Roles of pairing interactions in the formation of low- and high-energy Gamow-Teller excitations

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COMEX5, Sep. 14-18, 2015

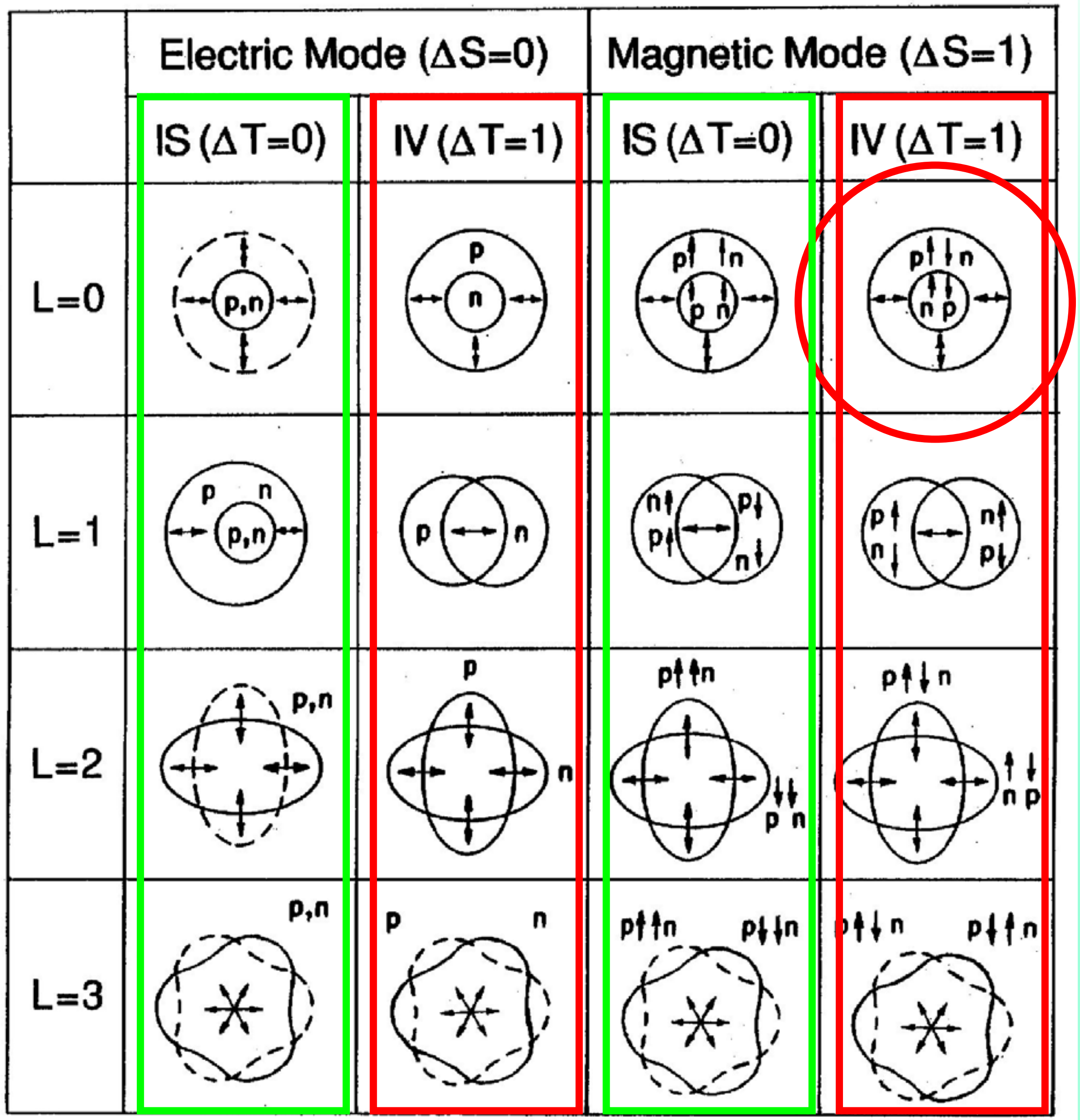
Neptune driving Waves

Neptune =
weak interaction

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

Walter Crane, 1892

Vibration Modes in Nuclei (Schematic)



Gamow-Teller mode

(στ)

Isovector
&
Spin
excitation

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 !

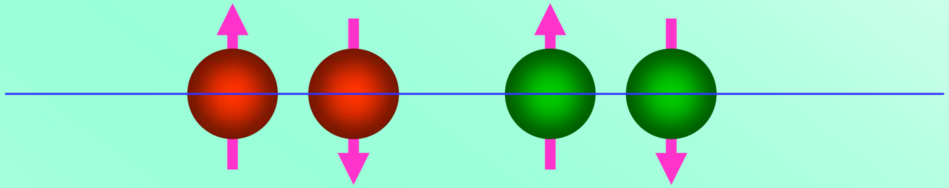
IS & IV pairing and "Residual Interactions"

However, J^{π} values of even-even nuclei are $J^{\pi}=0^{+}$.

➡ We notice the importance of the spin-spin coupling.

(pairing interaction)

ex. $1s_{1/2}$

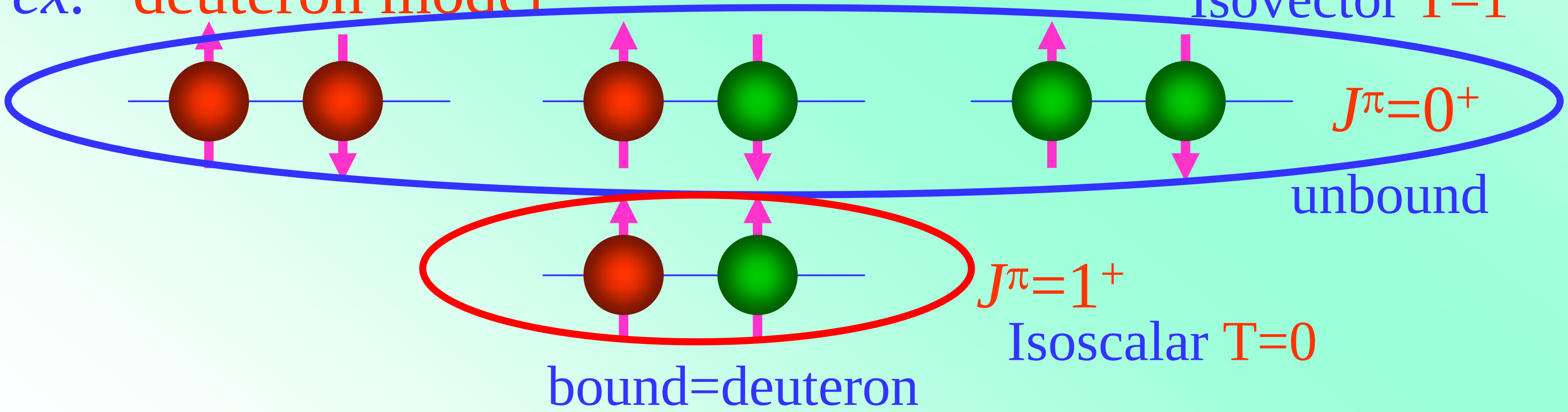


$={}^{4}\mathrm{He}=\alpha$

$J^{\pi}=0^{+}$

In general, interactions that are not included in a model are called "residual interactions"

ex. "deuteron model"



