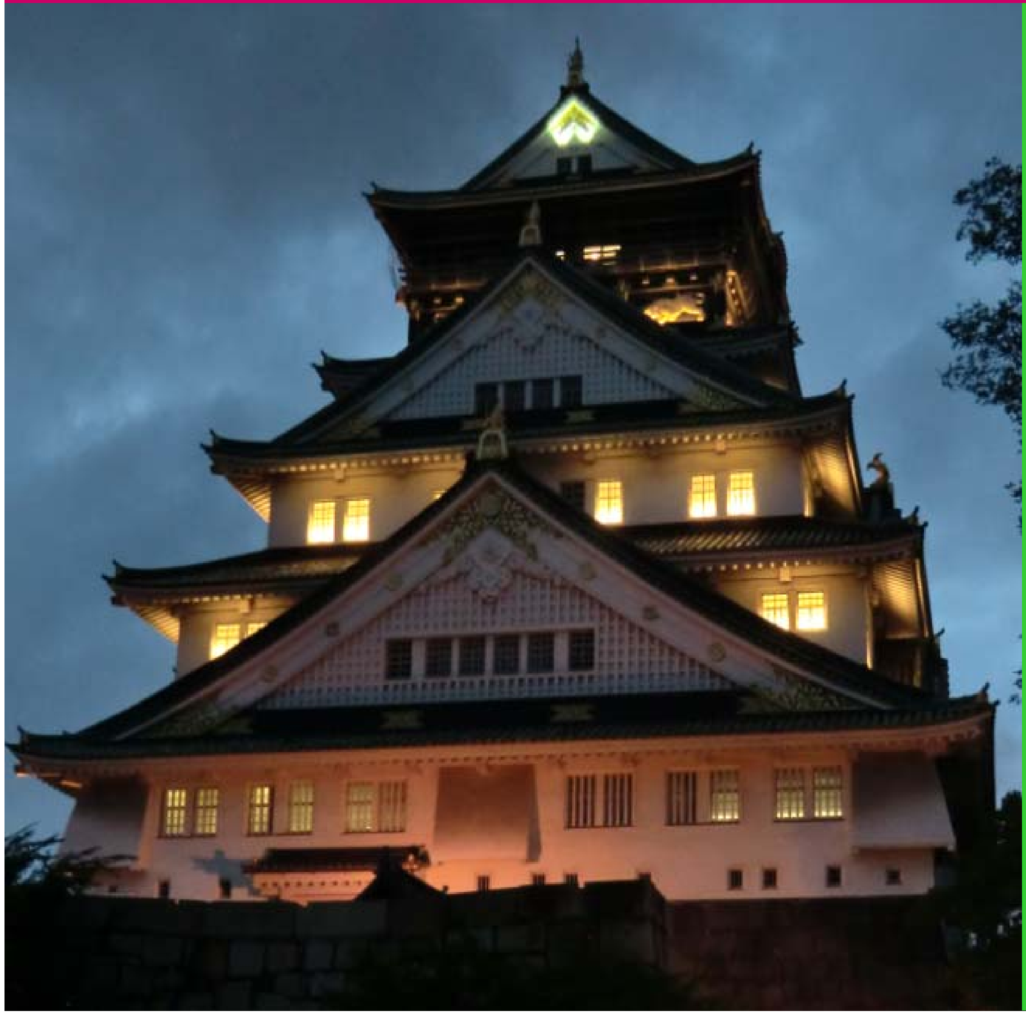
Studies of Gamow-Teller transitions using Weak and Strong Interactions



High-resolution Spectroscopy
&
Tensor Interaction

@ Nakanoshima, Osaka
Nov. 16 – Nov. 19, 2015

Yoshitaka FUJITA
RCNP, Osaka Univ.

Neptune driving Waves

Neptune =
weak interaction
➔ β decay

Powerful Waves = strong interaction)
➔ Charge-Exchange Reaction

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

_ Walter Crane, 1892

Gamow-Teller transitions

Mediated by $\sigma\tau$ operator: **both S &W int. has this *Op*.**

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 & 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 = |<f|στ|i>|^2

