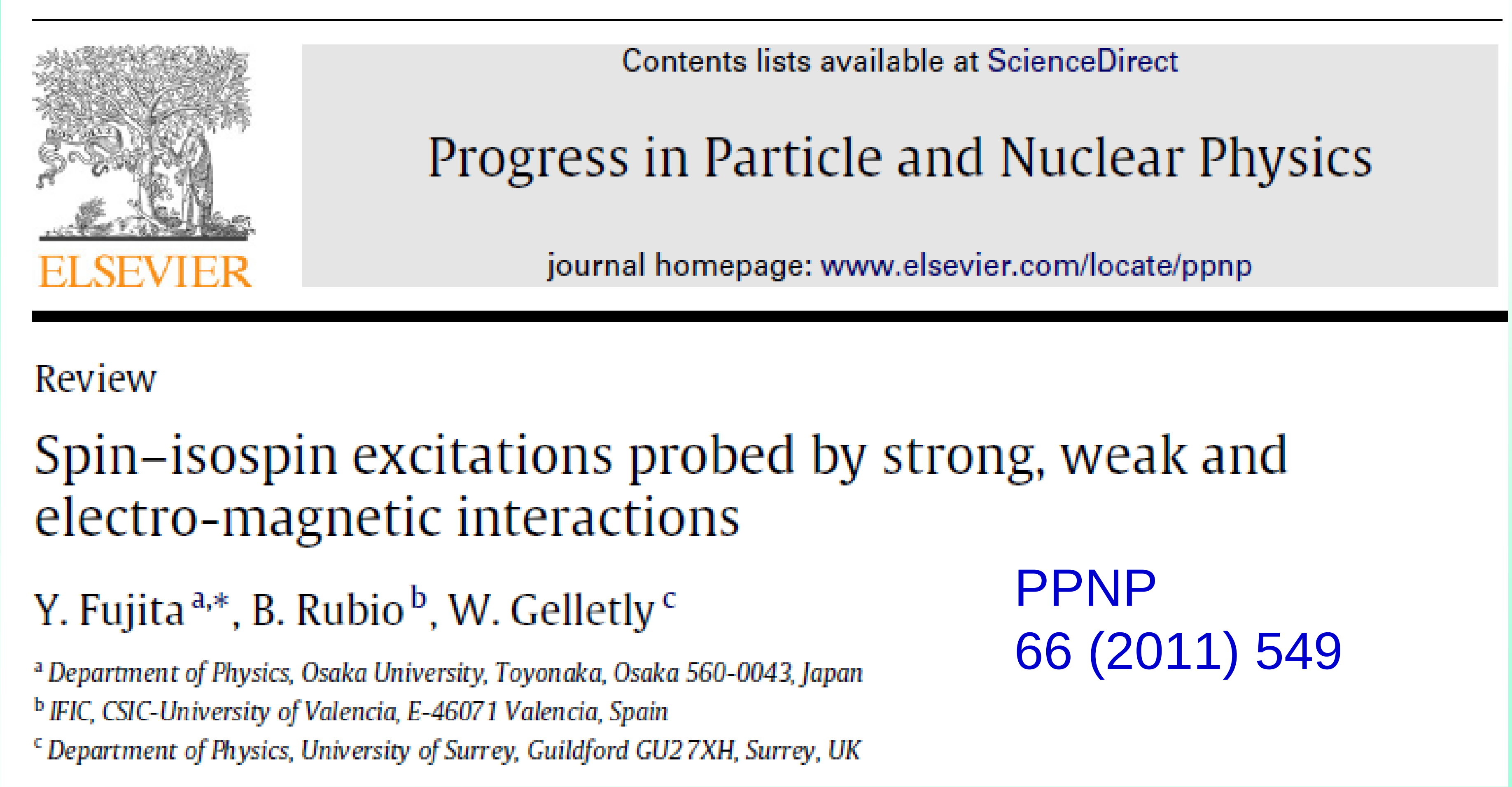
We got a key to study the IS *pn*-interaction !

(May be connected to Tensor ?)

GT-study Collaborations

Bordeaux (France) : β decay
GANIL (France) : β decay
Gent (Belgium) : (^{3}He, t), (d, ^{2}He), (γ, γ’), theory
GSI, Darmstadt (Germany) : β decay, theory
ISOLDE, CERN (Switzerland) : β decay
iThemba LABS. (South Africa) : (p, p’), (^{3}He, t)
Istanbul (Turkey): (^{3}He, t), β decay
Jyvaskyla (Finland) : β decay
Koeln (Germany) : γ decay, (^{3}He, t), theory
KVI, Groningen (The Netherlands) : (d, ^{2}He)
Leuven (Belgium) : β decay
LTH, Lund (Sweden) : theory
Osaka University (Japan) : (p, p’), (^{3}He, t), theory
Surrey (GB) : β decay
TU Darmstadt (Germany) : (e, e’), (^{3}He, t)
Valencia (Spain) : β decay
Michigan State University (USA) : theory, (t, ^{3}He)
Muenster (Germany) : (d, ^{2}He), (^{3}He,t)
Univ. Tokyo and CNS (Japan) : theory, β decay

Advertisement



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Review

Spin–isospin excitations probed by strong, weak and electro-magnetic interactions

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[b] *IFIC, CSIC-University of Valencia, E-46071 Valencia, Spain*
[c] *Department of Physics, University of Surrey, Guildford GU2 7XH, Surrey, UK*

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66 (2011) 549