**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 & Nuclear Reaction

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

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

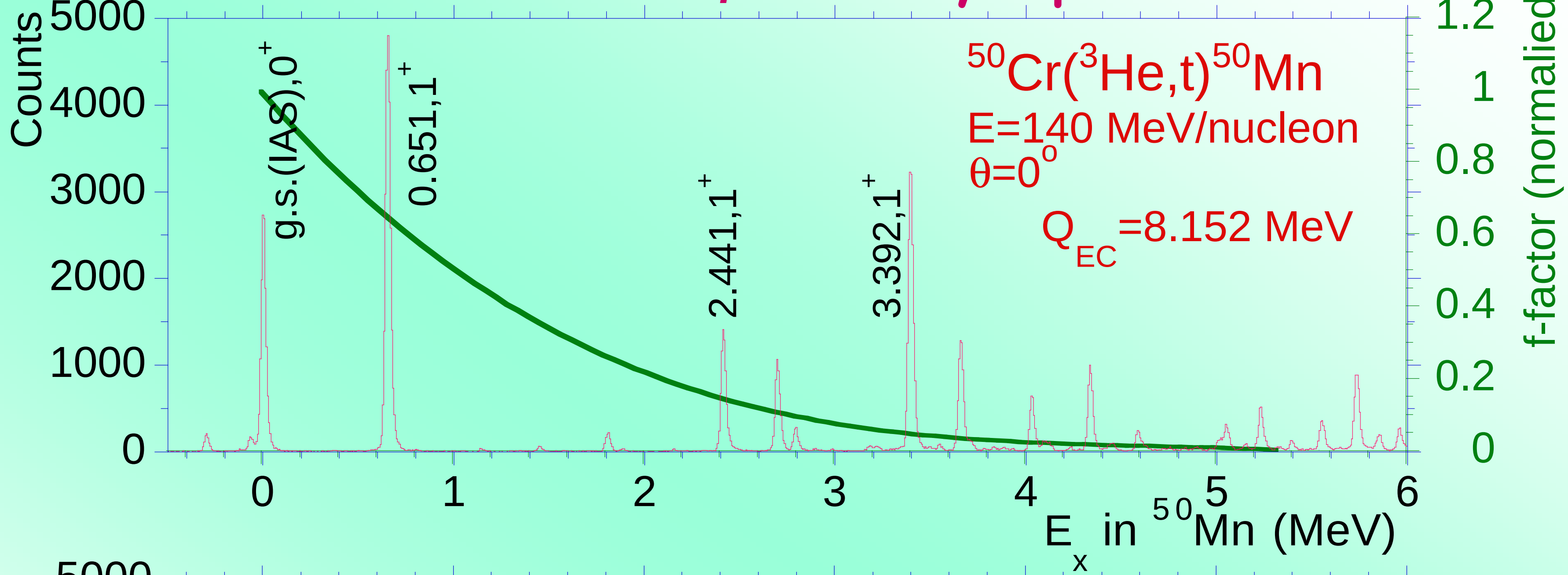
ⓧ structure

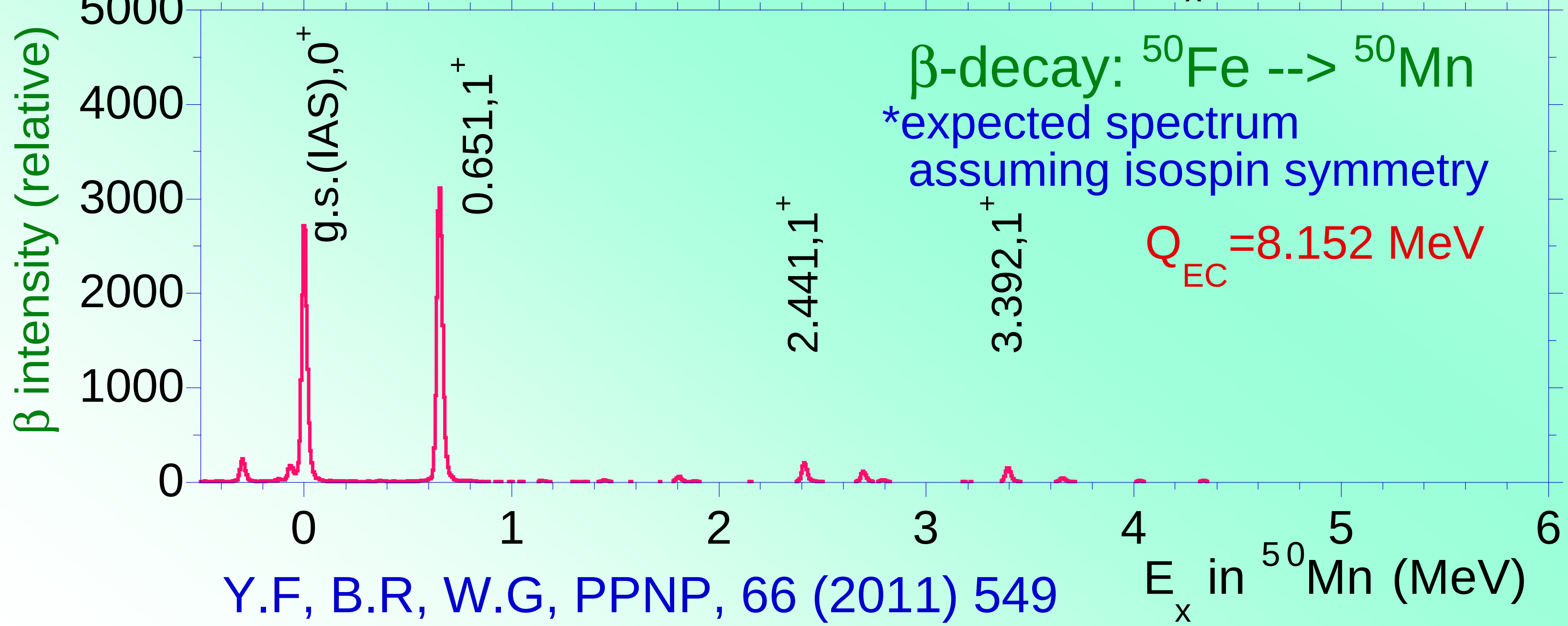
=(matrix element)^2

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

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

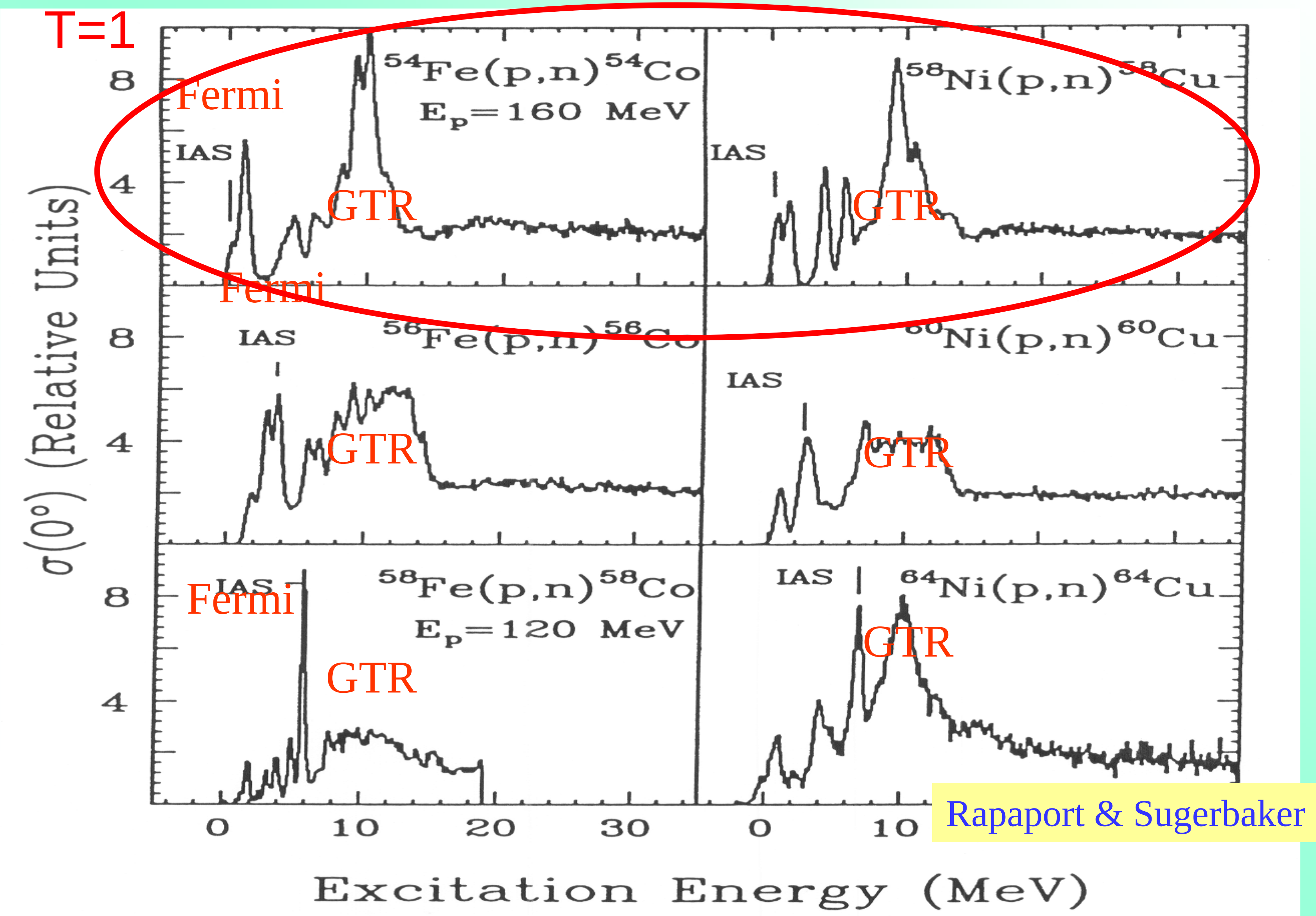
Simulation of β-decay spectrum



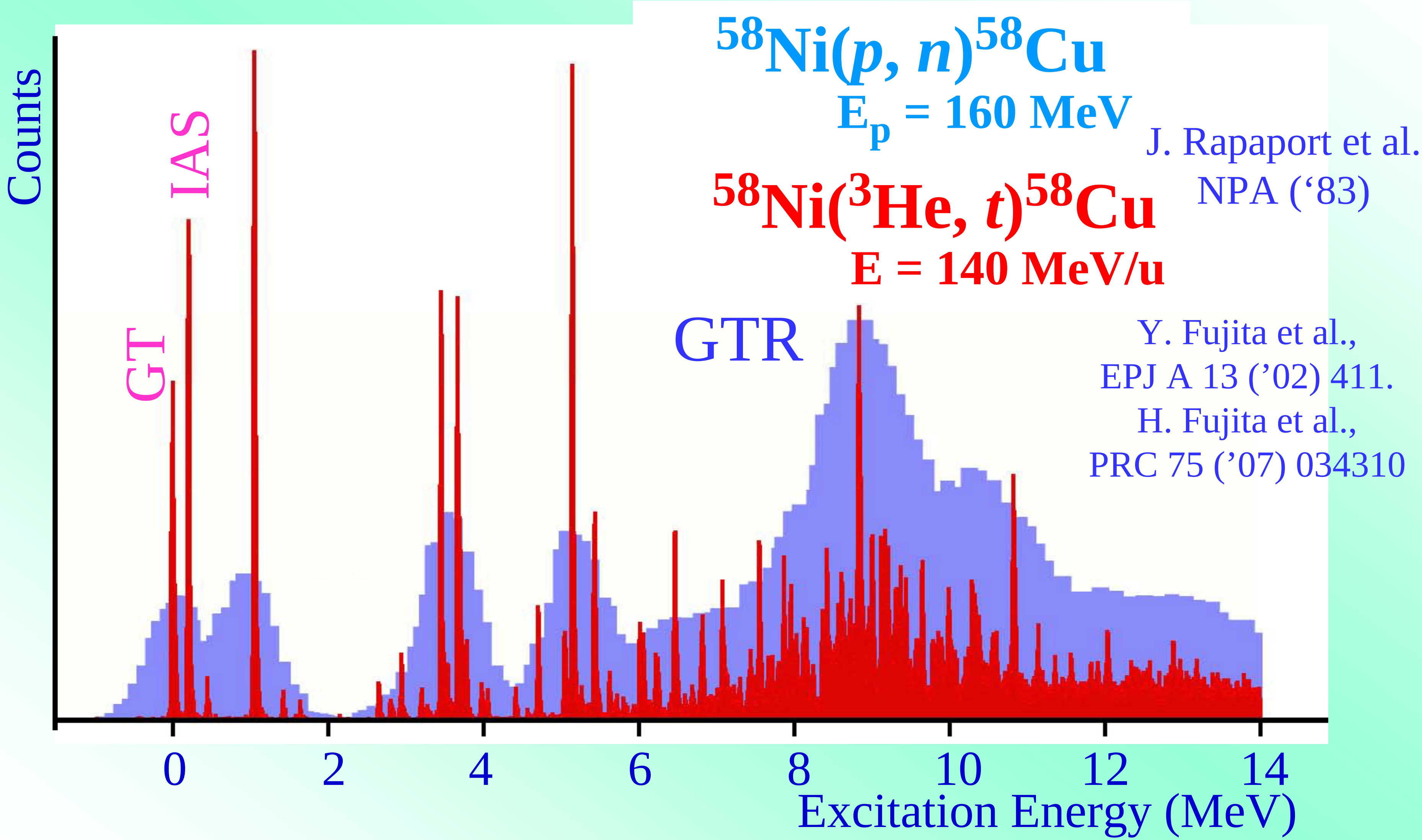


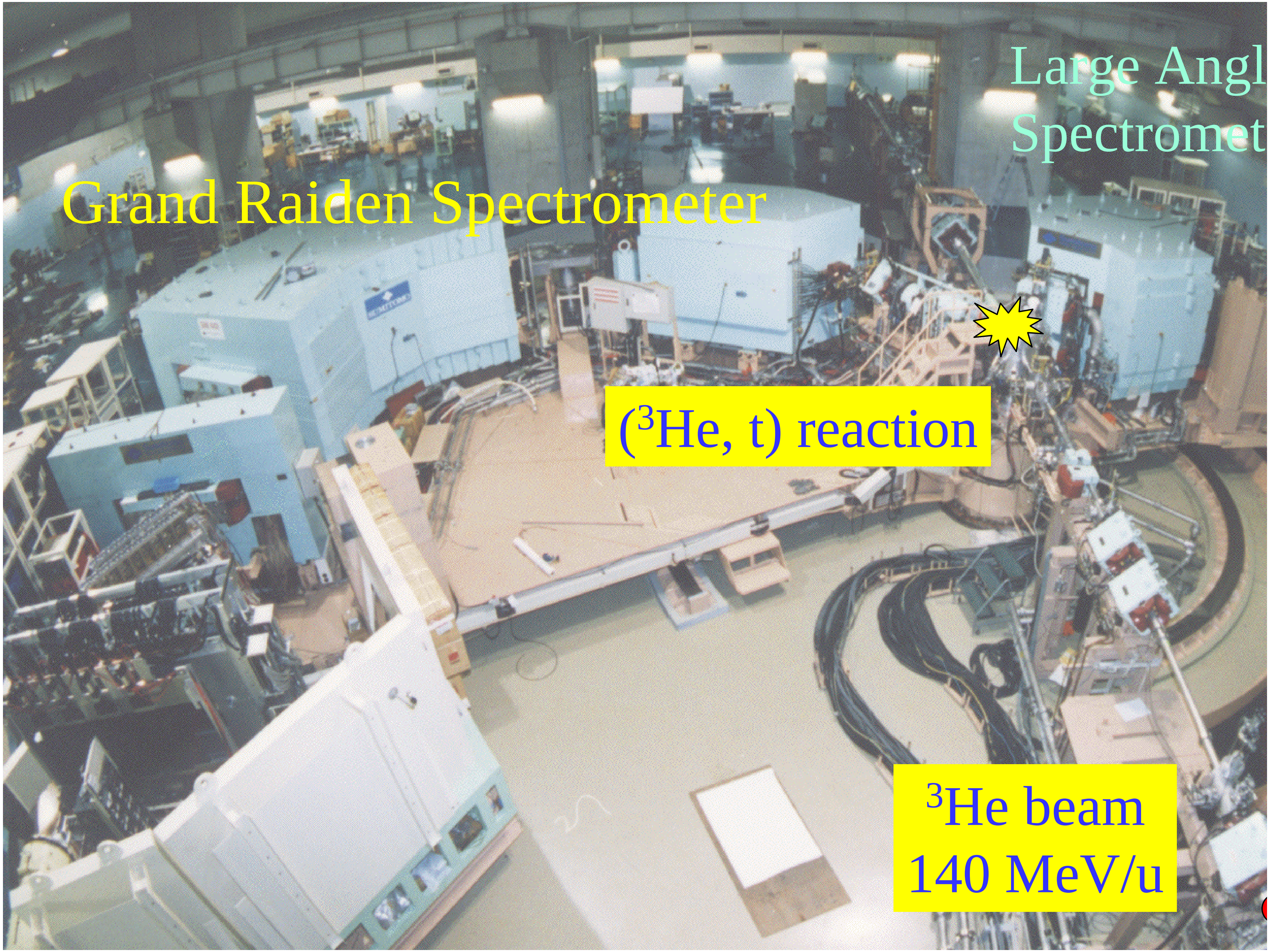
Y.F, B.R, W.G, PPNP, 66 (2011) 549

(p, n) spectra for Fe and Ni Isotopes

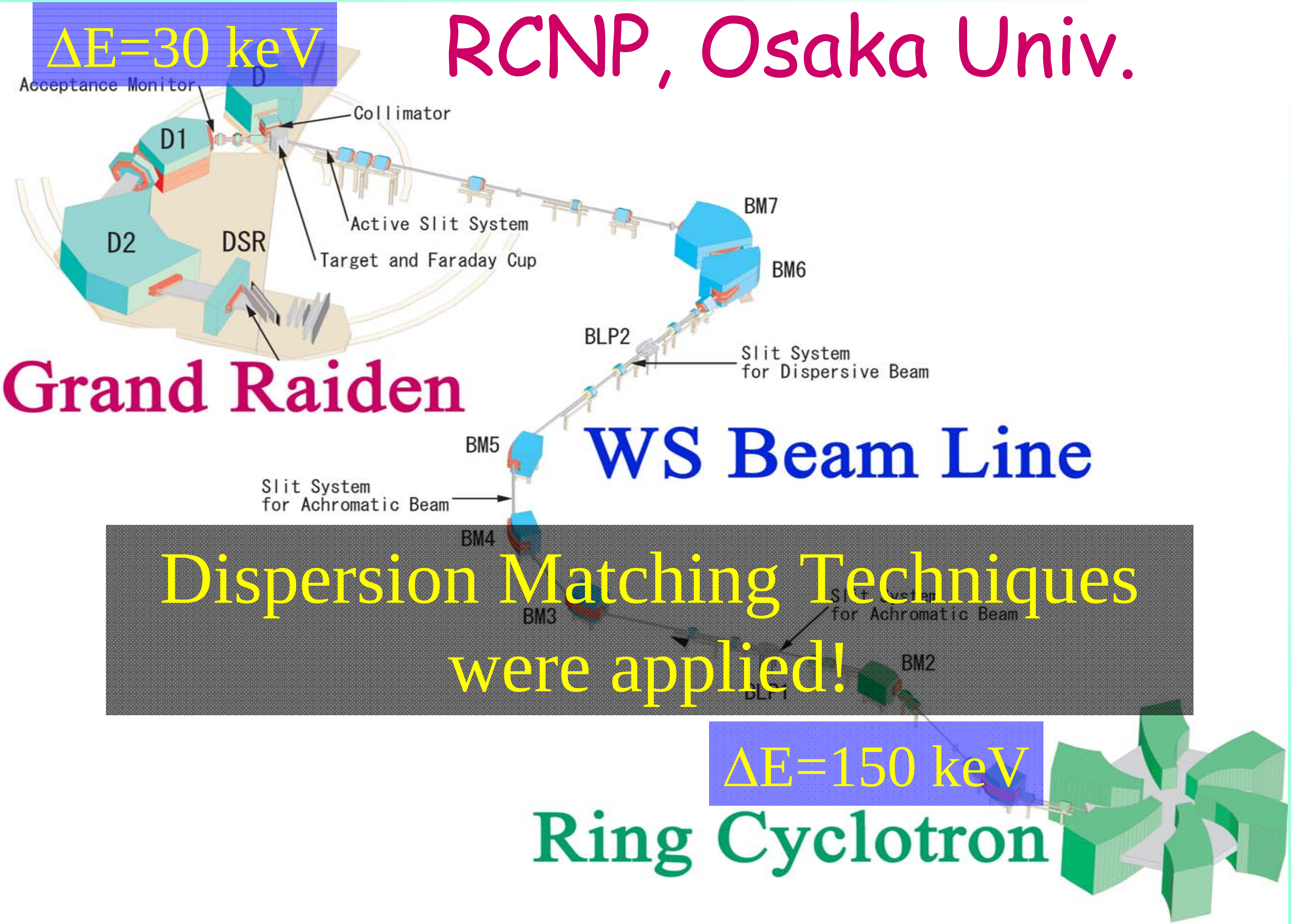


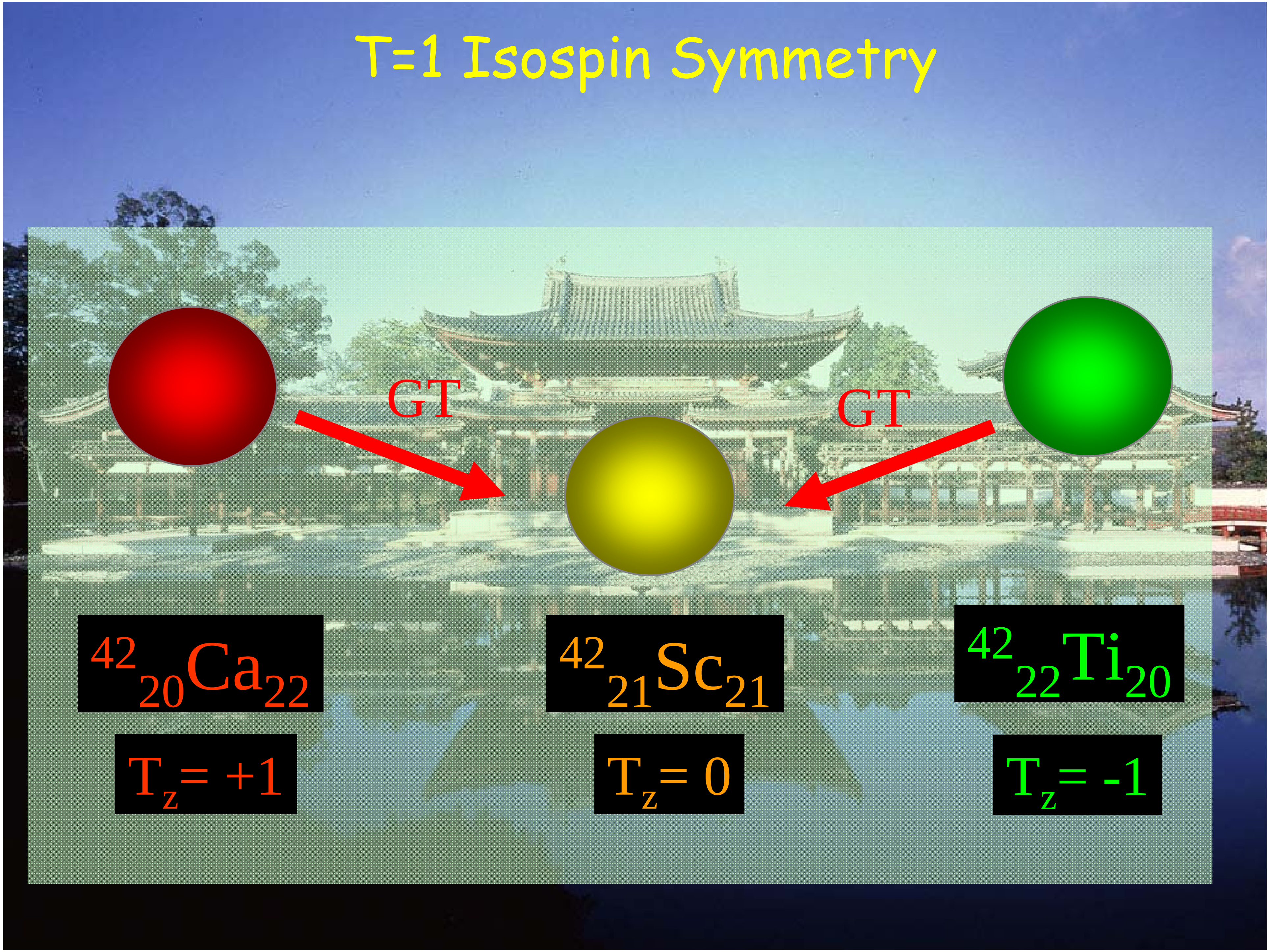
Comparison of (p, n) and (^{3}He,t) 0^o spectra



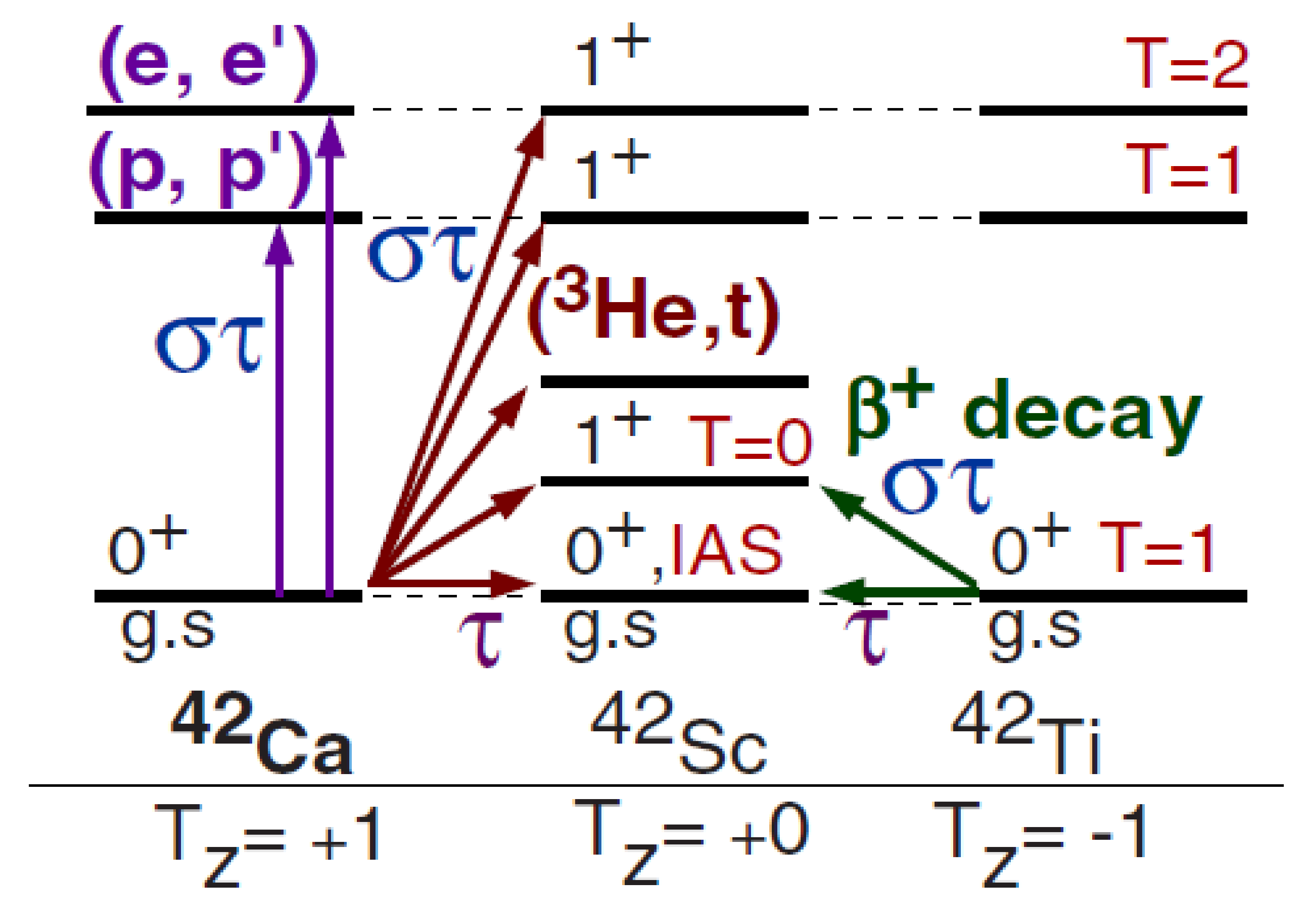

Large Angl
Spectromet
Grand Raiden Spectrometer
(^{3}He, t) reaction
^{3}He beam
140 MeV/u

RCNP, Osaka Univ.




T=1 Isospin Symmetry
GT
GT
$^{42}_{20}Ca_{22}$
$^{42}_{21}Sc_{21}$
$^{42}_{22}Ti_{20}$
$T_z = +1$
$T_z = 0$
$T_z = -1$

T=1 symmetry : Structures & Transitions



β-decay & Nuclear Reaction

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

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

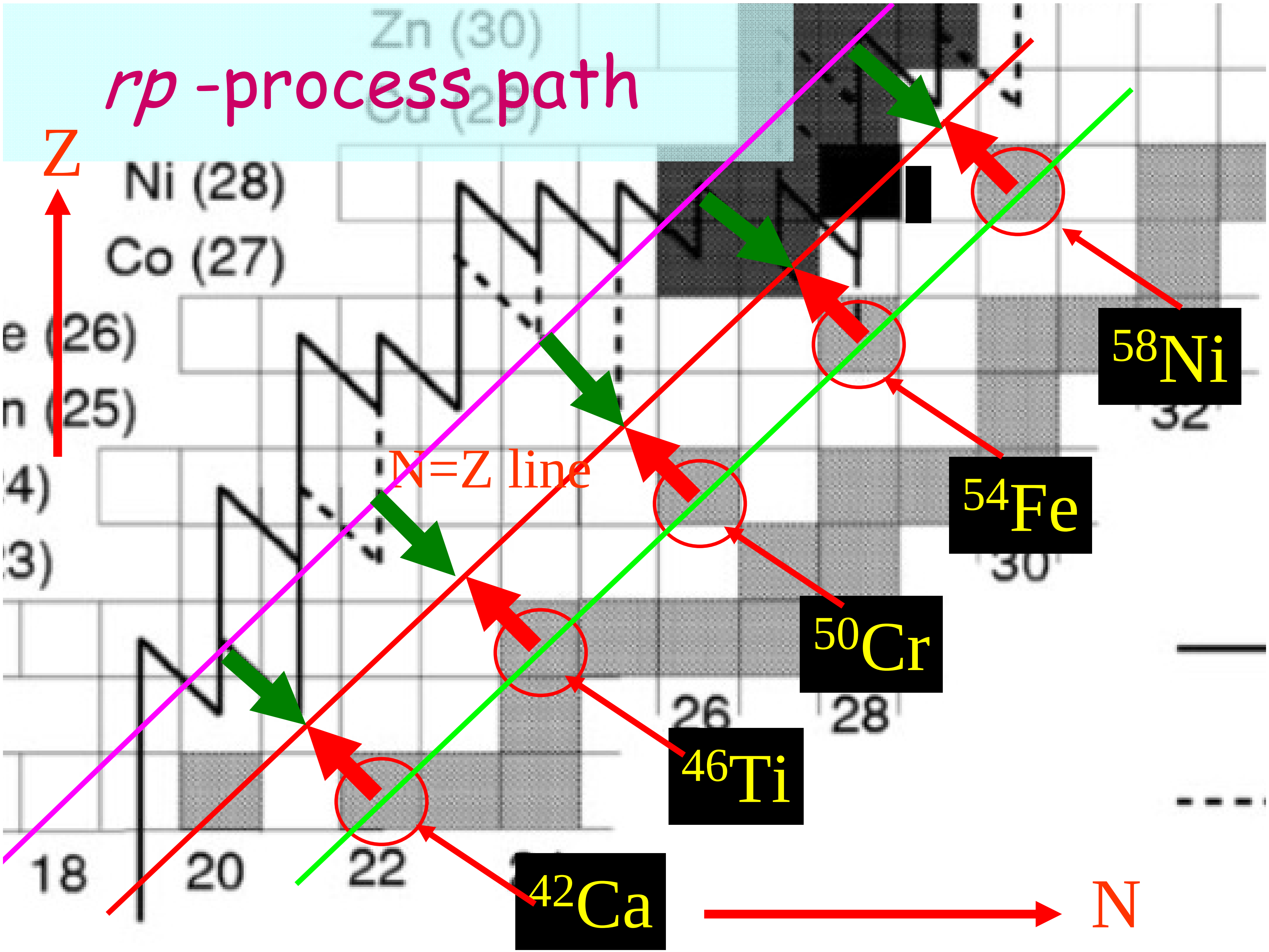
Study of Weak Response of Nuclei
by means of
Strong Interaction !
using β-decay as a reference

A simple reaction mechanism should be achieved !