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

= reaction mechanism

⊗ operator

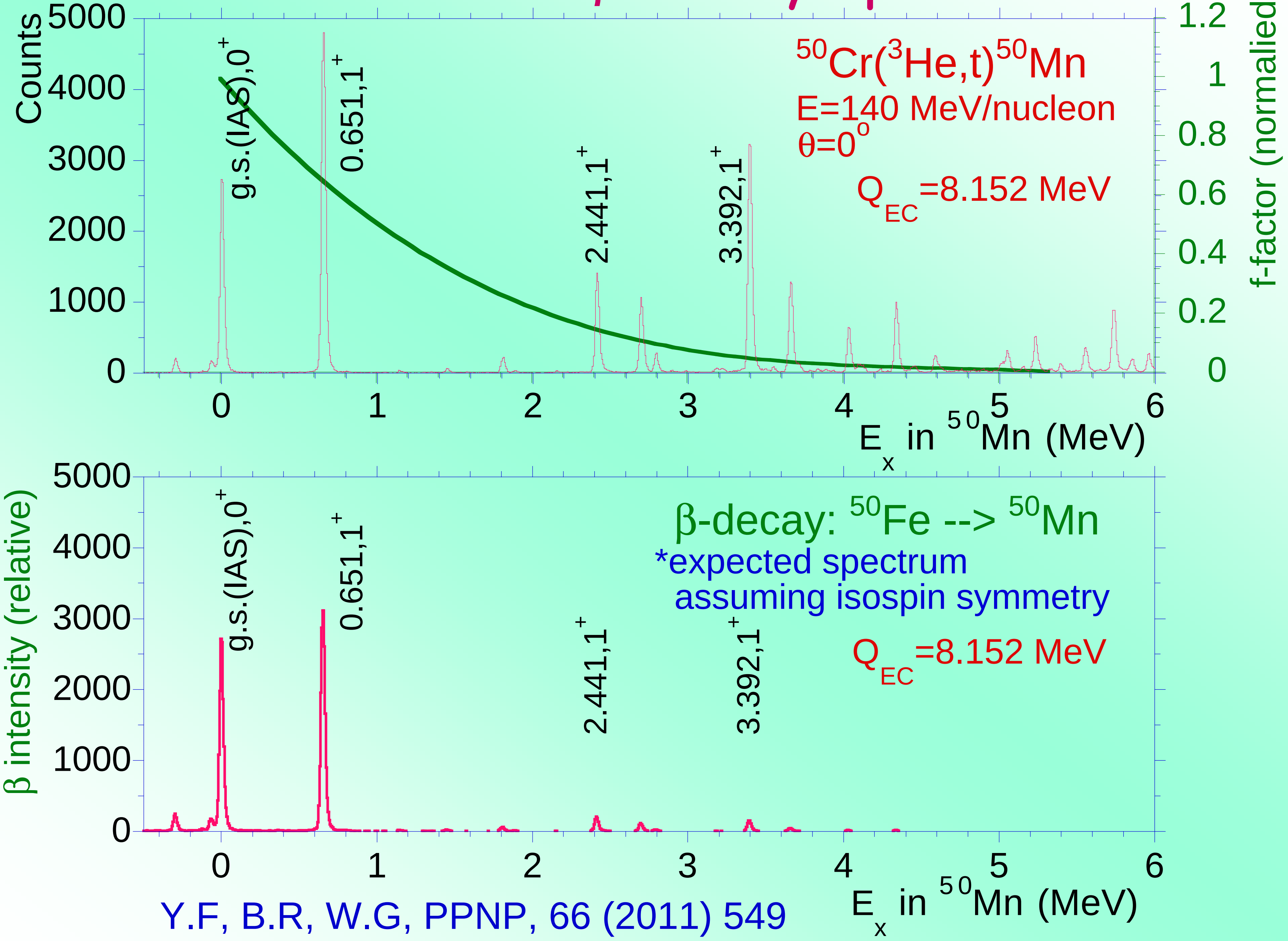
⊗ structure

=(matrix element)^2

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

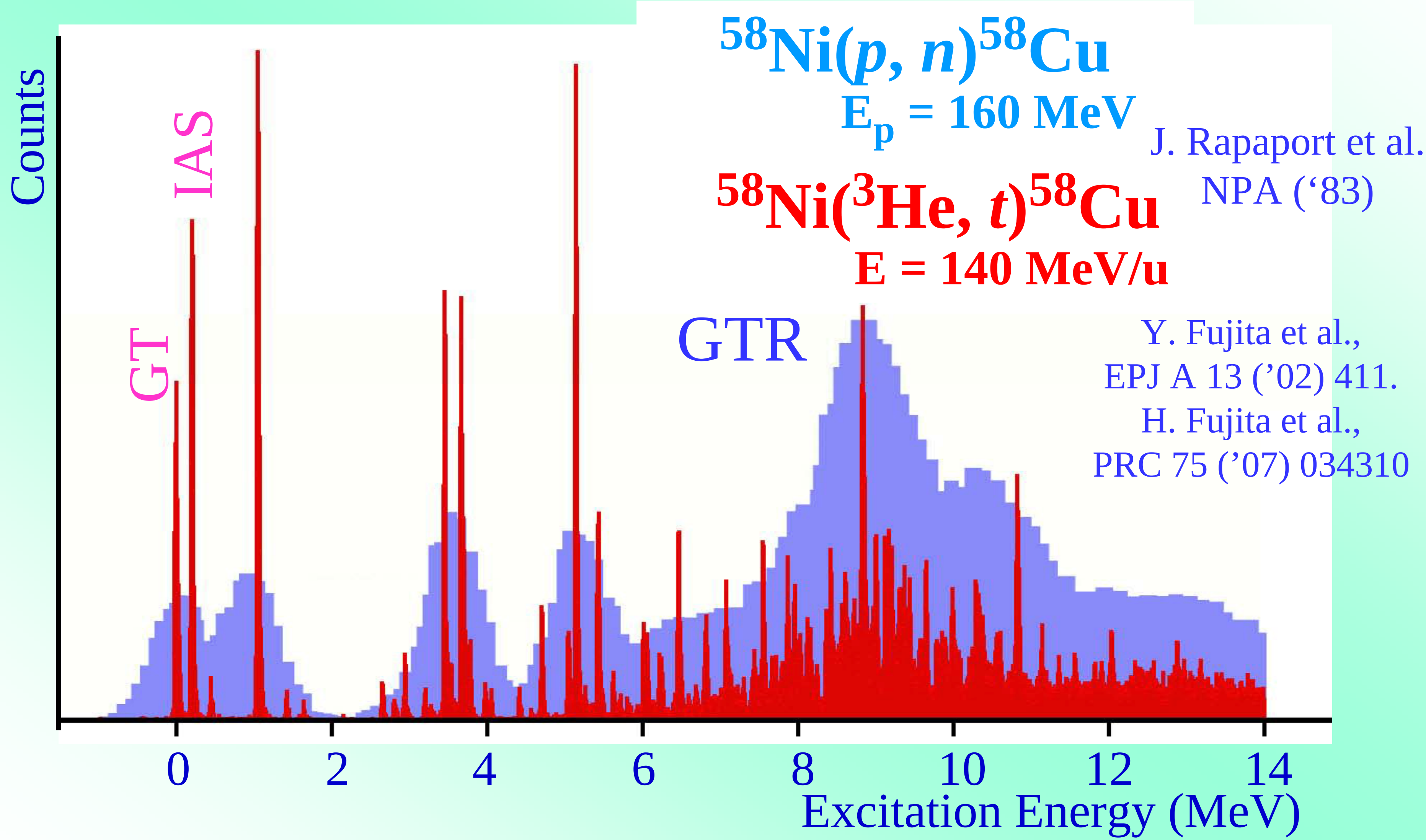
→ dσ/dω(q=0) : proportional to B(GT)

Simulation of β-decay spectrum

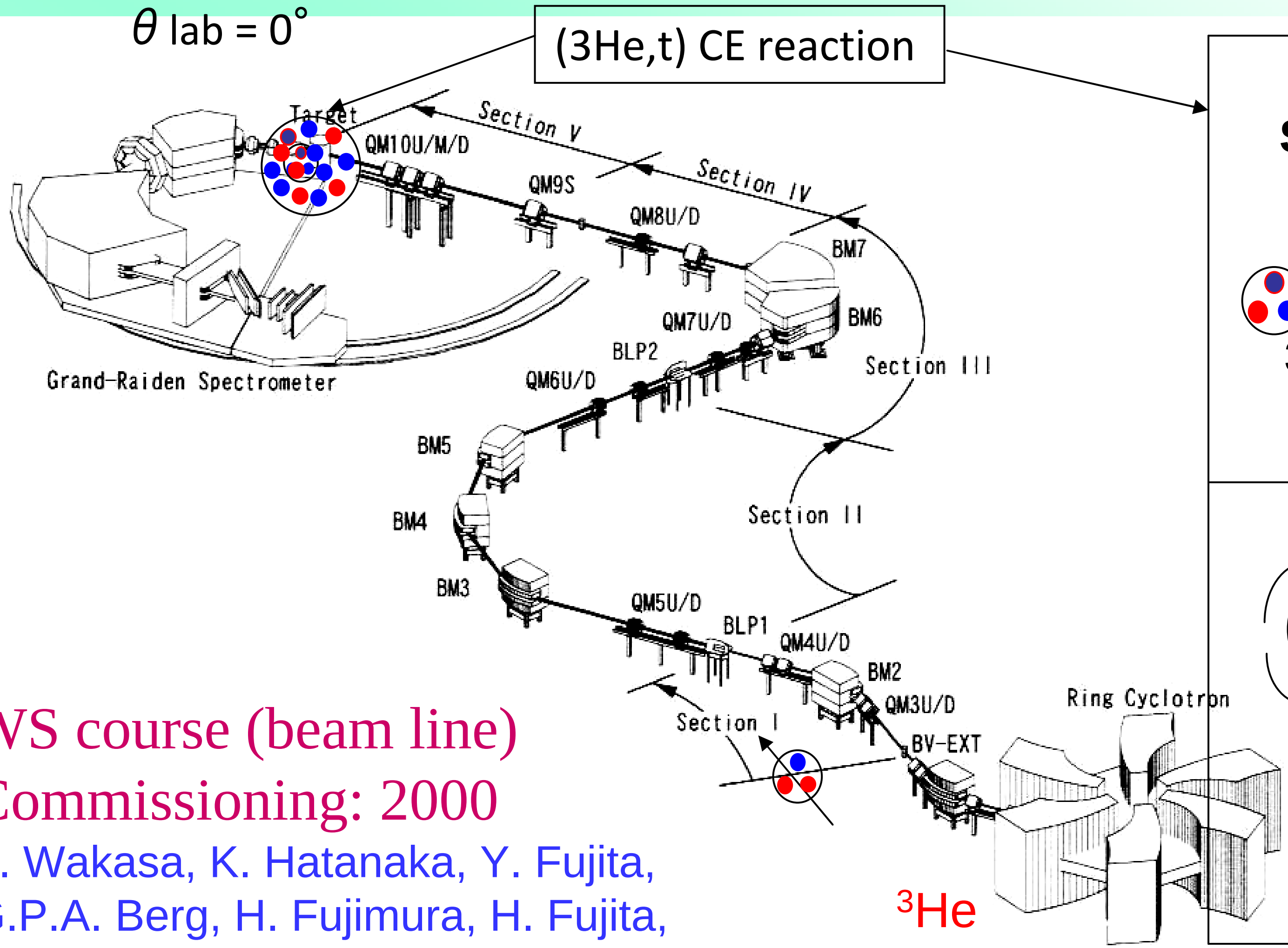


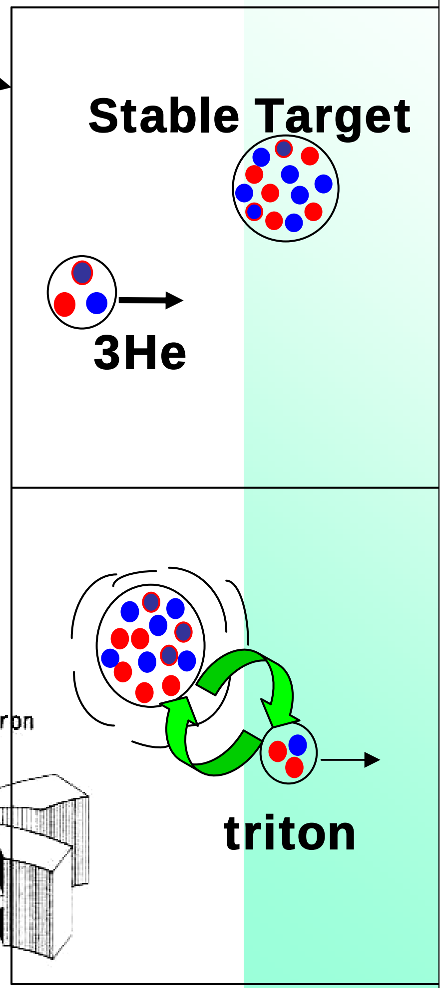
Y.F, B.R, W.G, PPNP, 66 (2011) 549

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



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





WS course (beam line)

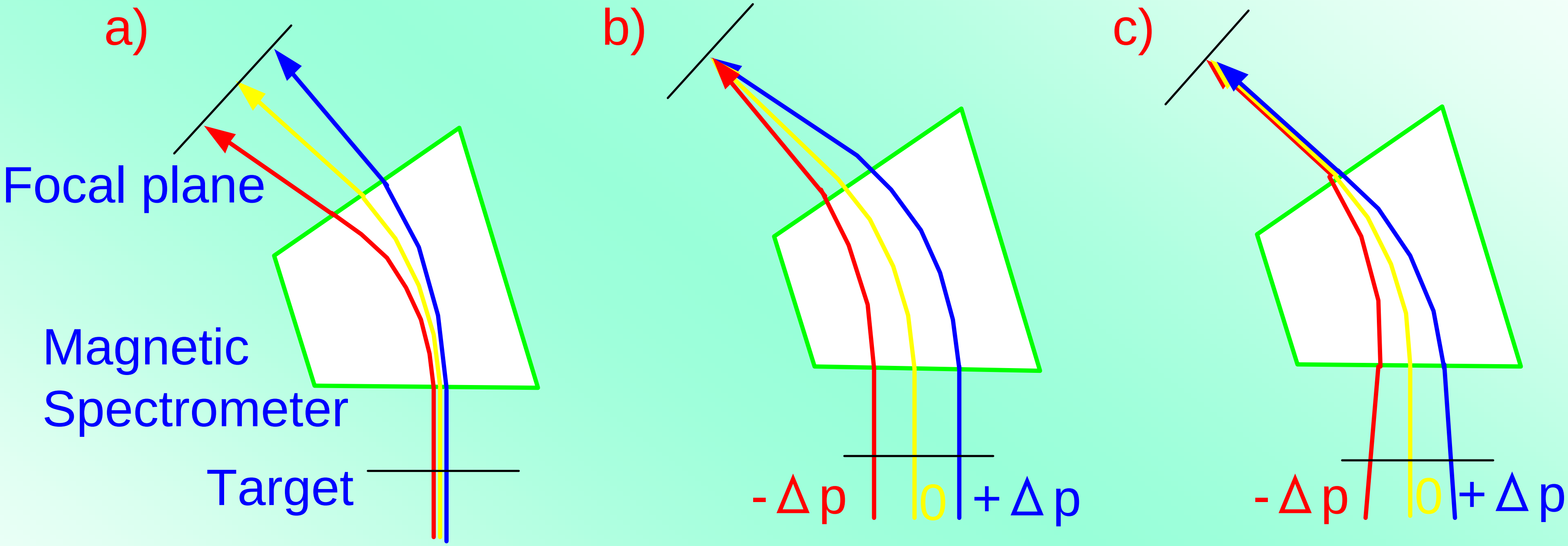
Commissioning: 2000

T. Wakasa, K. Hatanaka, Y. Fujita, G.P.A. Berg, H. Fujimura, H. Fujita, M. Itoh, J. Kamiya, T. Kawabata et al., N.I.M. A 482 (2002) 79.