→ we have to go to high incoming energy

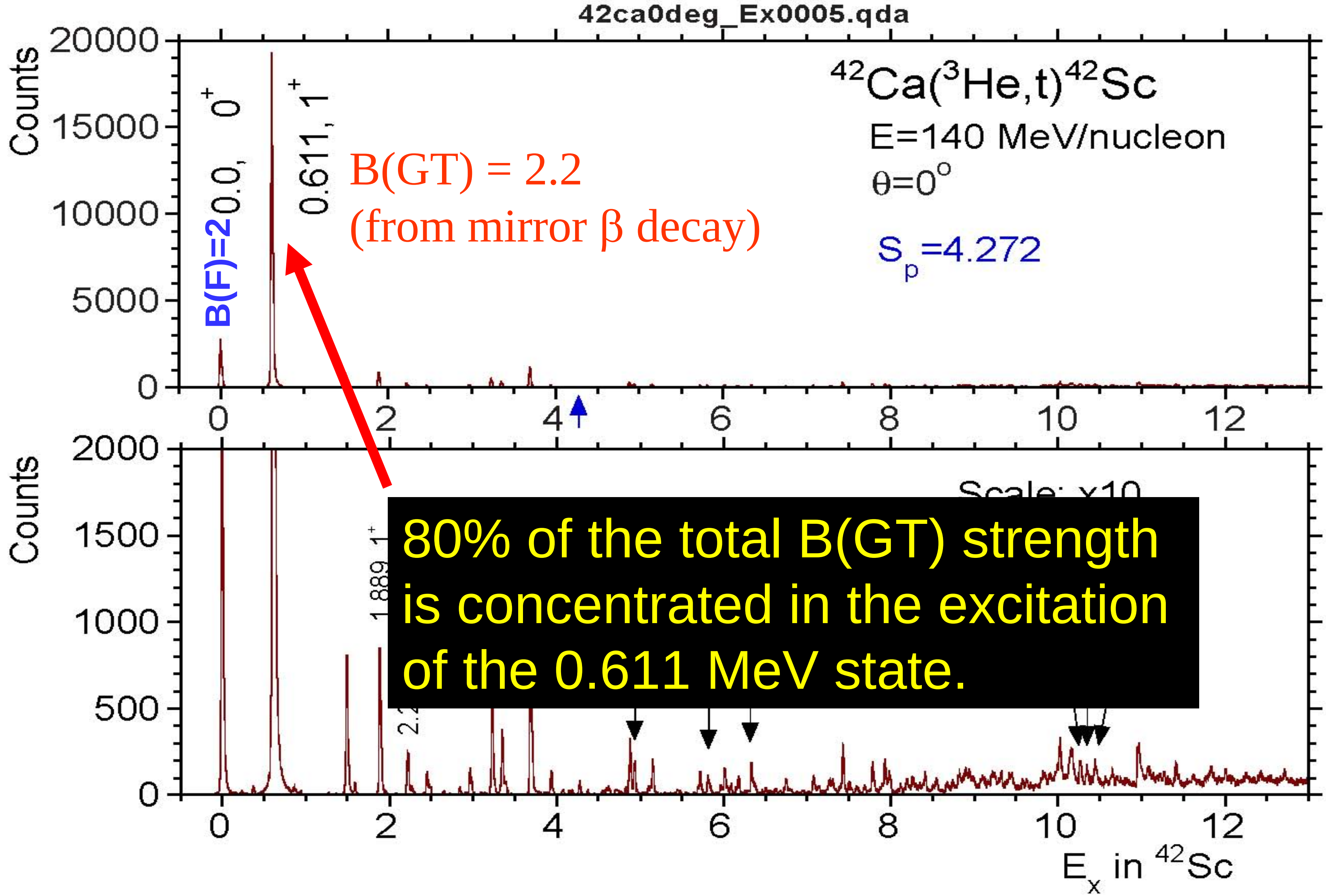
**GT transitions in each nucleus are UNIQUE !

- *pf*-shell nuclei -



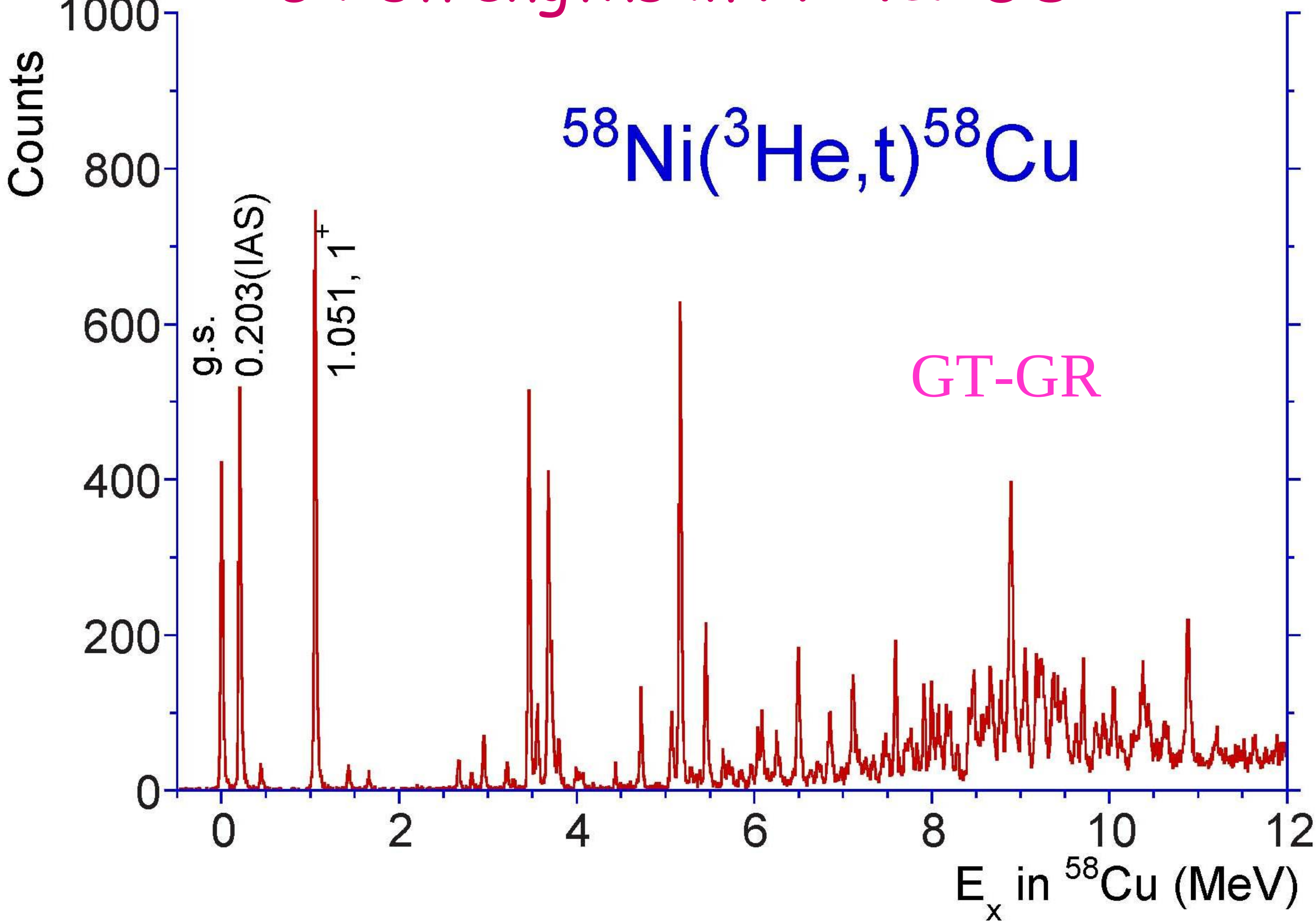
rp -process path
Zn (30)
Cu (29)
Ni (28)
Co (27)
Fe (26)
Mn (25)
(24)
(23)
Z
N=Z line
58Ni
54Fe
50Cr
46Ti
42Ca
18
20
22
24
26
28
30
32
N

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



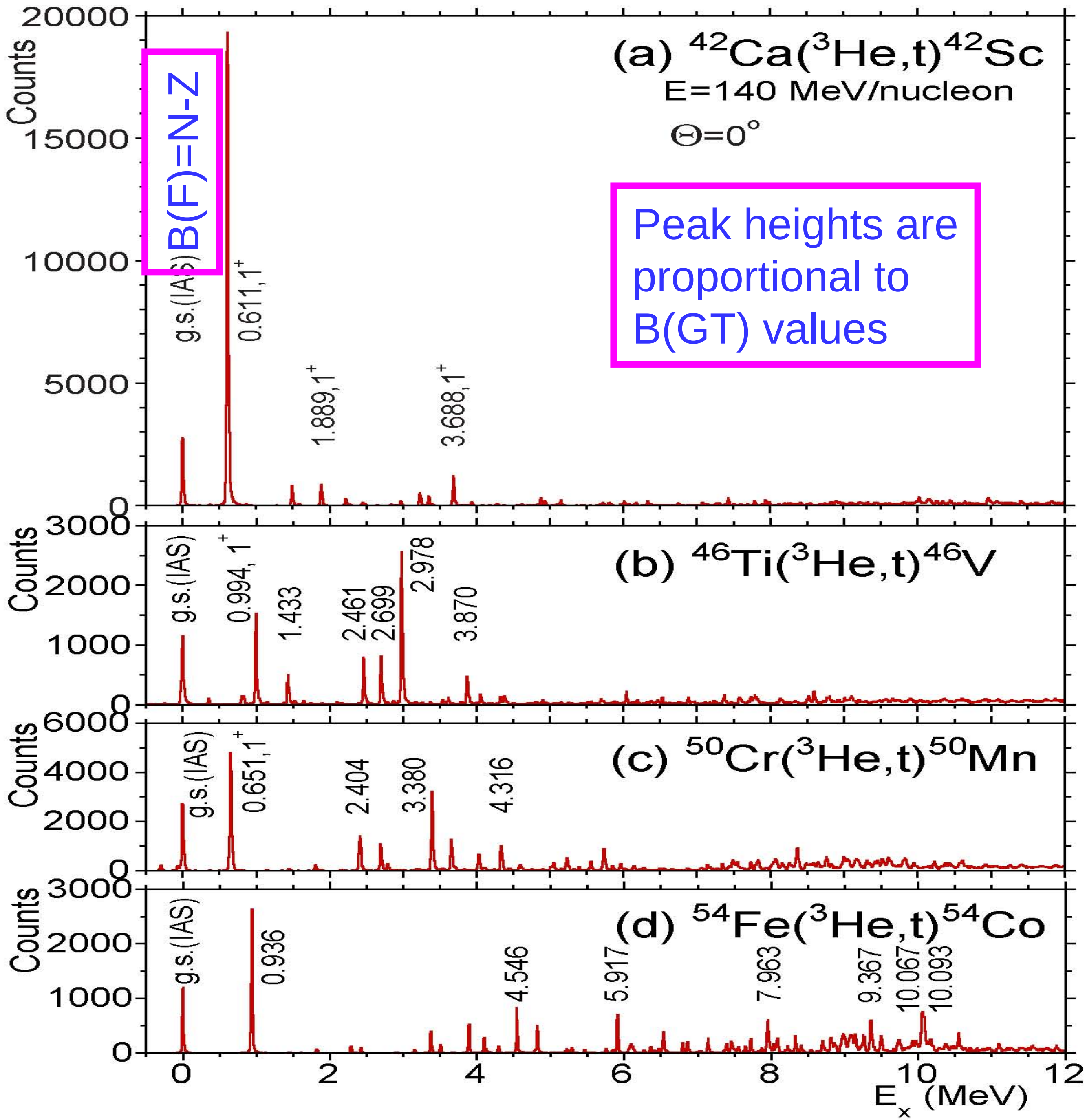
GT states in A=42-54 T_z=0 nuclei

Y. Fujita et al.
PRL 2014
PRC 2015

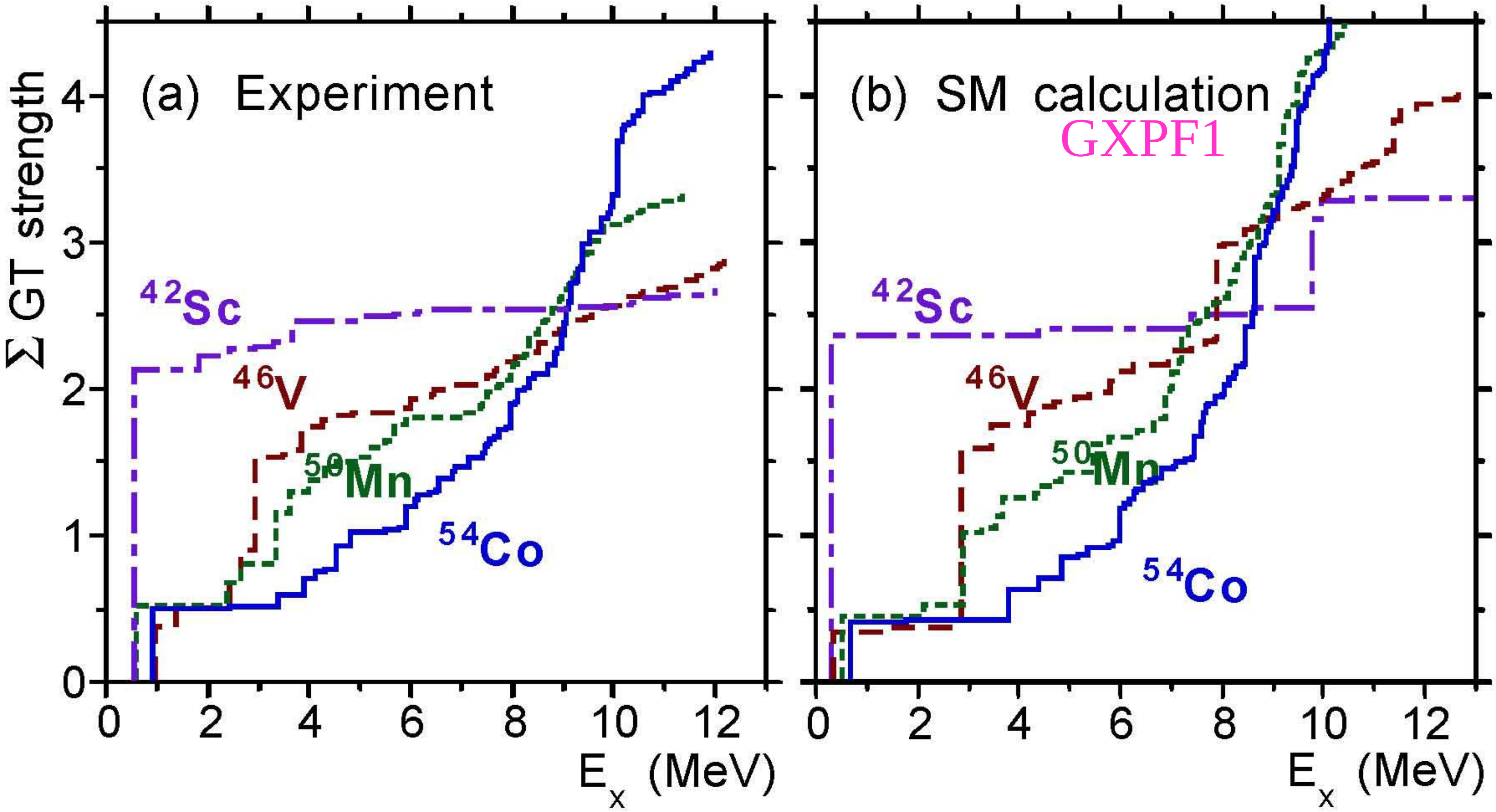
T. Adachi et al.
PRC 2006

Y. Fujita et al.
PRL 2005

T. Adachi et al.
PRC 2012

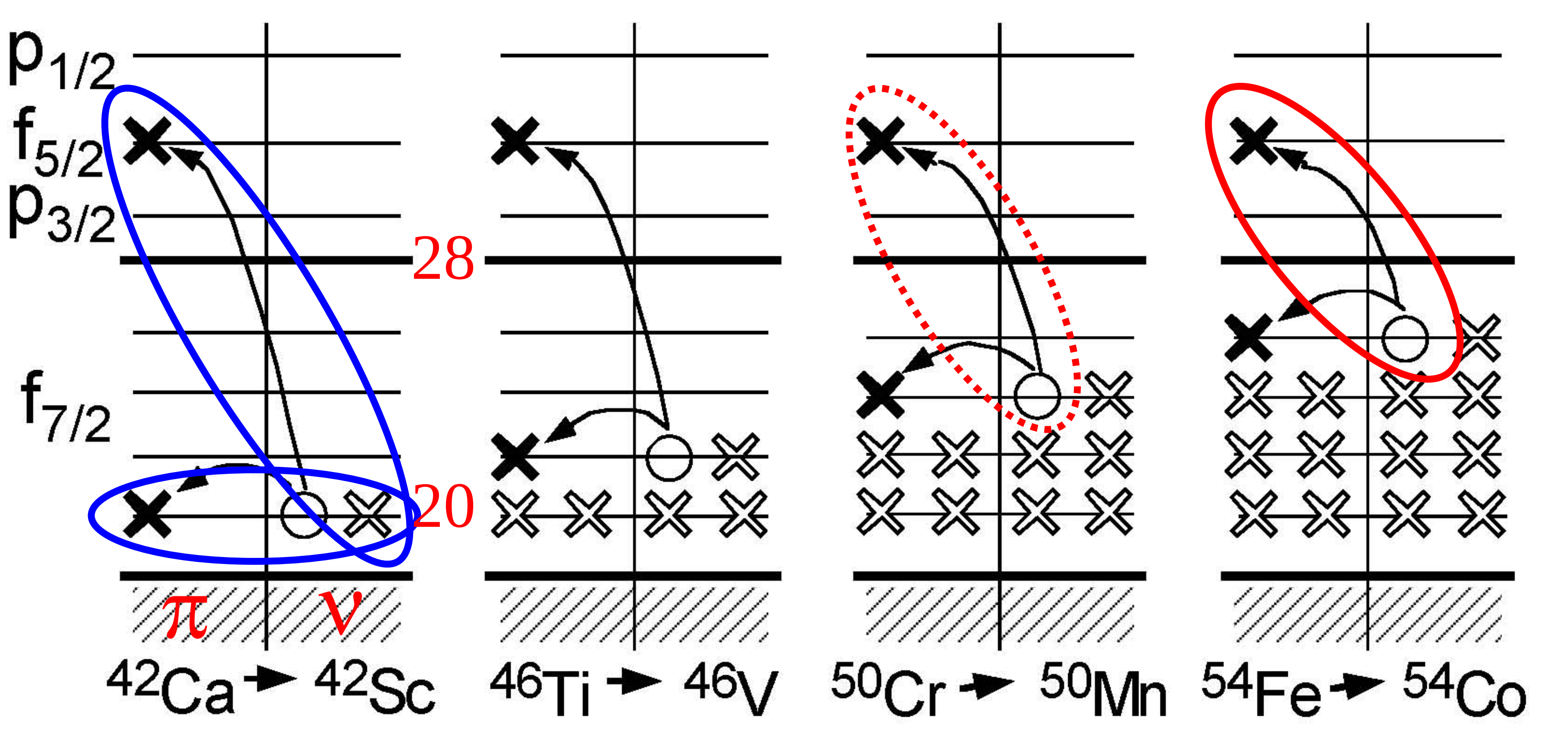


GT-strength: Cumulative Sum



M. Homma et al.

SM Configurations of GT transitions



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

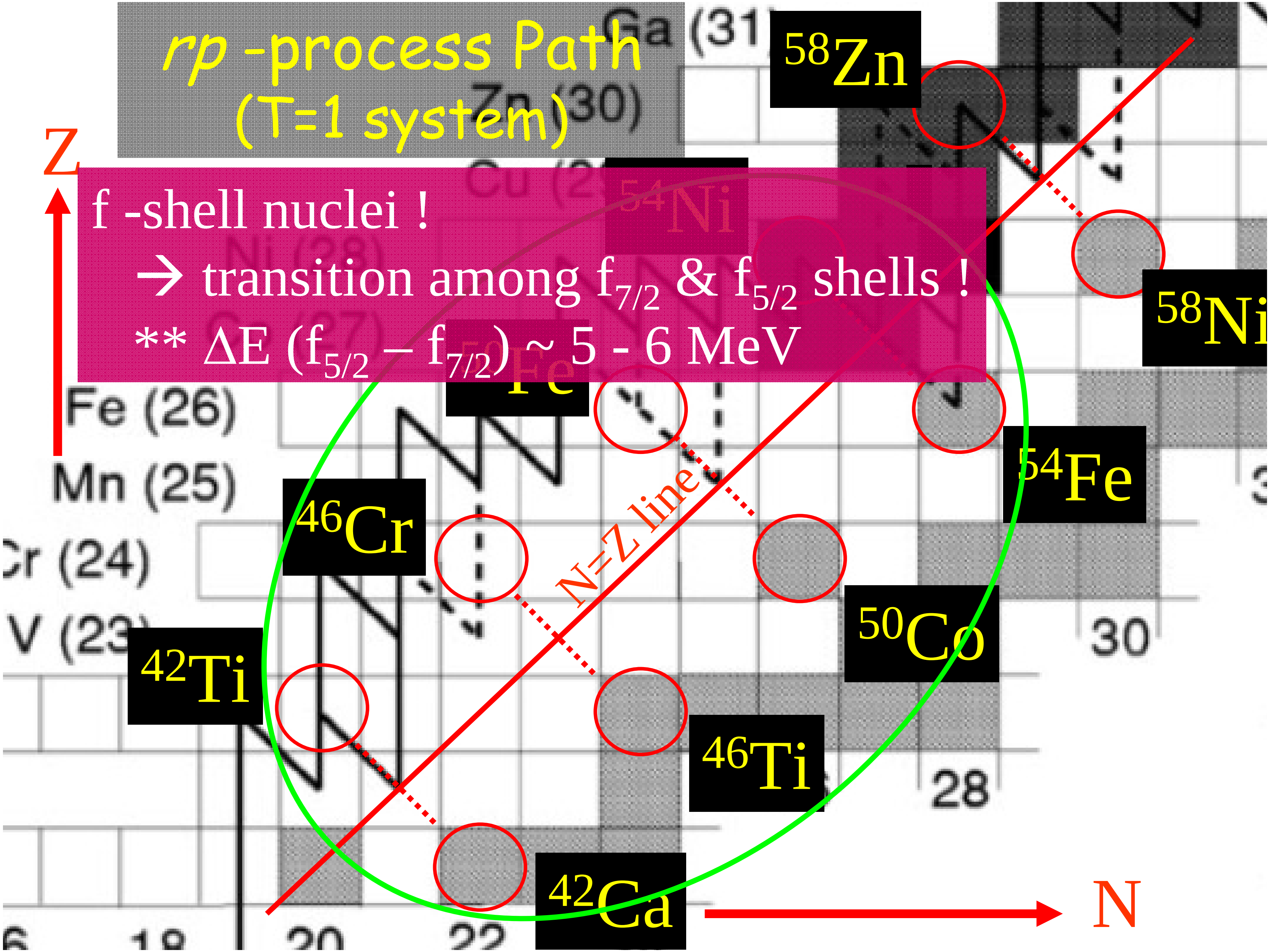
Final nuclei : $N = Z$ ($T_z = 0$)

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



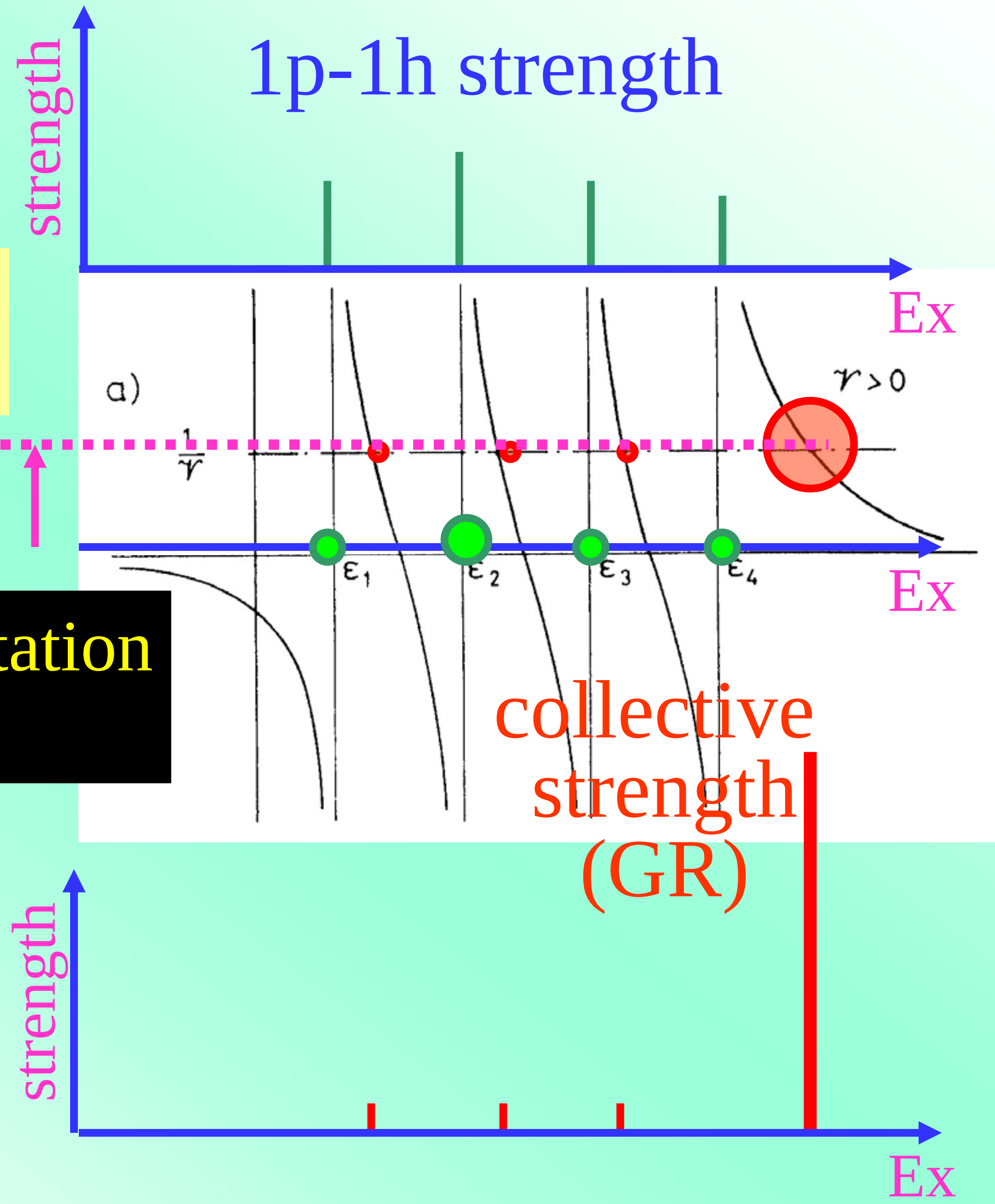
Role of Residual Int. (repulsive)

Single particle-hole strength distribution

Graphical solution of the RPA dispersive eigen-equation

positive = repulsive

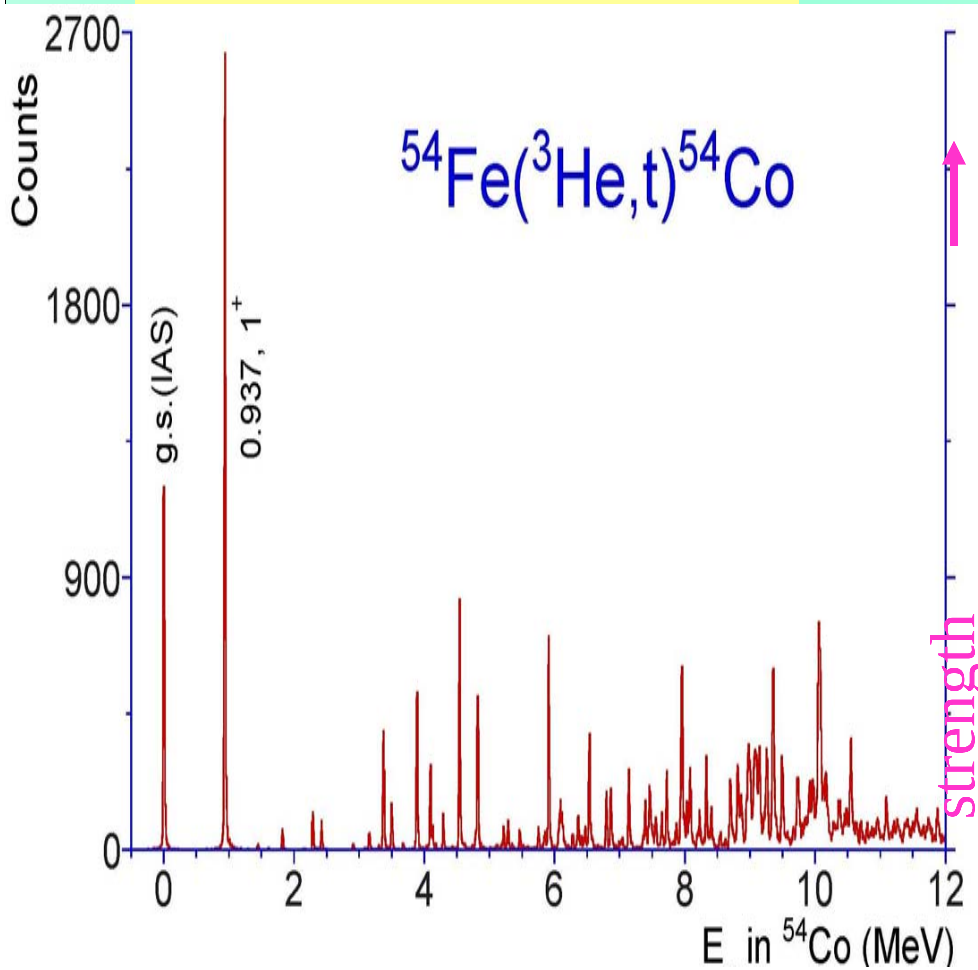
p-h configuration + IV excitation = repulsive

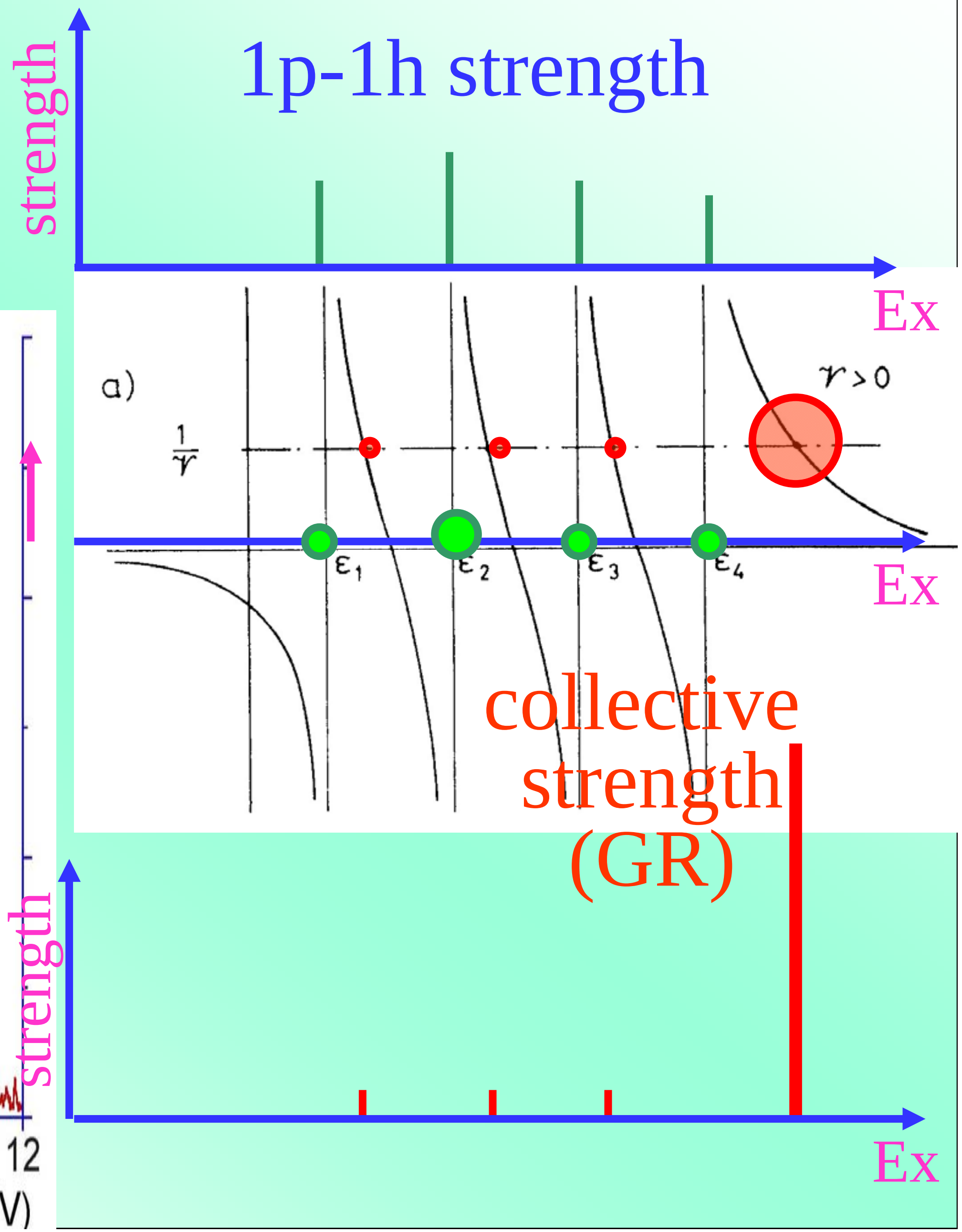


Collective excitation formed by the repulsive residual interaction

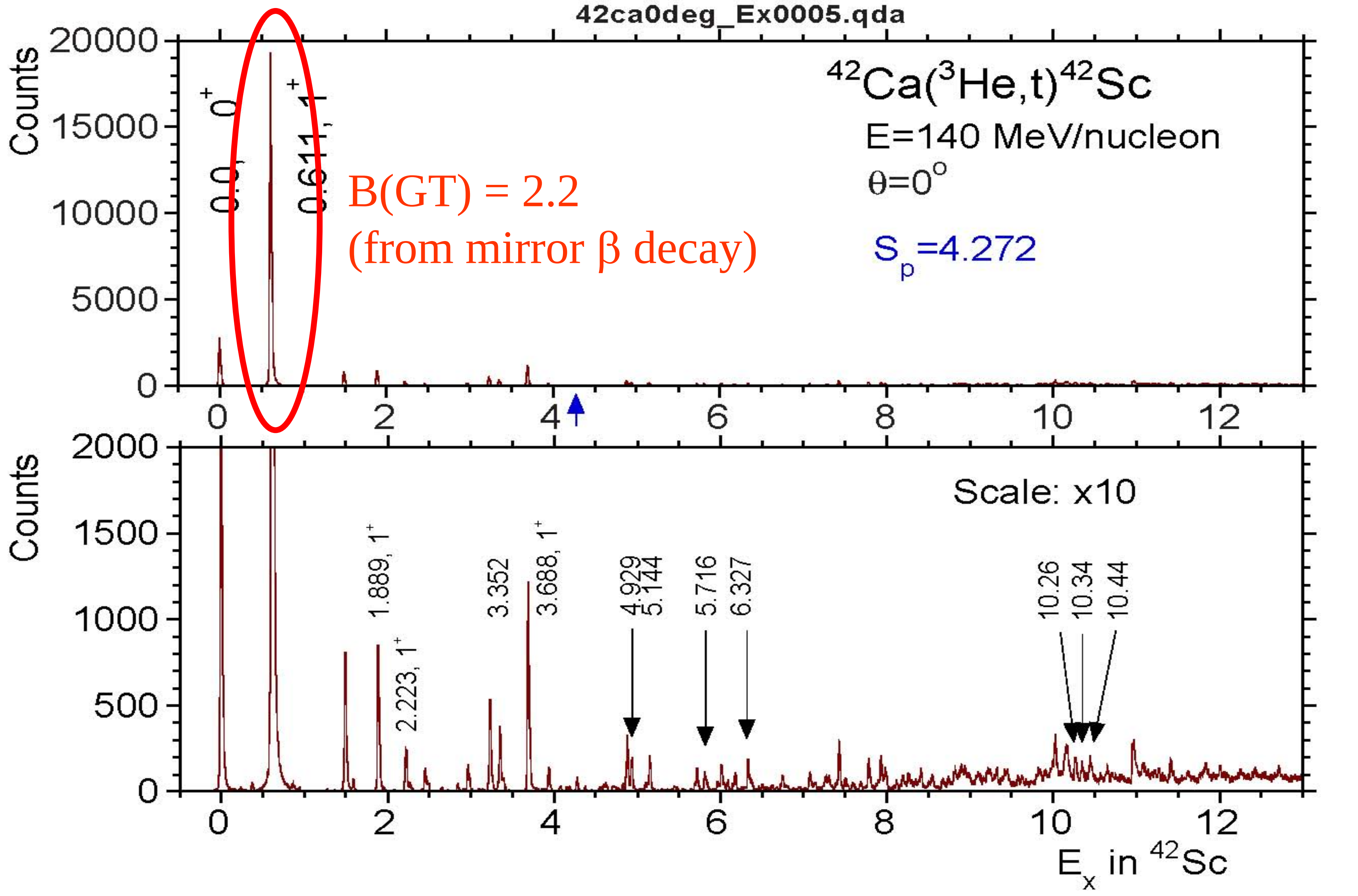
Role of Residual Int. (repulsive)