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

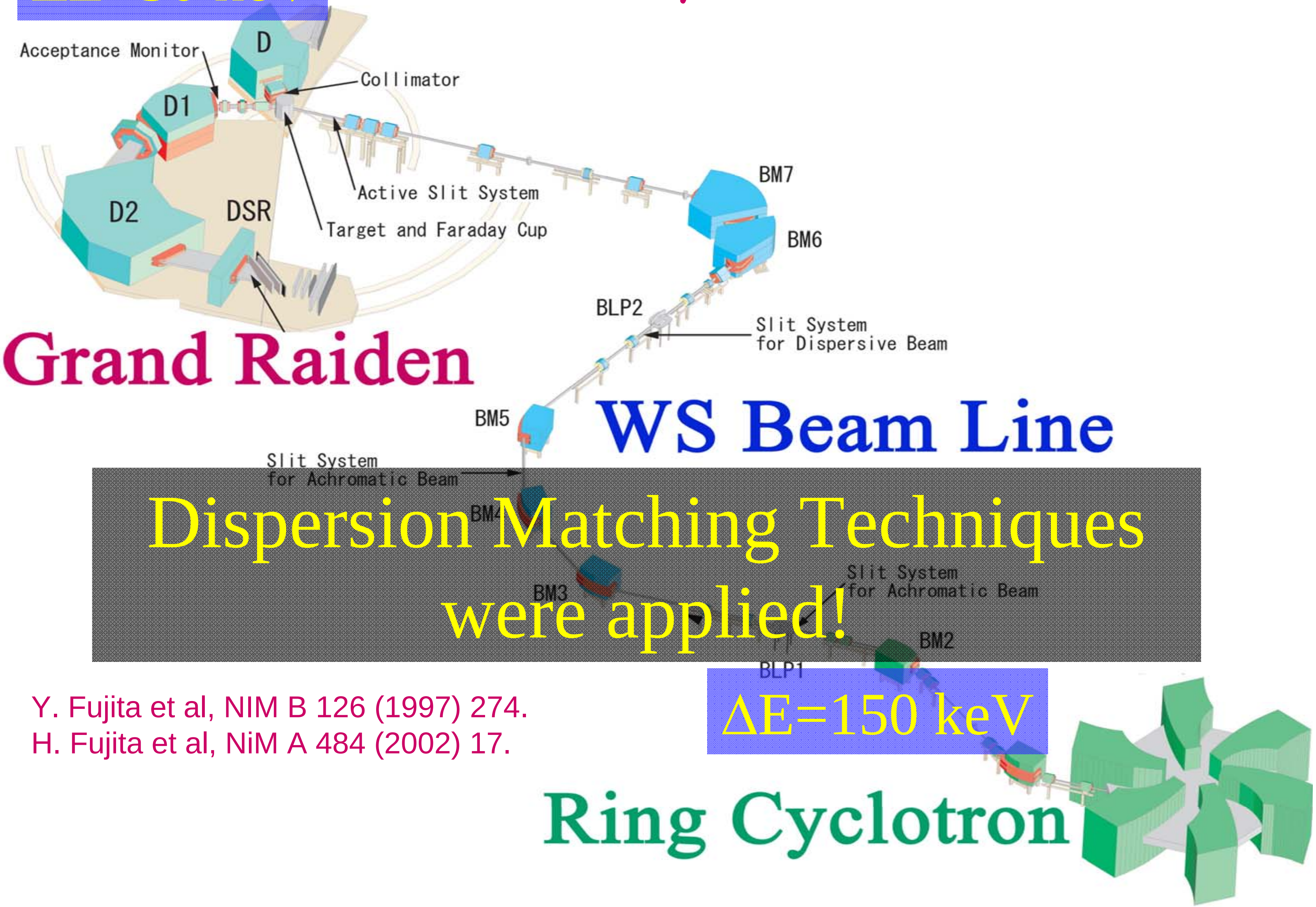
$\Delta E \sim 35$ keV
Horiz. angle resolution
$\Delta\theta_{sc} > 15$mrad

Angular dispersion matching

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

RCNP, Osaka Univ.

ΔE=30 keV



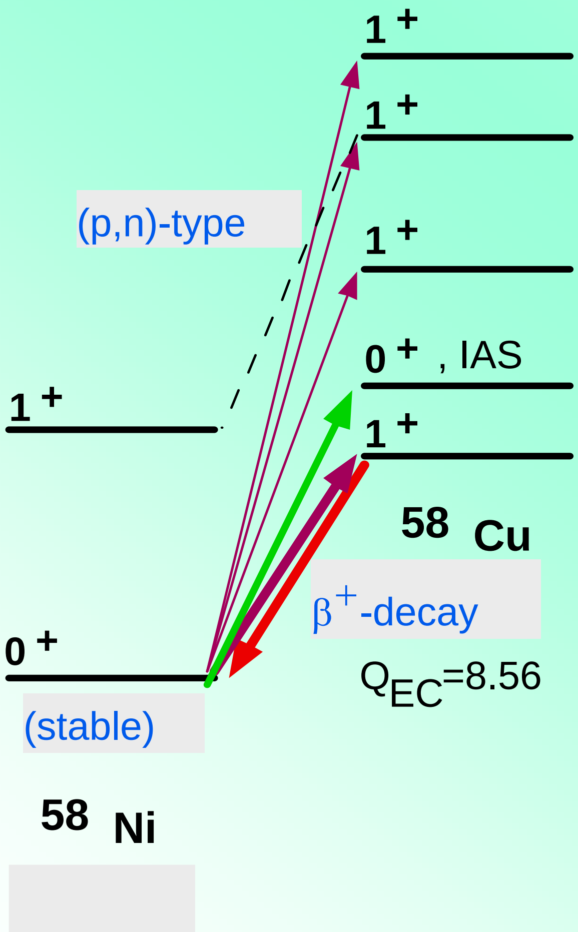
Dispersion Matching Techniques were applied!

ΔE=150 keV

Y. Fujita et al, NIM B 126 (1997) 274.
H. Fujita et al, NiM A 484 (2002) 17.

Connection: Charge Exchange & β decay

$0^+ \leftrightarrow 1^+$



** 0^+ & 1^+ relationship of g.s.

	log *ft*	
^{58}Ni	4.8	^{58}Cu
^{62}Ni	5.2	^{62}Ni
^{68}Zn	5.2	^{68}Ga
^{78}Se	4.8	^{78}Br
^{104}Ru	4.3	^{104}Rh
^{118}Sn	4.5	^{118}Sb
^{120}Sn	4.5	^{120}Sb
^{136}Ba	4.6	^{136}La
^{140}Ce	4.4	^{140}Pr
^{178}Hf	4.7	^{178}Ta