Collective excitation formed by the repulsive residual interaction



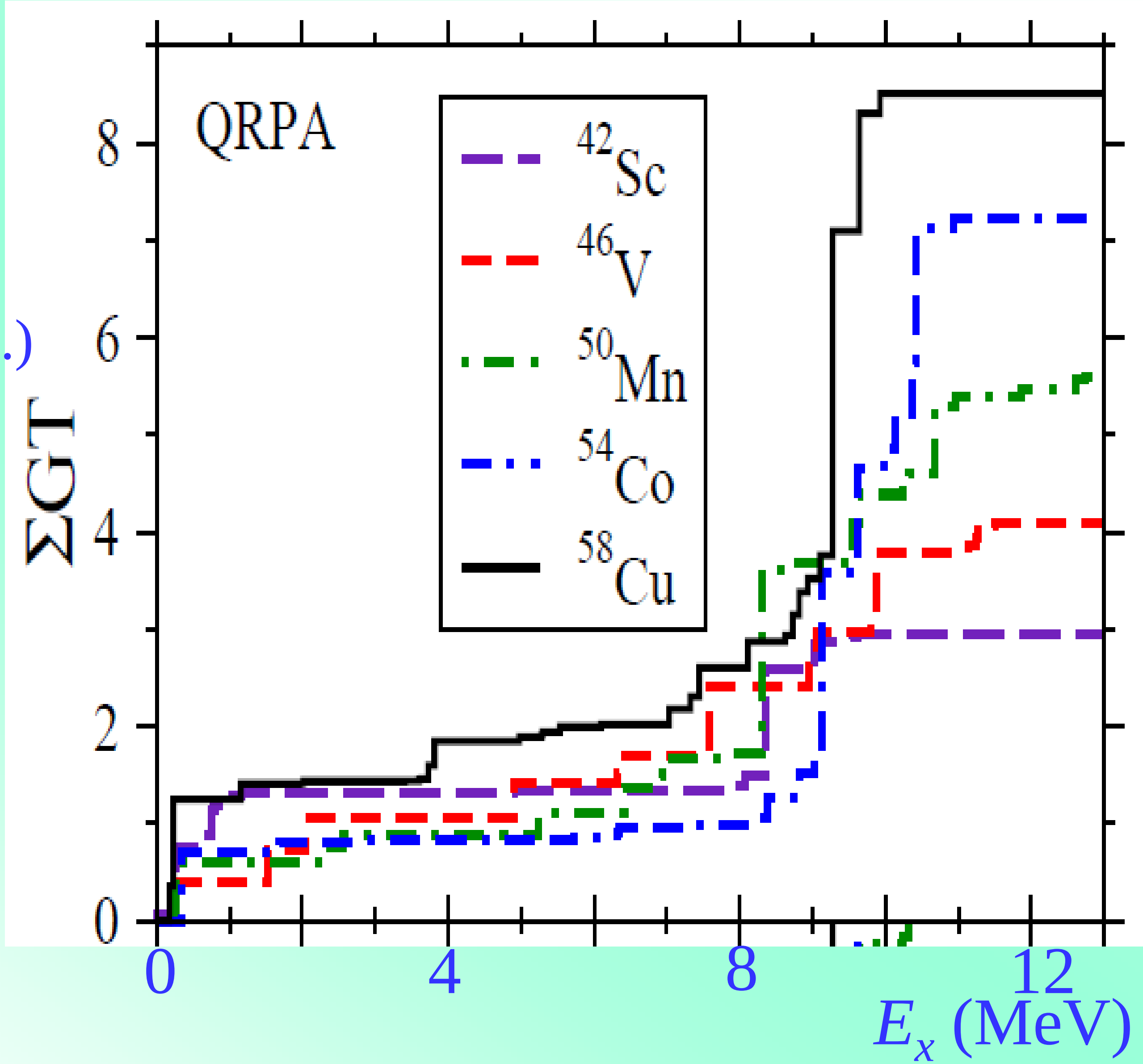


$^{42}Ca(^{3}He,t)^{42}Sc$ in 2 scales



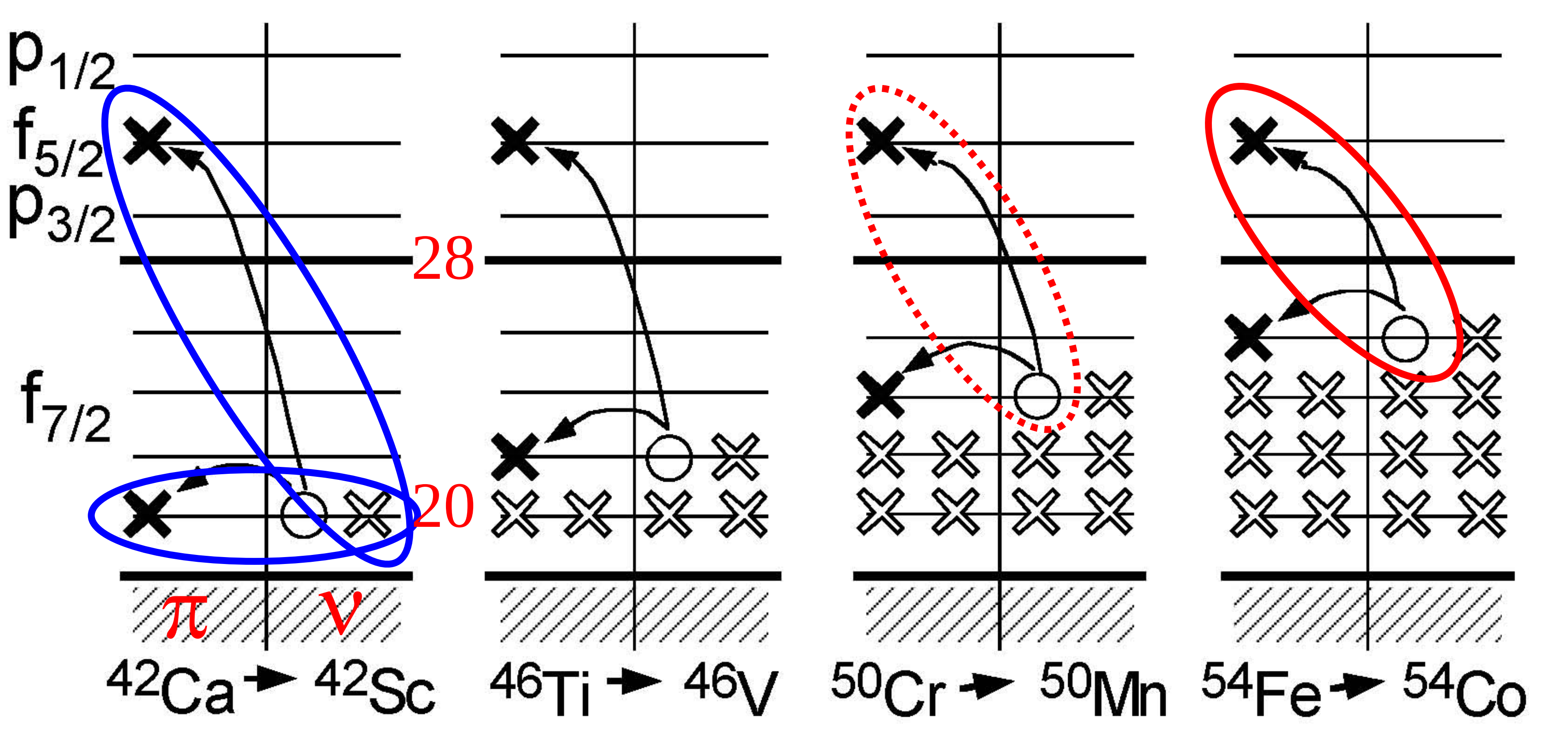
QRPA calculations

using Skyrme int.
(with IV pairing corr.)



Calculation by
P. Sarrigren,
CSIC, Madrid

SM Configurations of GT transitions

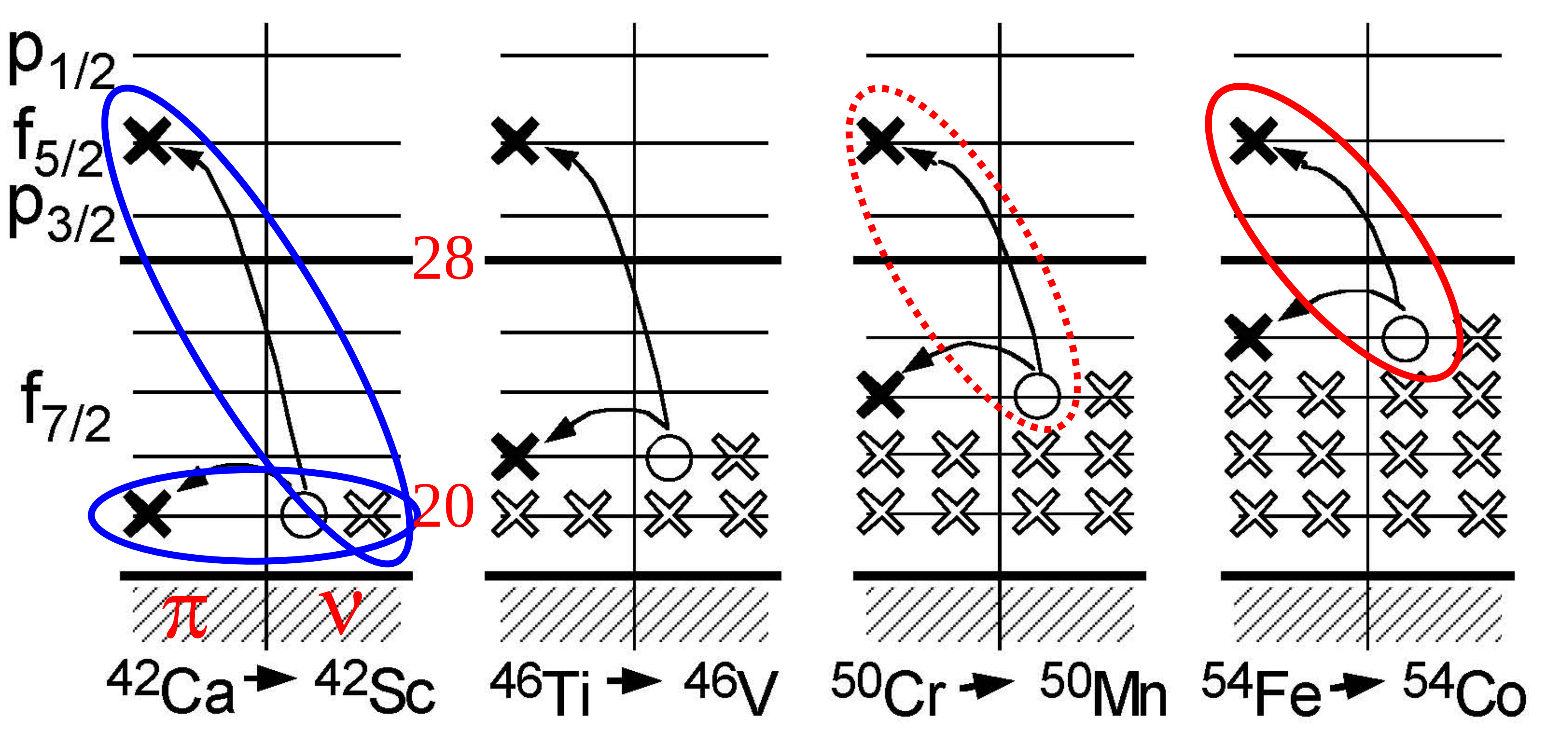


particle-hole configuration

+ IV-type int.

= REPULSIVE

SM Configurations of GT transitions

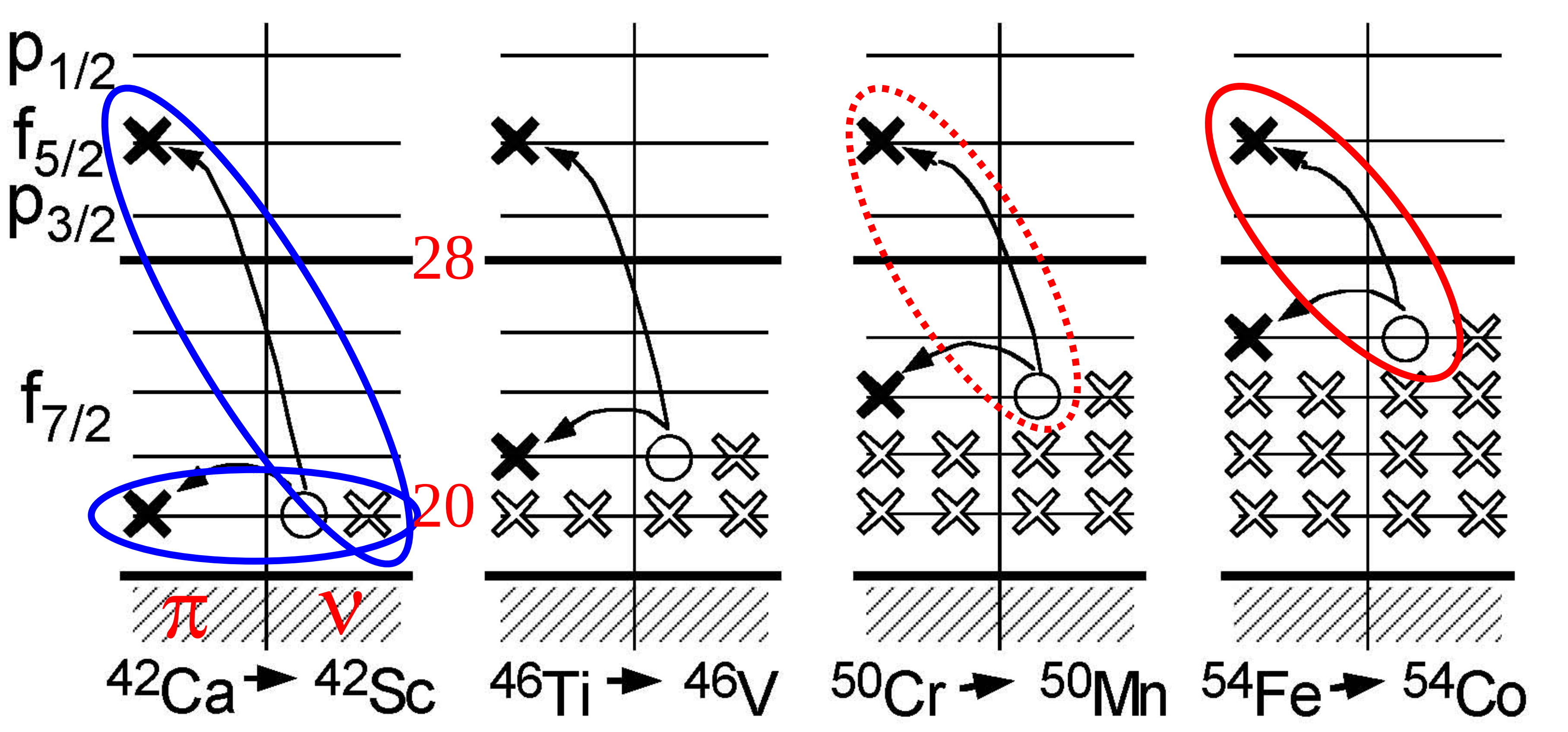


π-p - ν-p configurations
sensitive to IS pairing int.
➔attractive
(spin-triplet, IS int. is stronger
than spin-singlet, IV int.)

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)

(IS p-n int. is attractive)

Isoscalar interaction
can play Important roles !

GT strength Calculations: HFB+QRPA + pairing int.

Bai, Sagawa, Colo et al., PL B 719 (2013) 116

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

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

IS $$V_{T=0}(\mathbf{r}_1,\mathbf{r}_2)=fV_0\frac{1+P_\sigma}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}_1-\mathbf{r}_2), \quad (2)$$

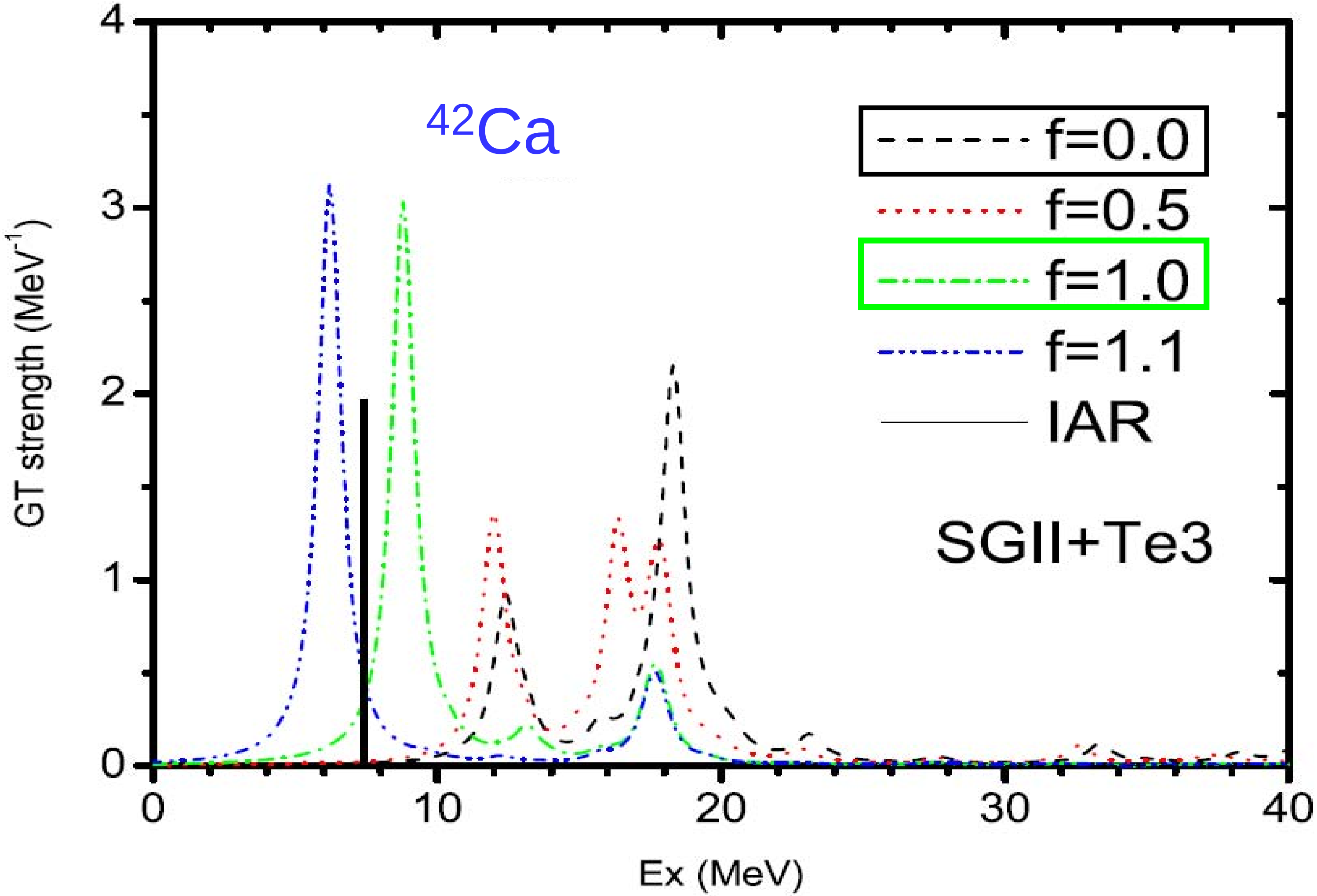
Results (using Skyrme int. SGII)

at f =0: there is little strength in the lower energy part,

at f =1.0~1.7: coherent low-energy strength develops!