***Isospin Symmetry

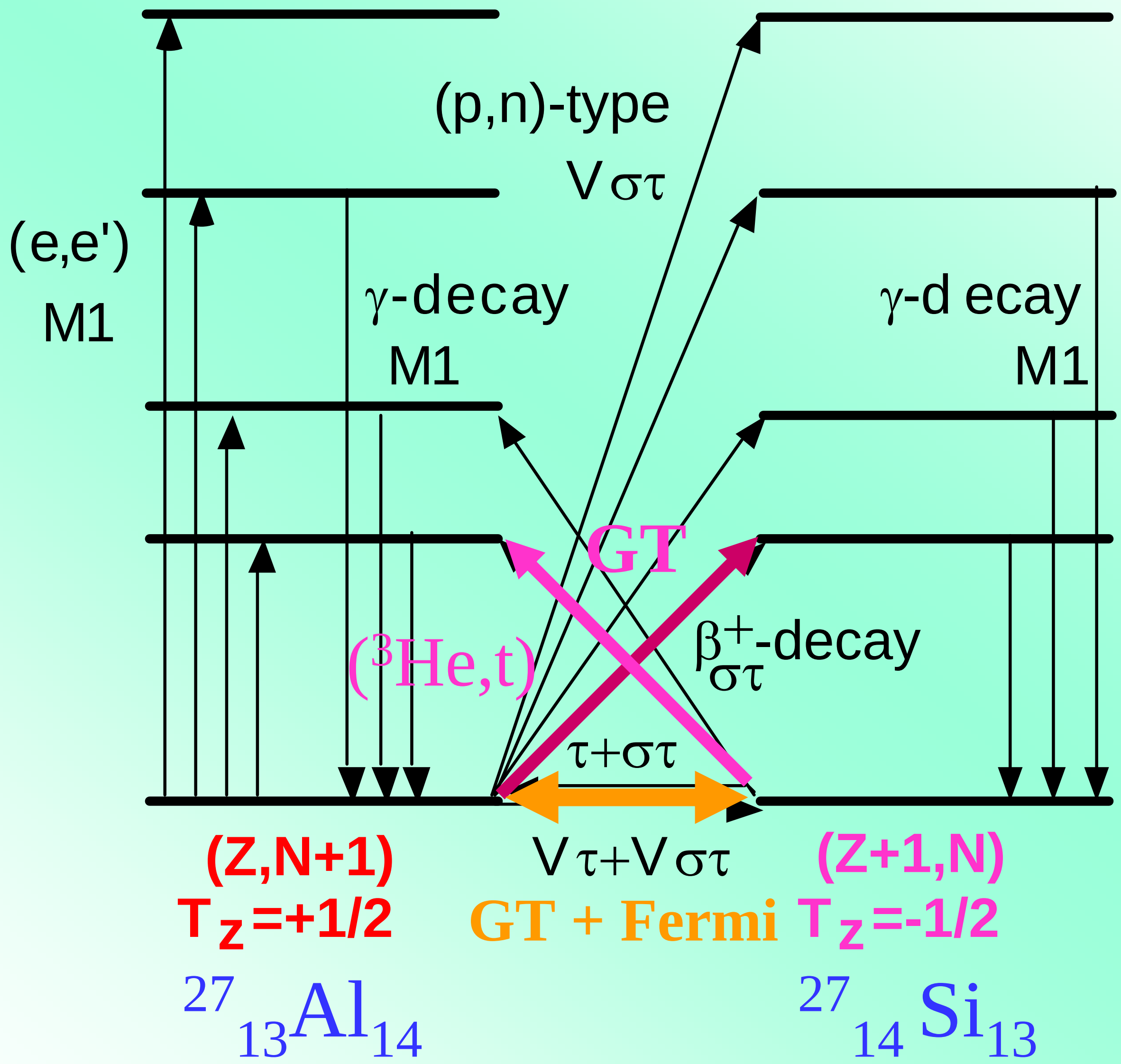
an important idea to see the connection of
decays and excitations caused
by Strong, EM and Weak interactions !

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

T=1/2 Isospin Symmetry

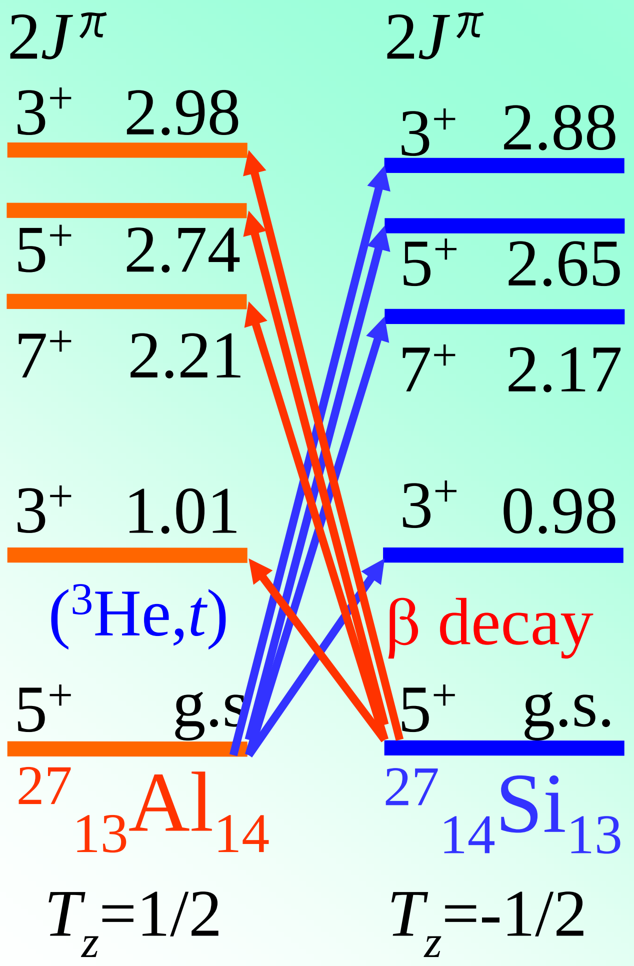
Koelner Dom
Koeln, Germany
(157m high)

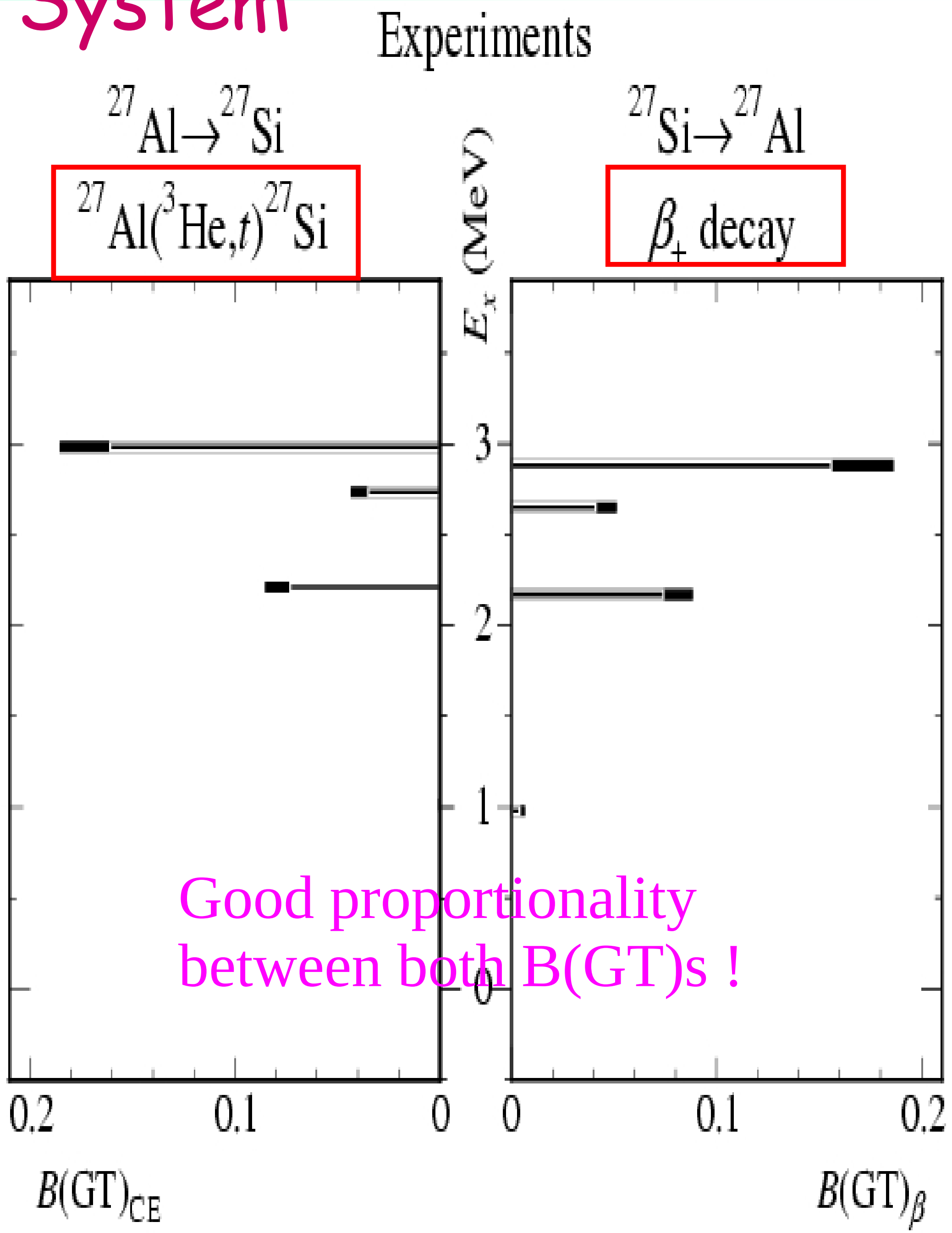
T=1/2 Mirror Nuclei : Structures & Transitions