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

by Bai Sagawa Colo



^{42}Ca→^{42}Sc (Q-value)

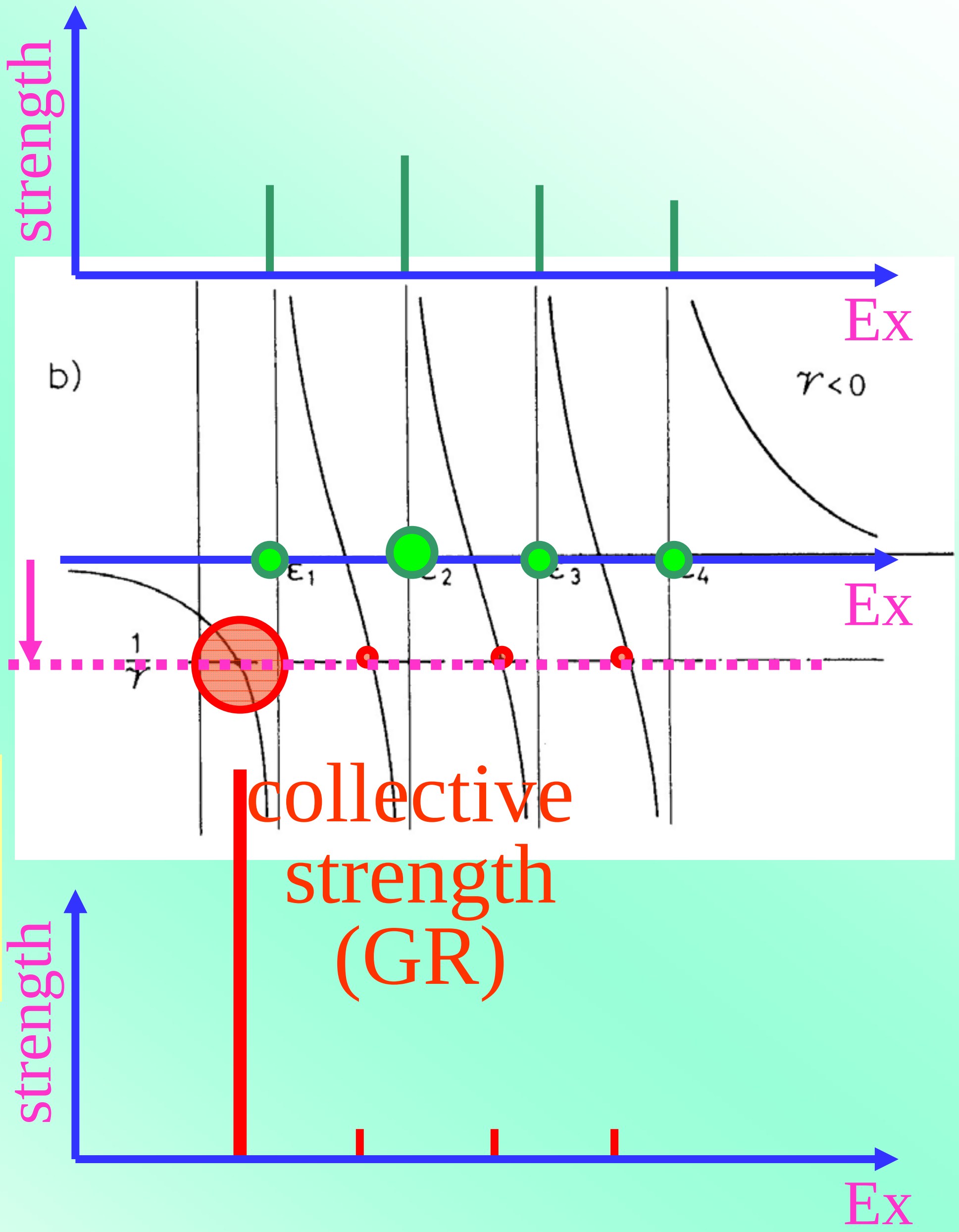
Role of Residual Int. (attractive)

Single particle-hole strength distribution

Graphical solution of the RPA dispersive eigen-equation

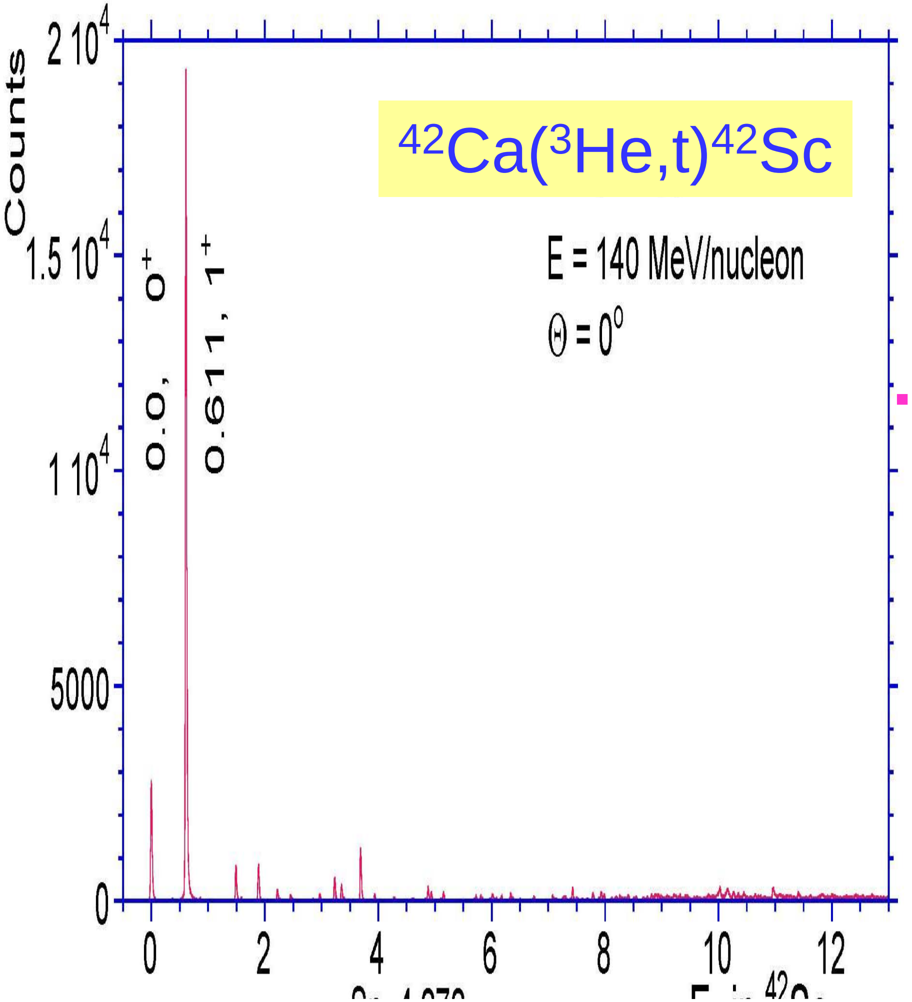
negative=attractive

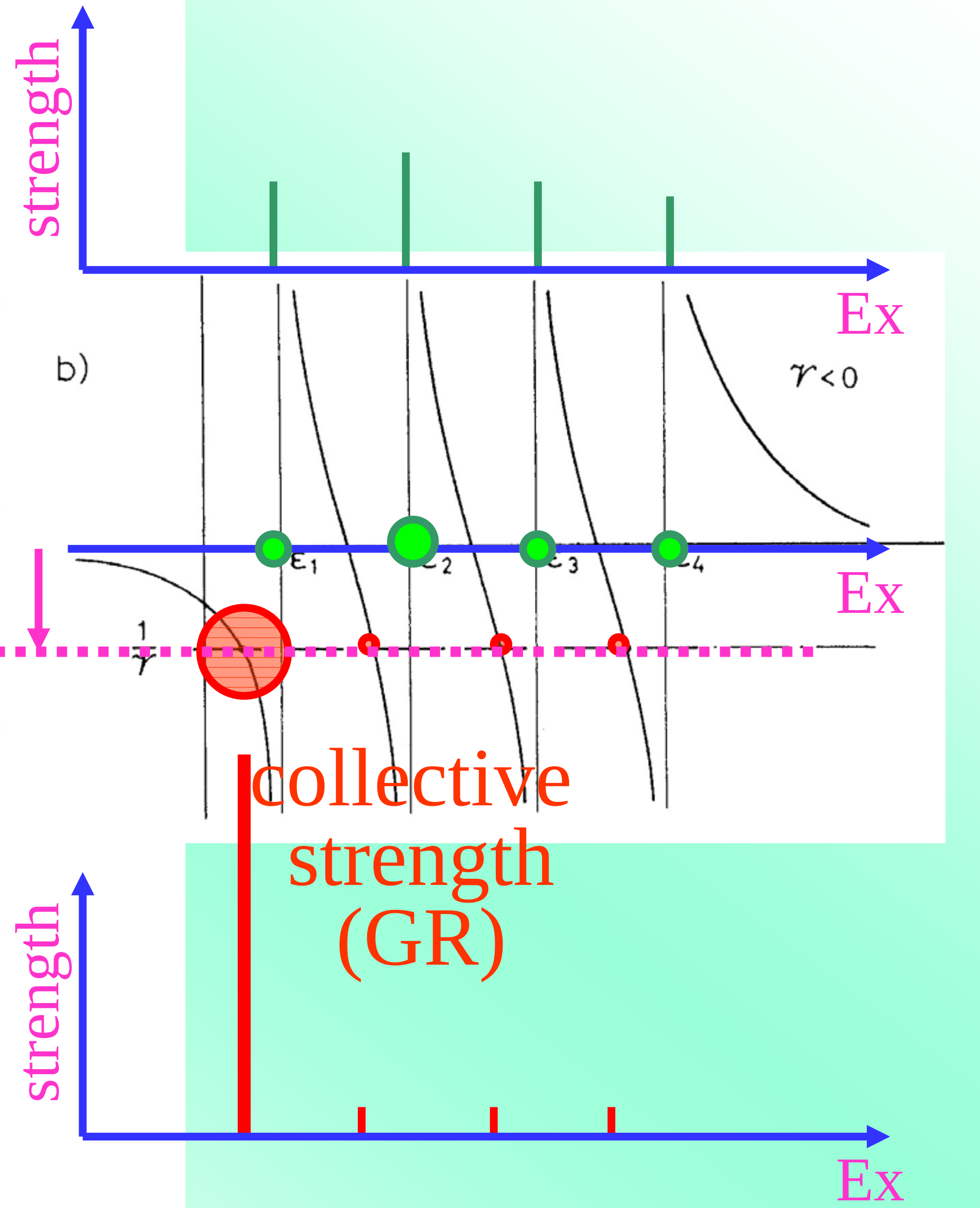
Collective excitation formed by the attractive IS residual interaction



Role of Residual Int. (attractive)

Collective excitation formed by the attractive IS residual interaction





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!

$^{42}Ca \rightarrow {}^{42}Sc$: Shell Model Cal.: Transition Matrix Elements

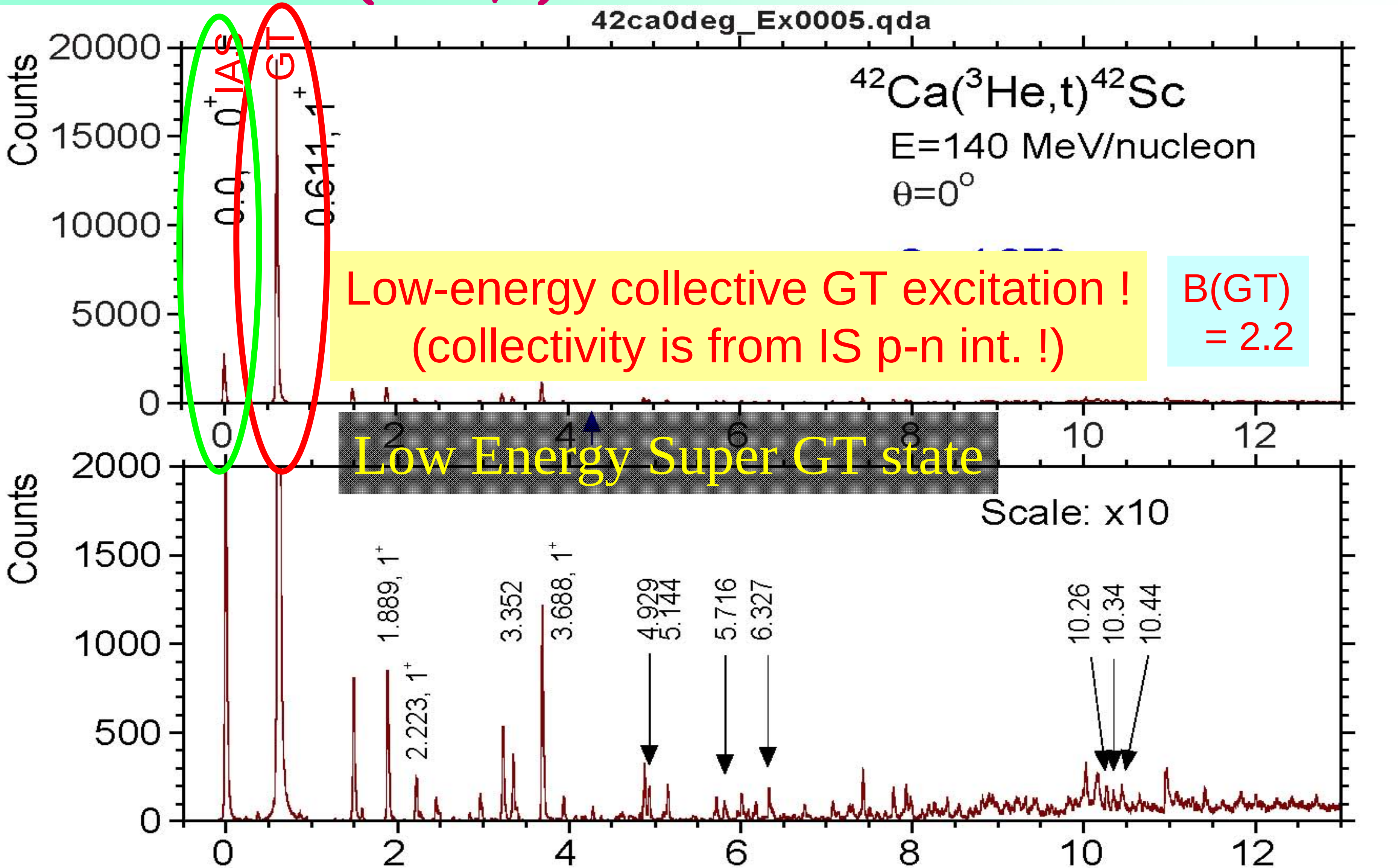
TABLE VI. Results of the pf-shell SM calculation using the GXPF1J interaction. The matrix elements M(GT) of GT transitions exciting individual $J^{\pi} = 1^{+}$ GT states in ^{42}Sc from the g.s. of ^{42}Ca are shown for each configuration. The results are shown for all excited GT states predicted in the region up to 9.82 MeV. The notation $f7 \rightarrow f7$, for example, stands for the transition with the $\nu f_{7/2} \rightarrow \pi f_{7/2}$ type and $p3 \rightarrow p3$ the $\nu p_{3/2} \rightarrow \pi p_{3/2}$. The summed value of the matrix elements is denoted by ΣM(GT) and its squared value is the B(GT), where the B(GT) values do not include the quenching factor of the SM calculation.

SM cal: M. Honma

States in ^{42}Sc		Configurations						Transition strengths	
E_x (MeV)	T	$f7 \rightarrow f7$	$f7 \rightarrow f5$	$f5 \rightarrow f7$	$p3 \rightarrow p3$	$p3 \rightarrow p1$	$p1 \rightarrow p3$	ΣM(GT)	B(GT)
0.33 1^{+}_{1}	0	1.383	0.548	0.063	0.031	0.024	0.016	2.07	4.28
4.41	0	0.719	−0.742	−0.085	−0.079	−0.073	−0.048	−0.31	0.09
7.41	0	0.193	−0.788	−0.090	0.142	0.060	0.040	−0.44	0.19
8.62	0	−0.151	0.385	0.044	0.109	−0.071	−0.047	0.30	0.09
9.82	1	0.0	1.196	−0.137	0.0	−0.053	0.035	1.04	1.08

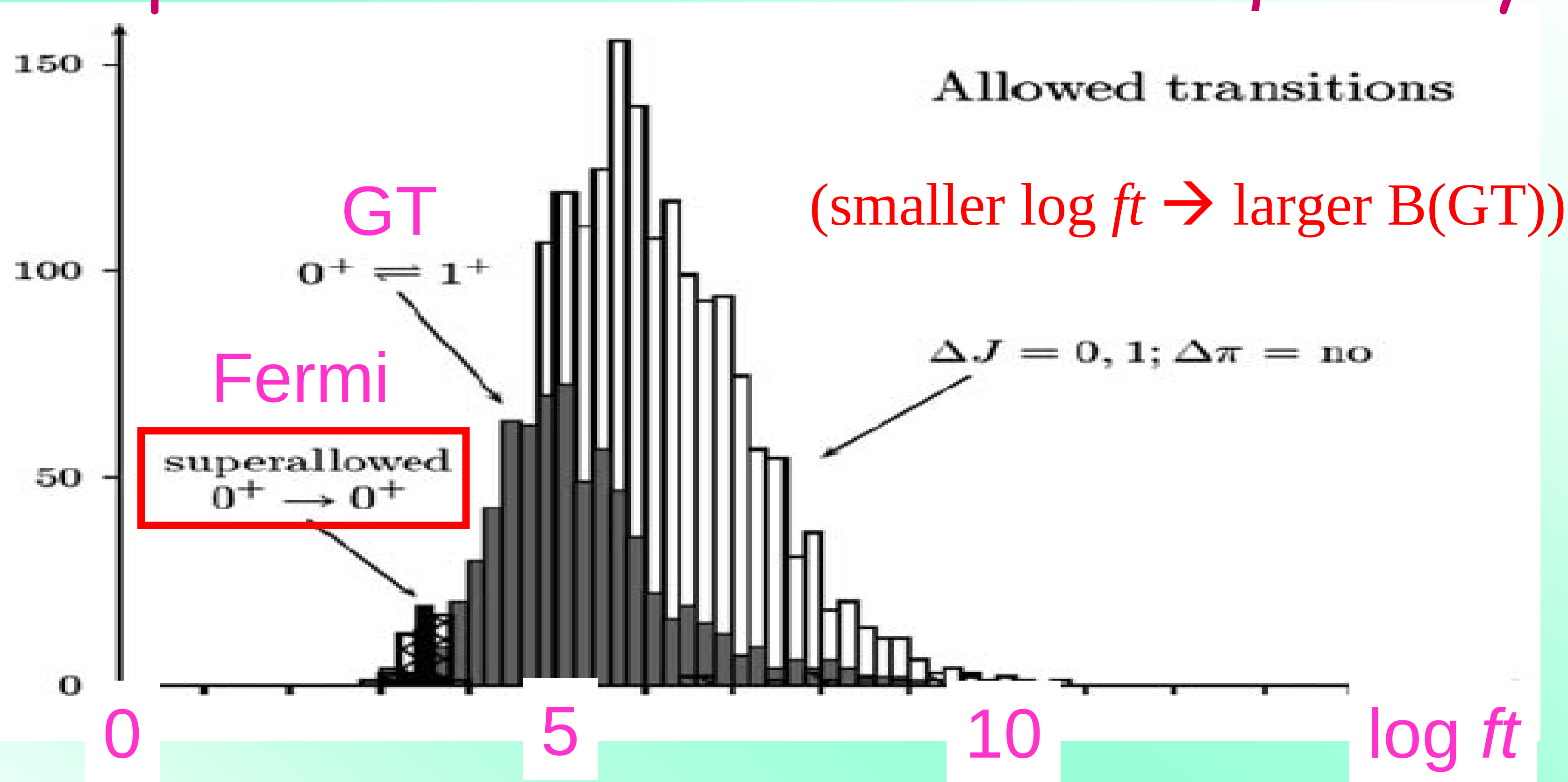
Matrix Elements are **in-phase** !