Symmetry in A=27 System

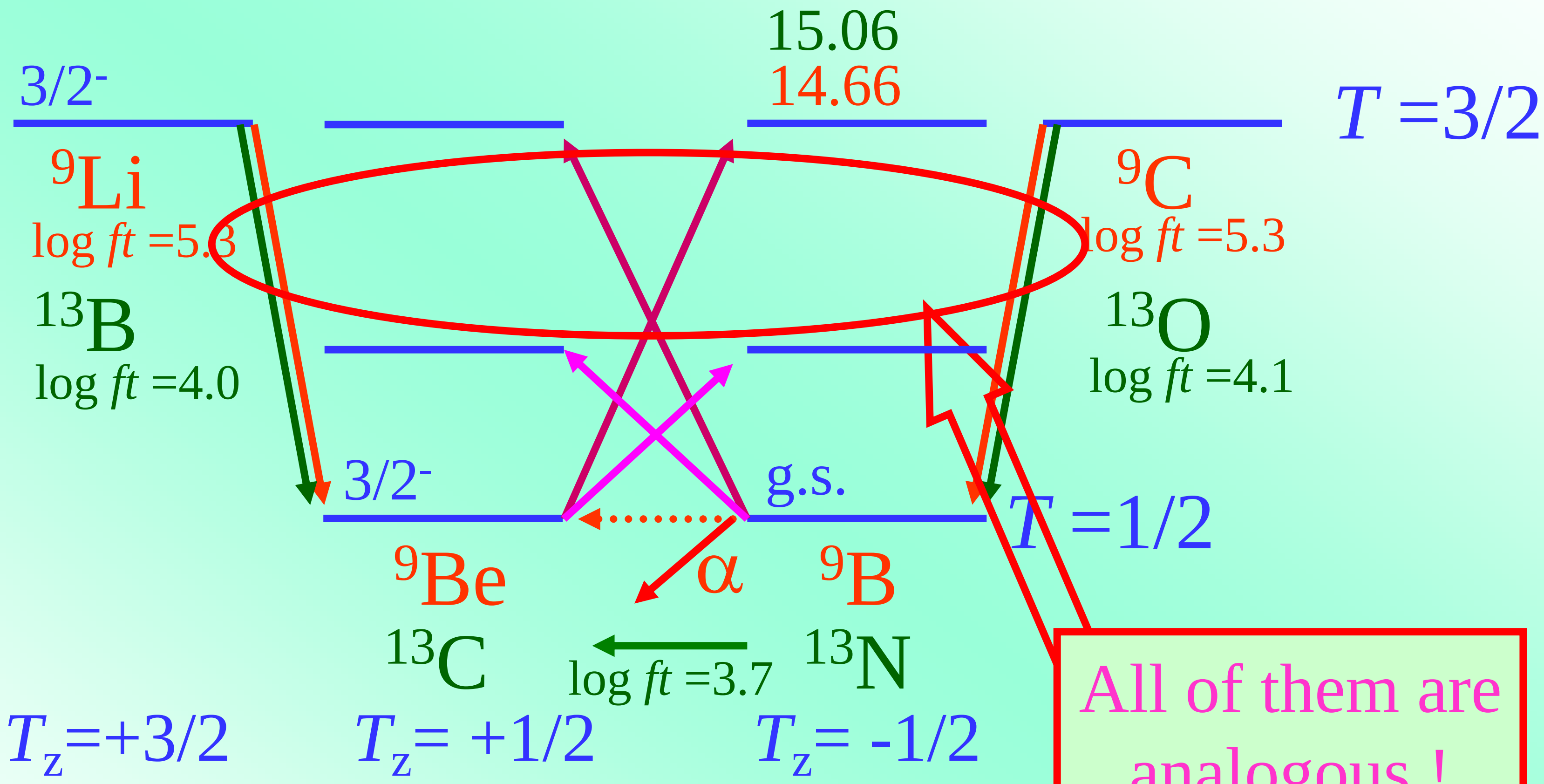
$$\frac{d\sigma}{d\Omega}(q \to 0) = K N |J|^2 B(GT)$$





Good proportionality
between both B(GT)s !