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



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

Super-allowed GT transitions in β decay



^{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

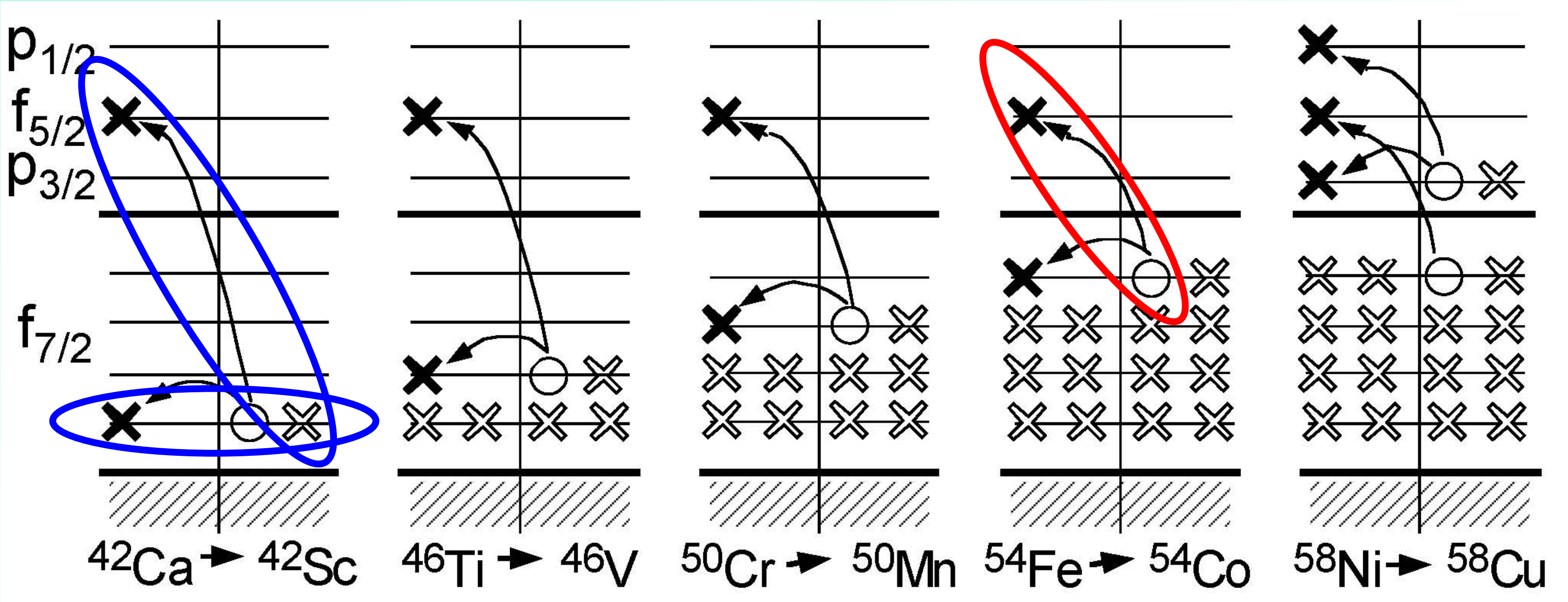
Super-Multiplet State

*proposed by Wigner (1937)

In the limit of null *L*·*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 !

SM Configurations of GT transitions



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

particle-hole int. (repulsive)

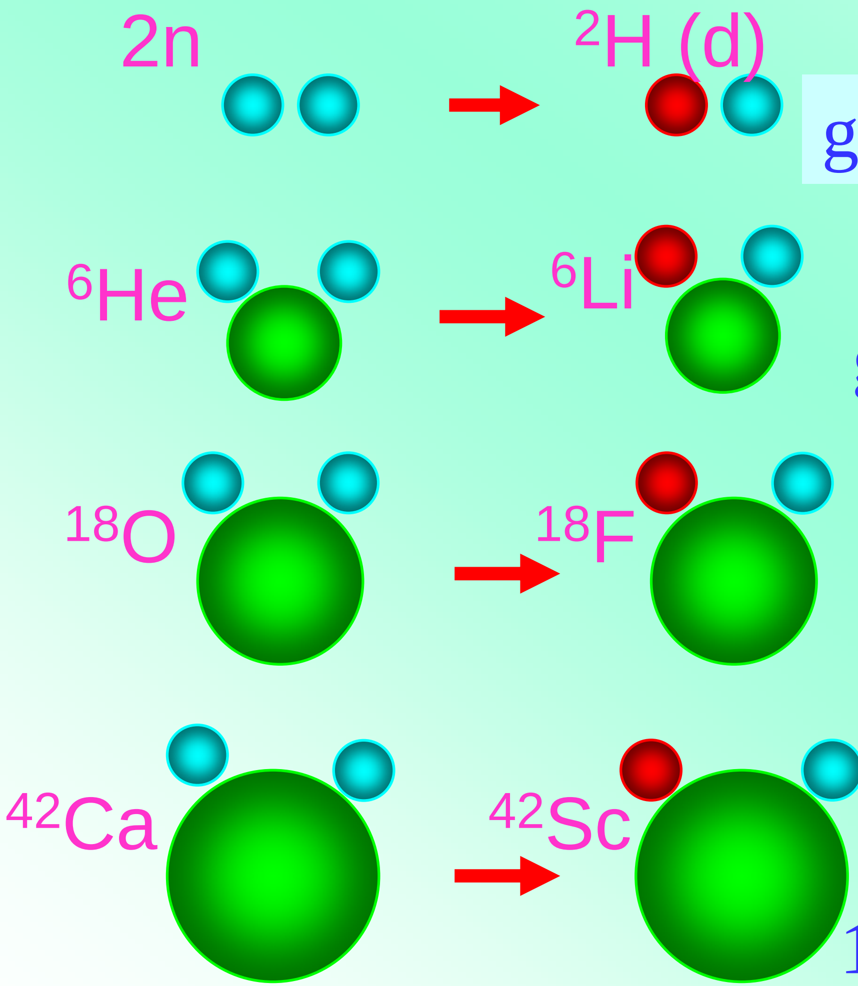
Isoscalar interaction
can play Important roles !

← *N=Z* LS-closed Core
+ 2 nucleon system !

GT transitions forming Low-Energy Super GT state

$J^{\pi} = 0^{+} \rightarrow 1^{+}$

Σ (Sum rule) = 3 x |N-Z| = 6



g.s. B(GT) = 6.0 ? Large !

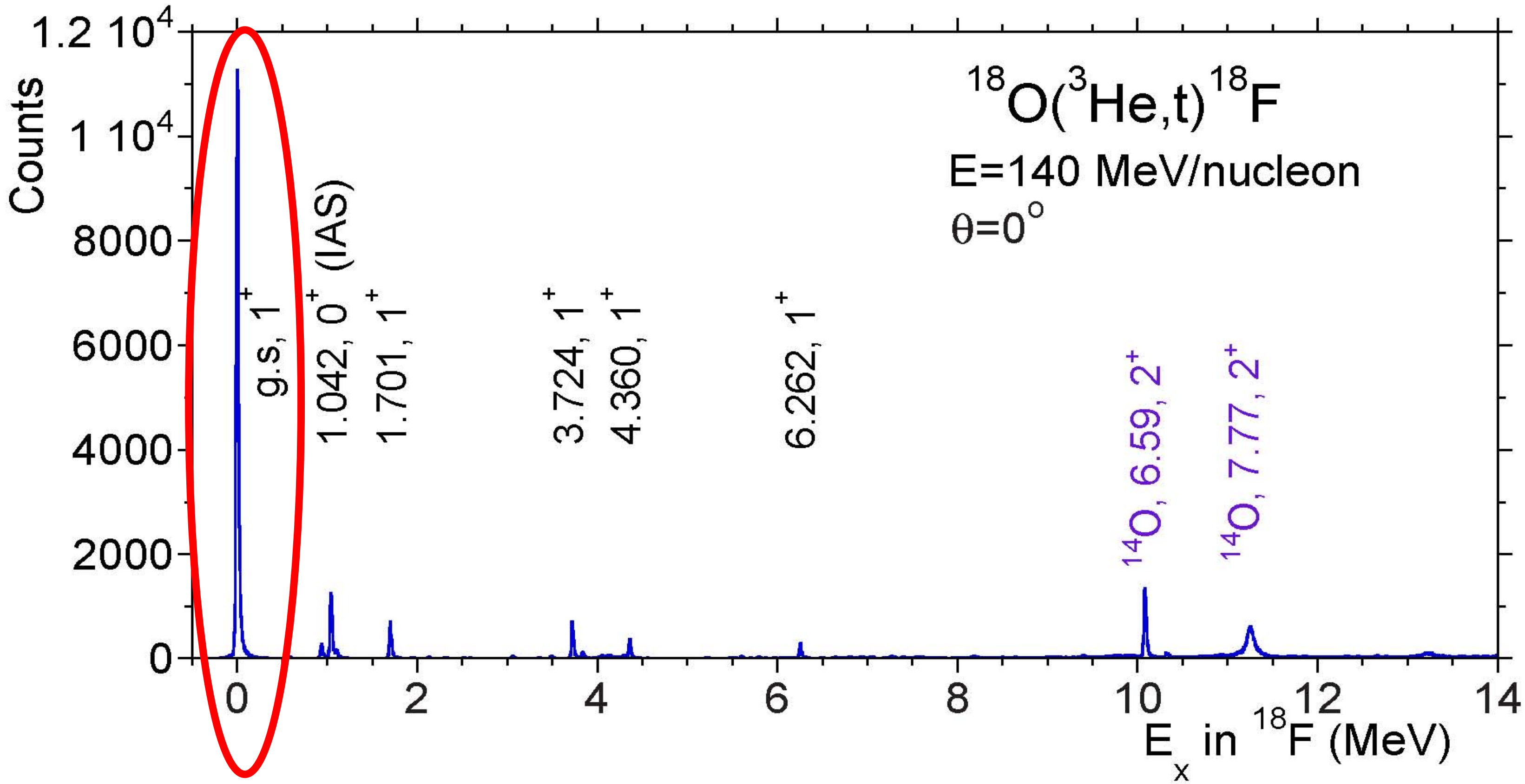
g.s. B(GT) = 4.73

g.s. B(GT) = 3.09

B(GT) = 2.17 Smaller !

1^{st} E_x state (IAS is the g.s.)

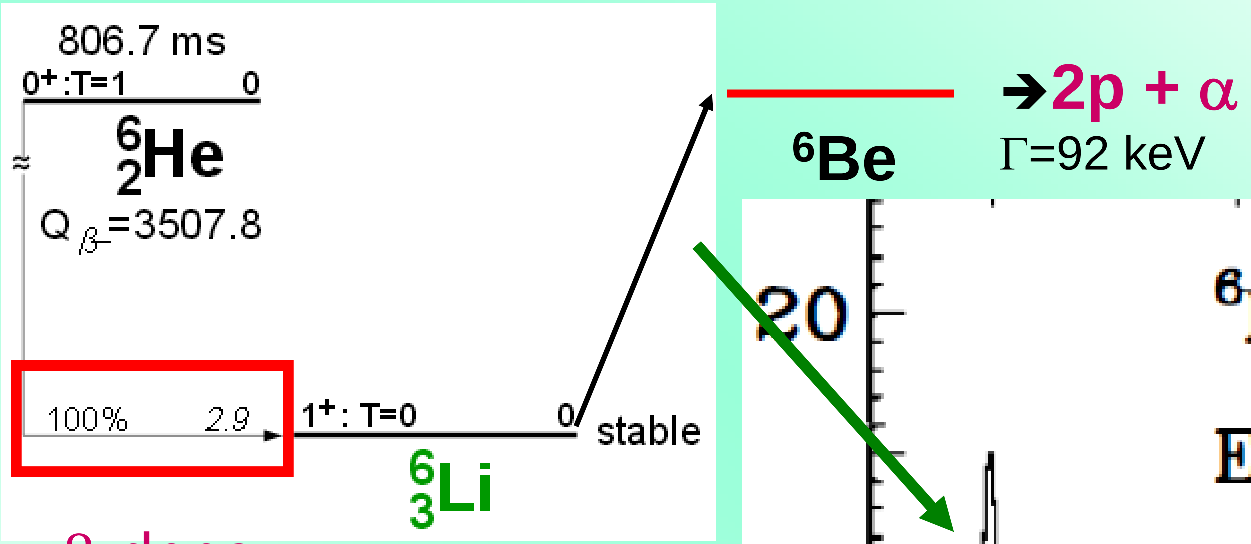
$^{18}O(^{3}He,t)^{18}F$ at 0°

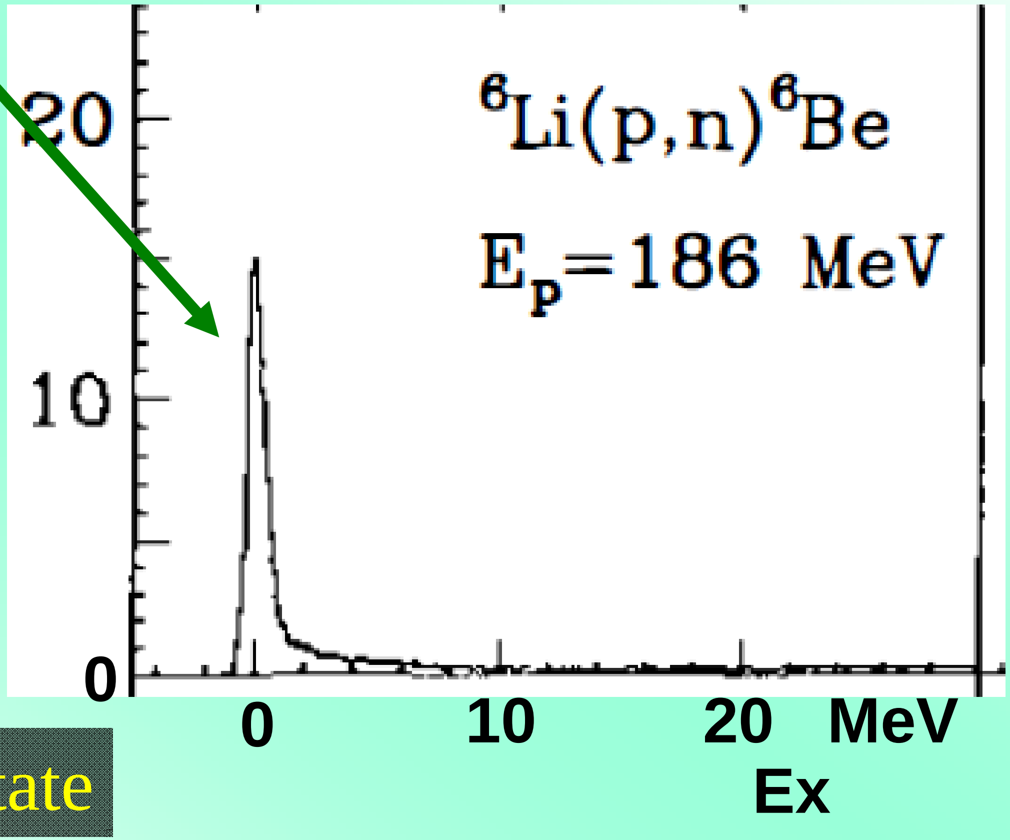


Low-energy collective GT excitation: B(GT)=3.1

Low Energy Super GT state

^{6}He β^{-}-decay & ^{6}Li(p,n)^{6}Be



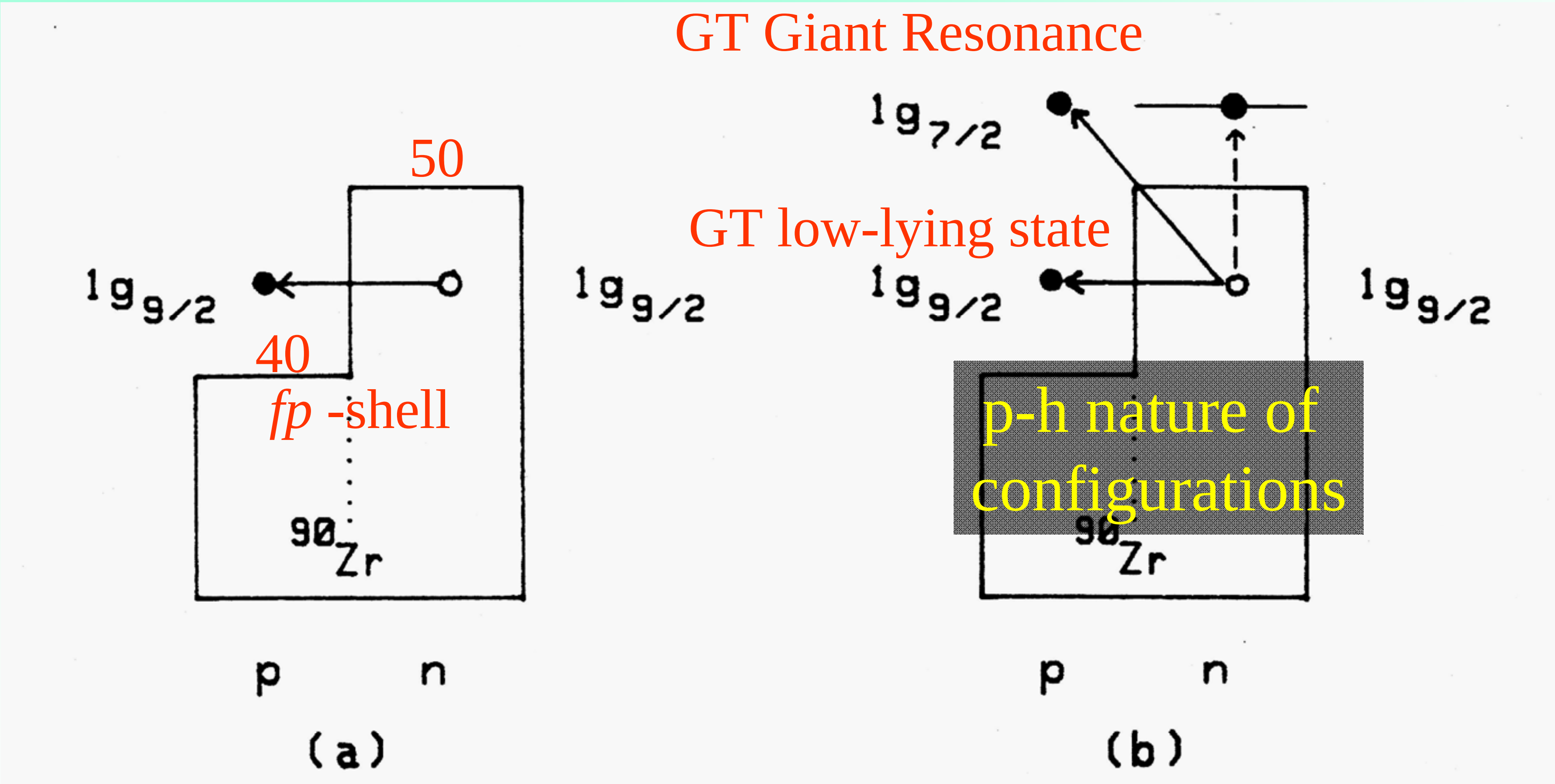


β-decay
log *ft* = 2.9
[B(GT) = 4.7]