Analogous relationship: A=9, 13 system

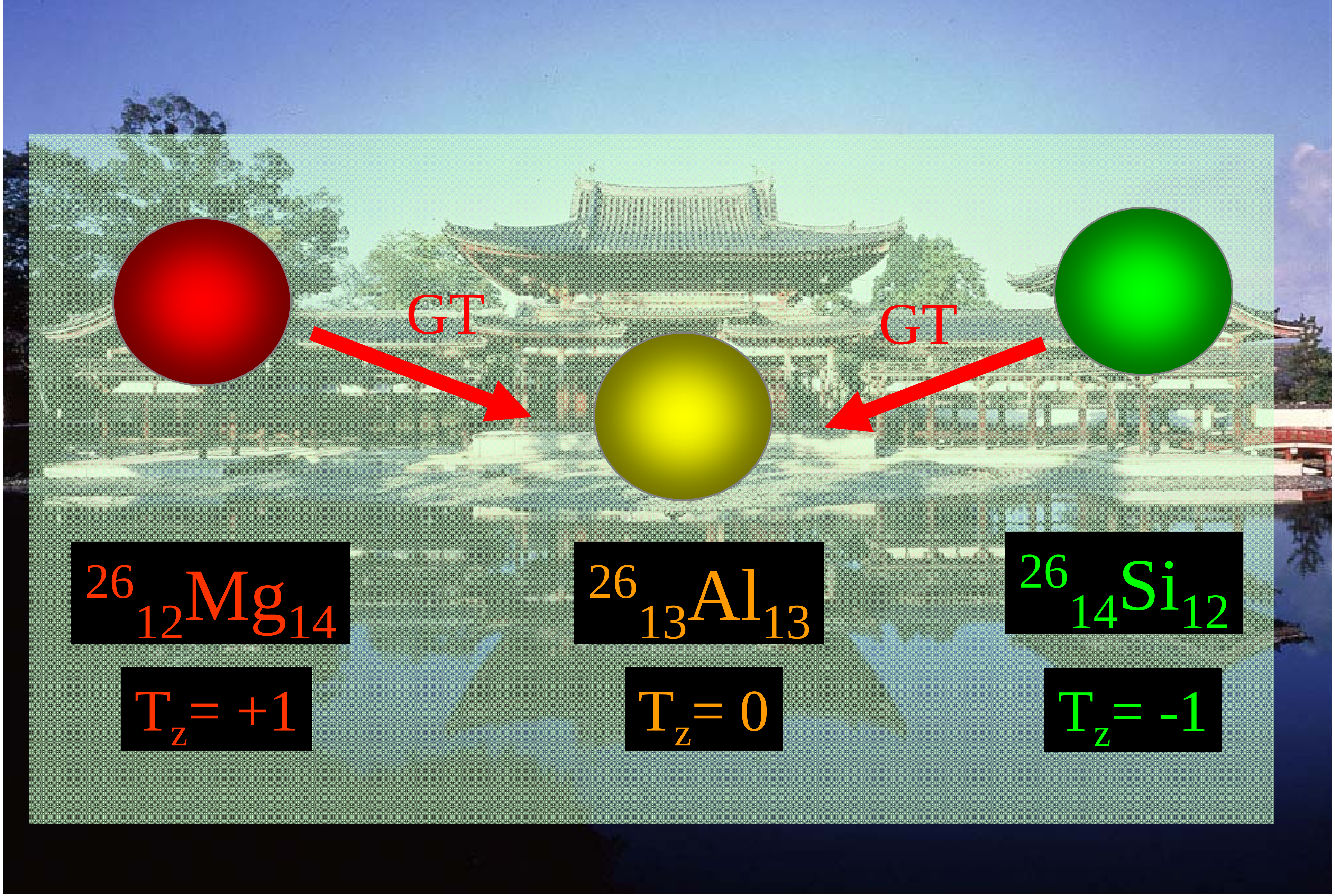


*Small isospin asymmetry can be seen for T_z=+3/2→+1/2 and T_z=-1/2← -3/2 GT transitions.