Low Energy Super GT state

^{90}Zr : Fermi & GT transitions

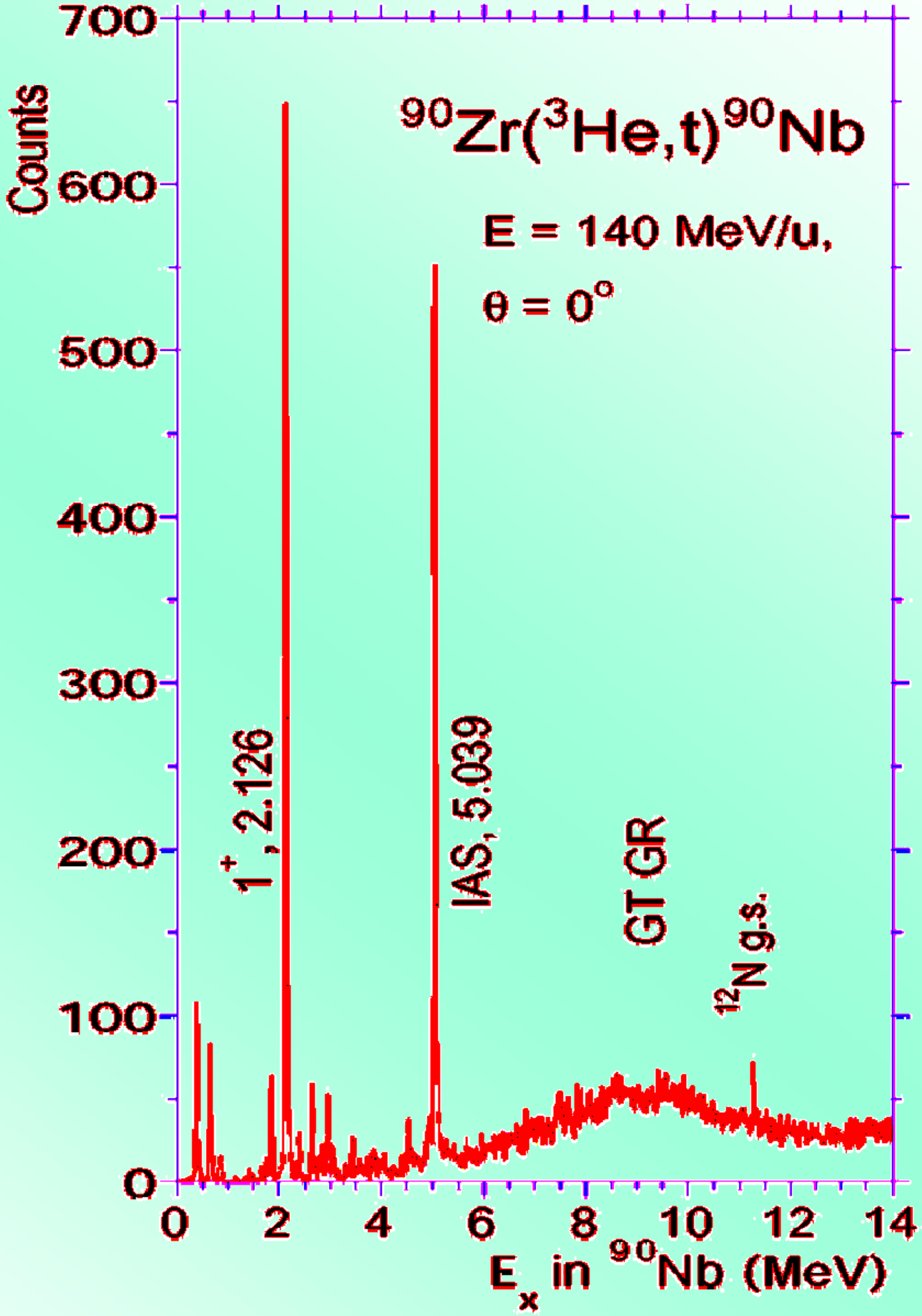
Schematic Picture of Single-Particle Transitions



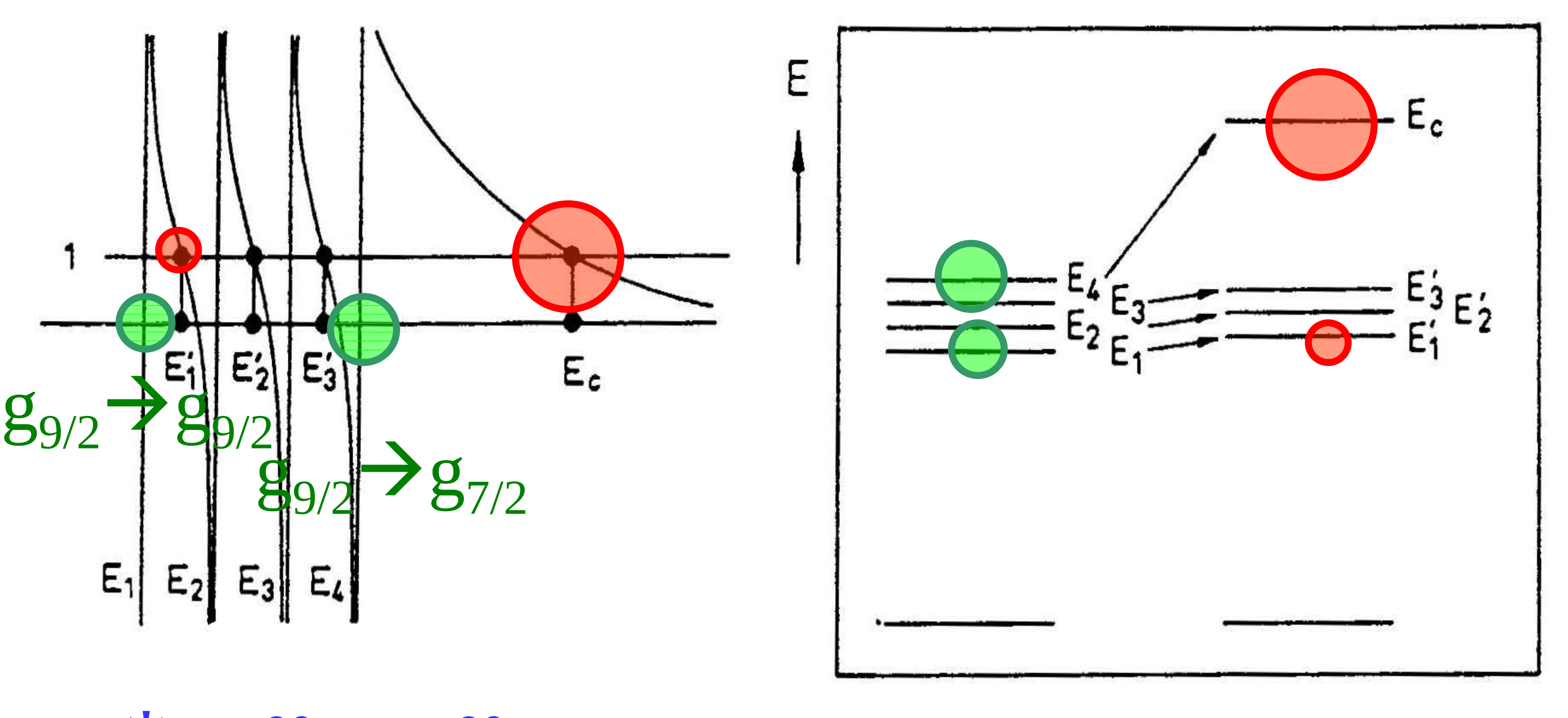
Fermi transition

Gamow-Teller transitions

Discrete States and GTR in ^{90}Nb



Formation of GT-GR in ^{90}Nb

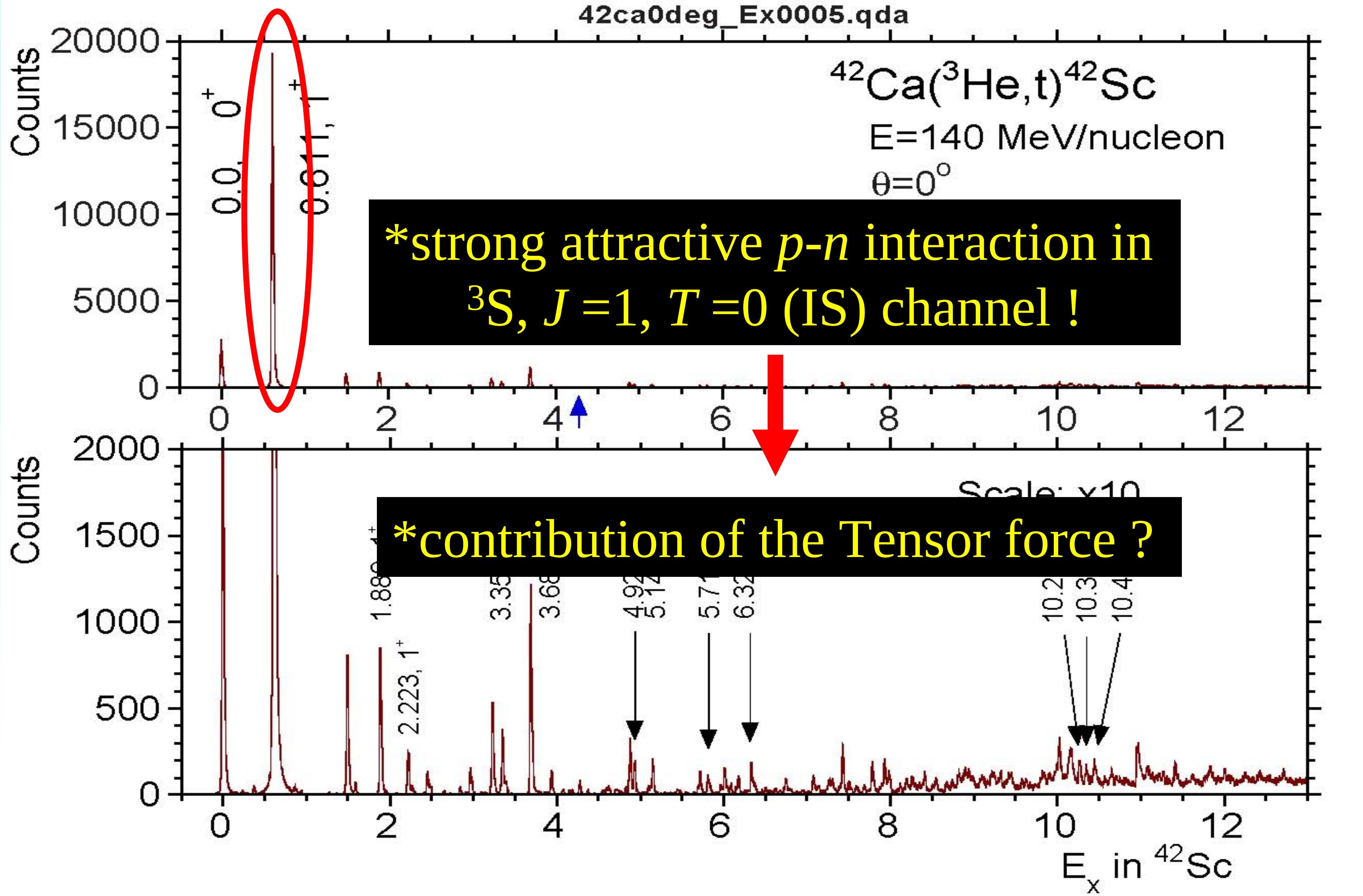


*in $^{90}Zr \rightarrow ^{90}Nb$ transitions

*$\sigma\tau$ int. : repulsive nature

*both configurations : p-h nature (repulsive)

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



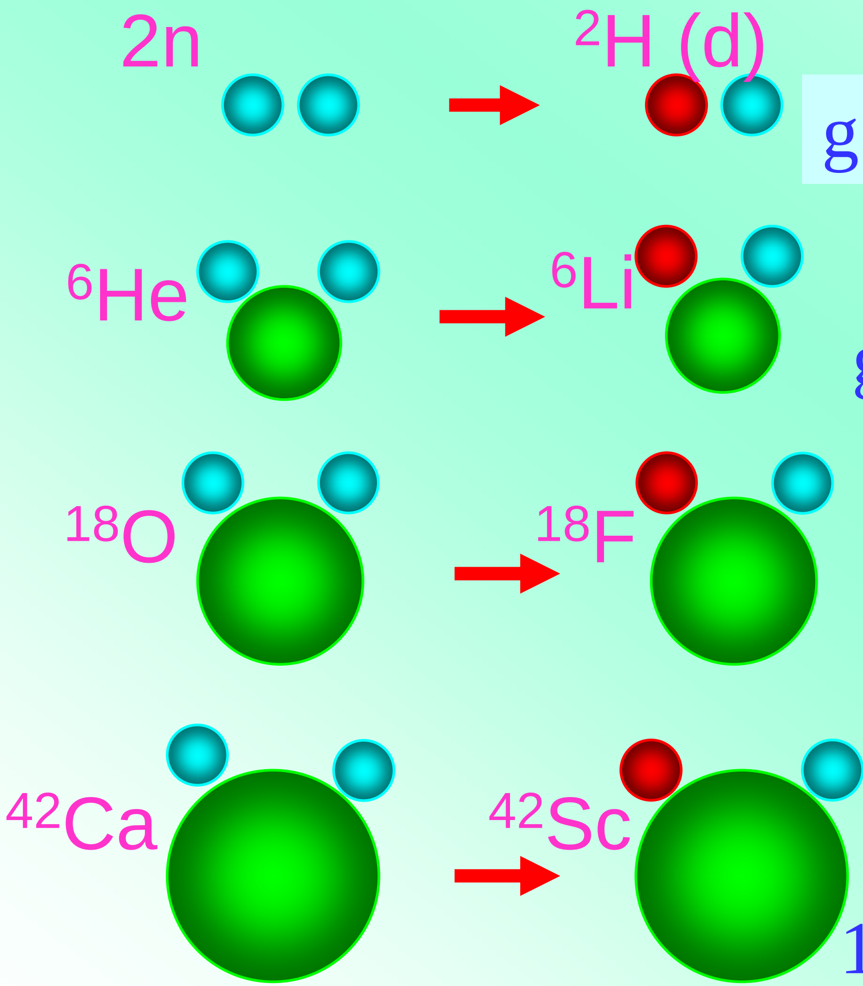
*strong attractive *p-n* interaction in ^{3}S, *J* =1, *T* =0 (IS) channel !

*contribution of the Tensor force ?

GT transitions forming Low-Energy Super GT state

$J^{\pi} = 0^{+} \rightarrow 1^{+}$

Σ (Sum rule) = 3 x |N-Z| = 6



g.s. B(GT) = 6.0 ? Large !

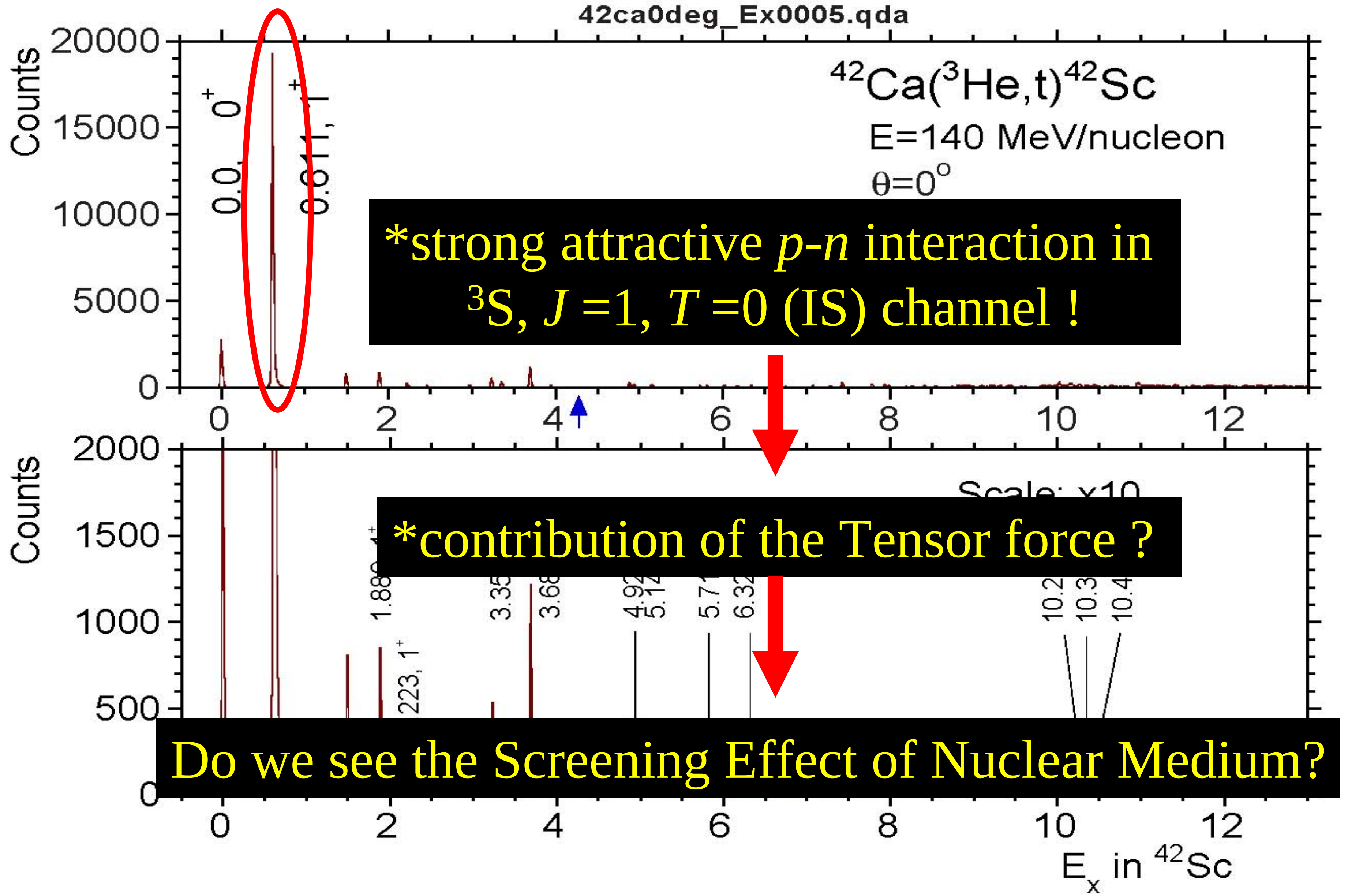
g.s. B(GT) = 4.73

g.s. B(GT) = 3.09

B(GT) = 2.17 Smaller !

1st E_x state (IAS is the g.s.)

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



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

*contribution of the Tensor force ?

Do we see the Screening Effect of Nuclear Medium?

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)

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

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Progress in Particle and Nuclear Physics

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Review

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

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