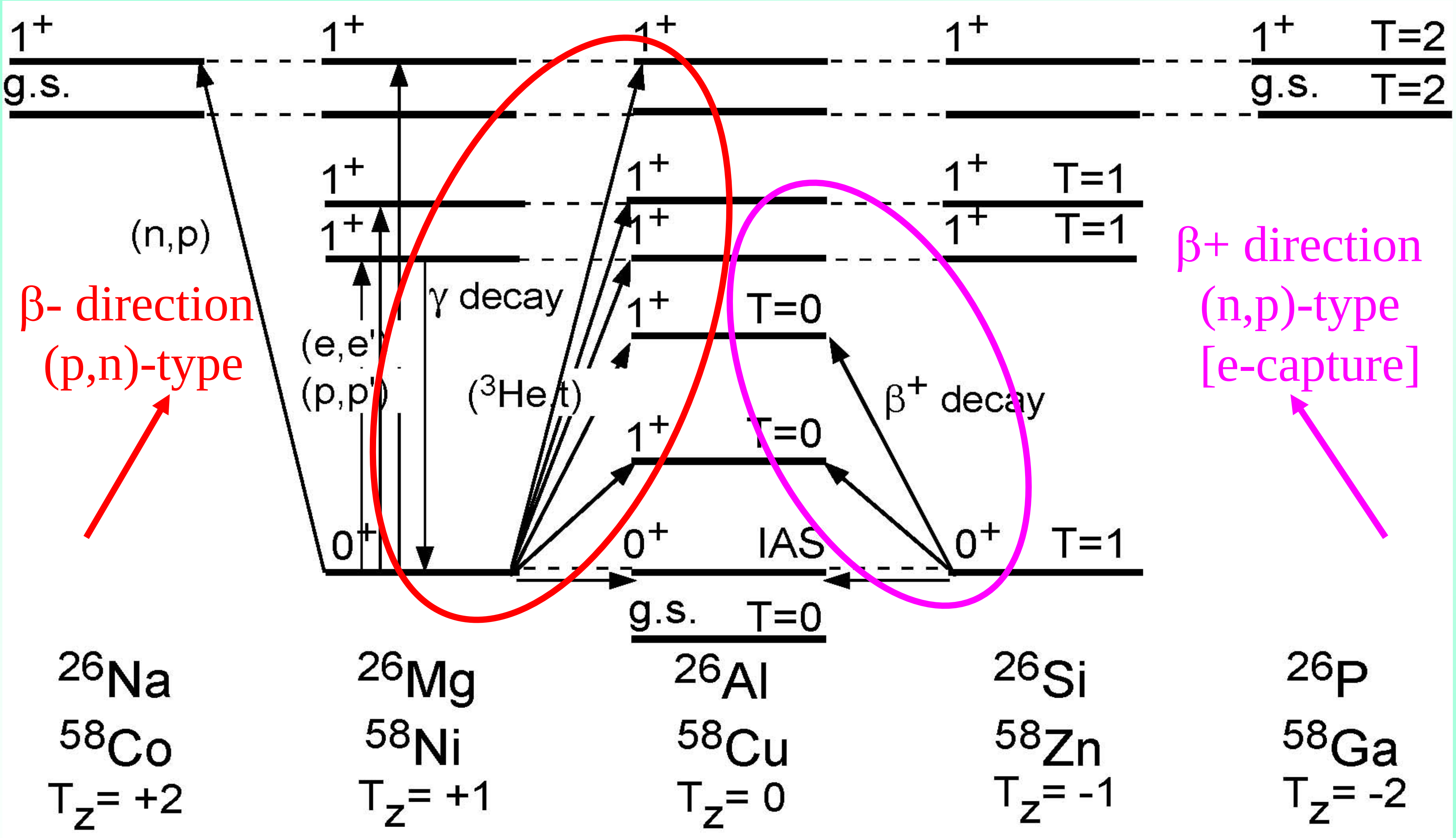
T=1 Isospin Symmetry

Byodoin-temple,
Uji, Kyoto

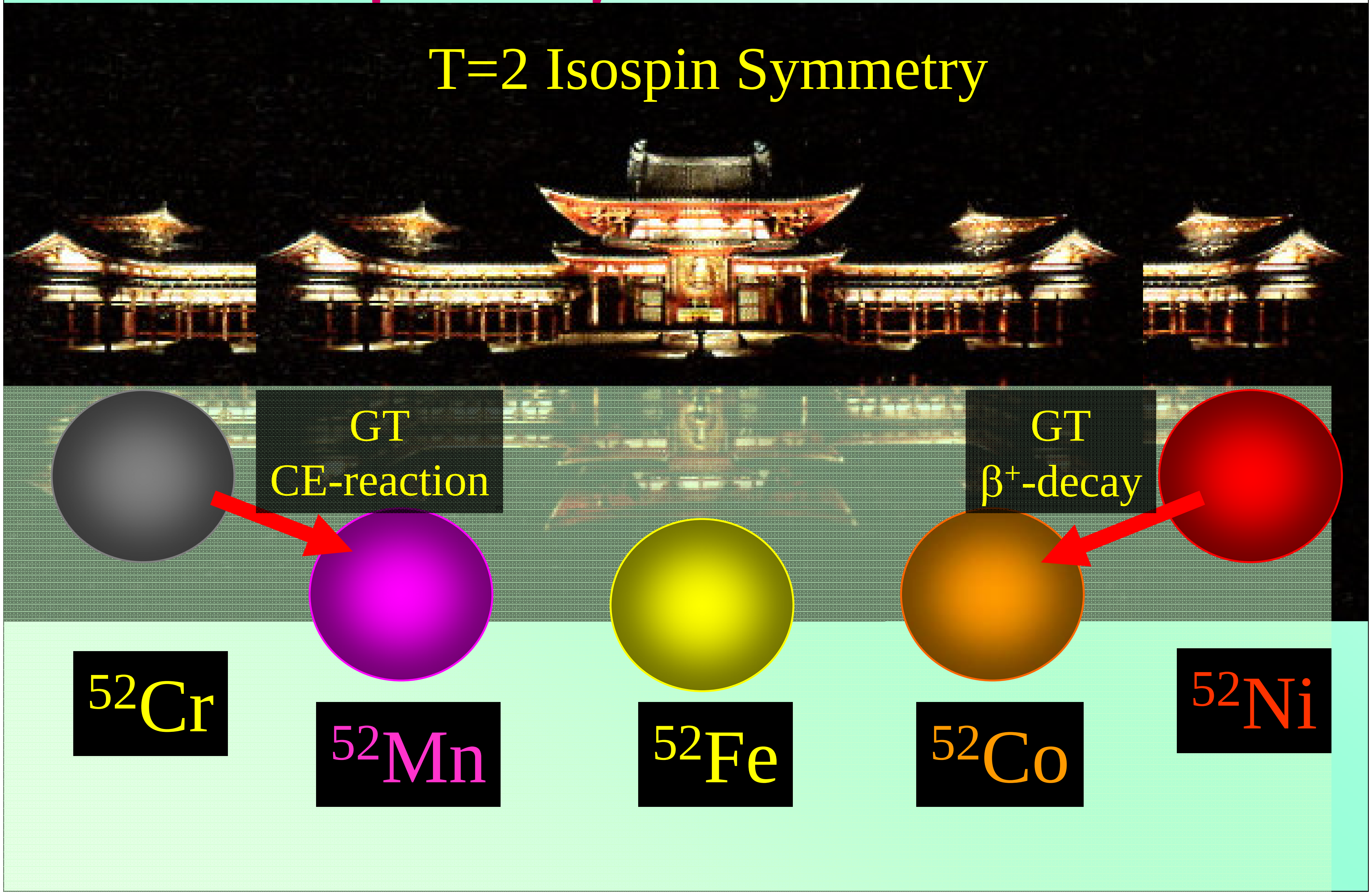
T=1 Isospin Symmetry



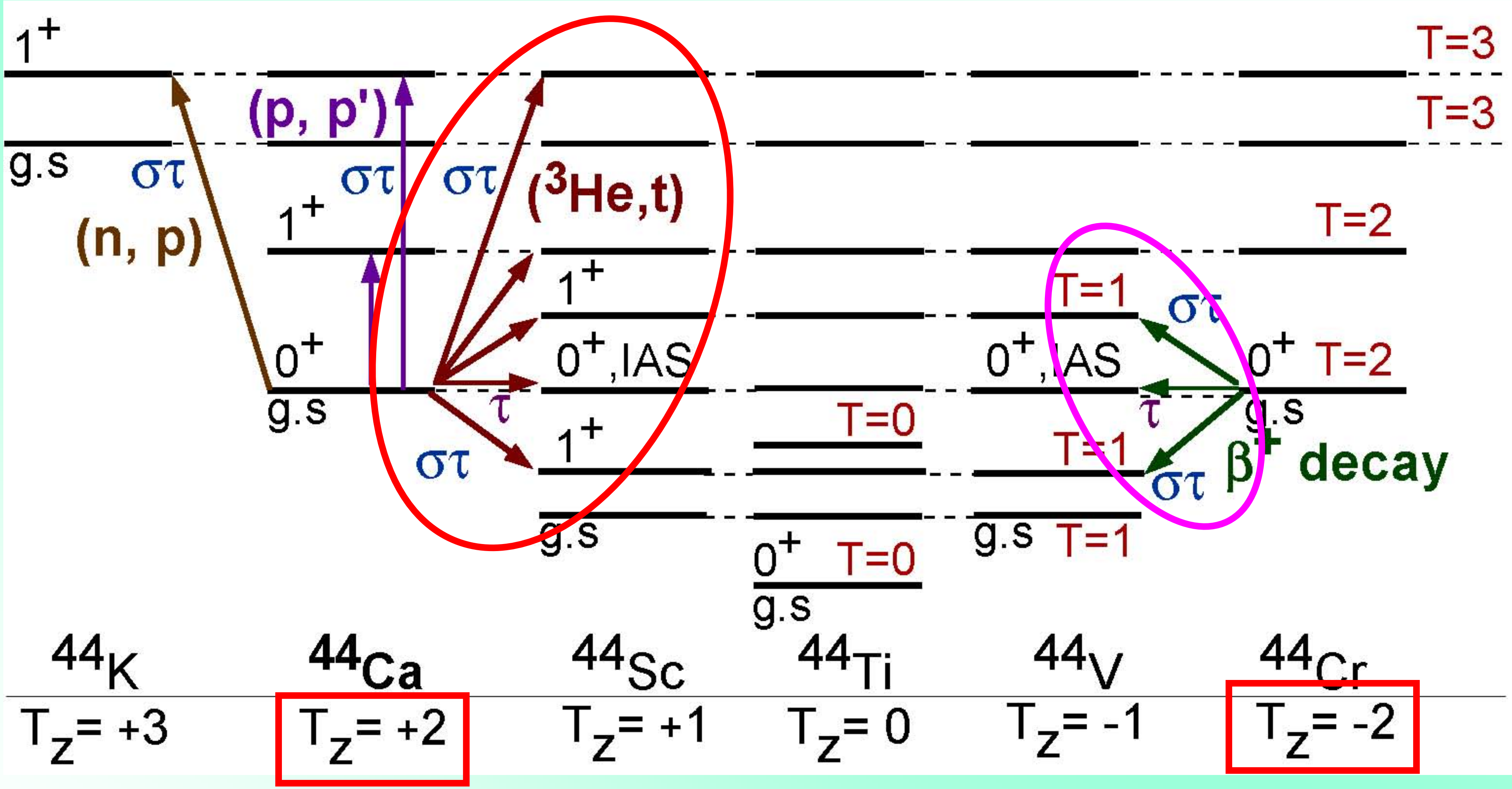
Tz=+1 → 0 ← -1 Symmetry



Super-Byodoin 平等院



Isospin Structure of T=2 system

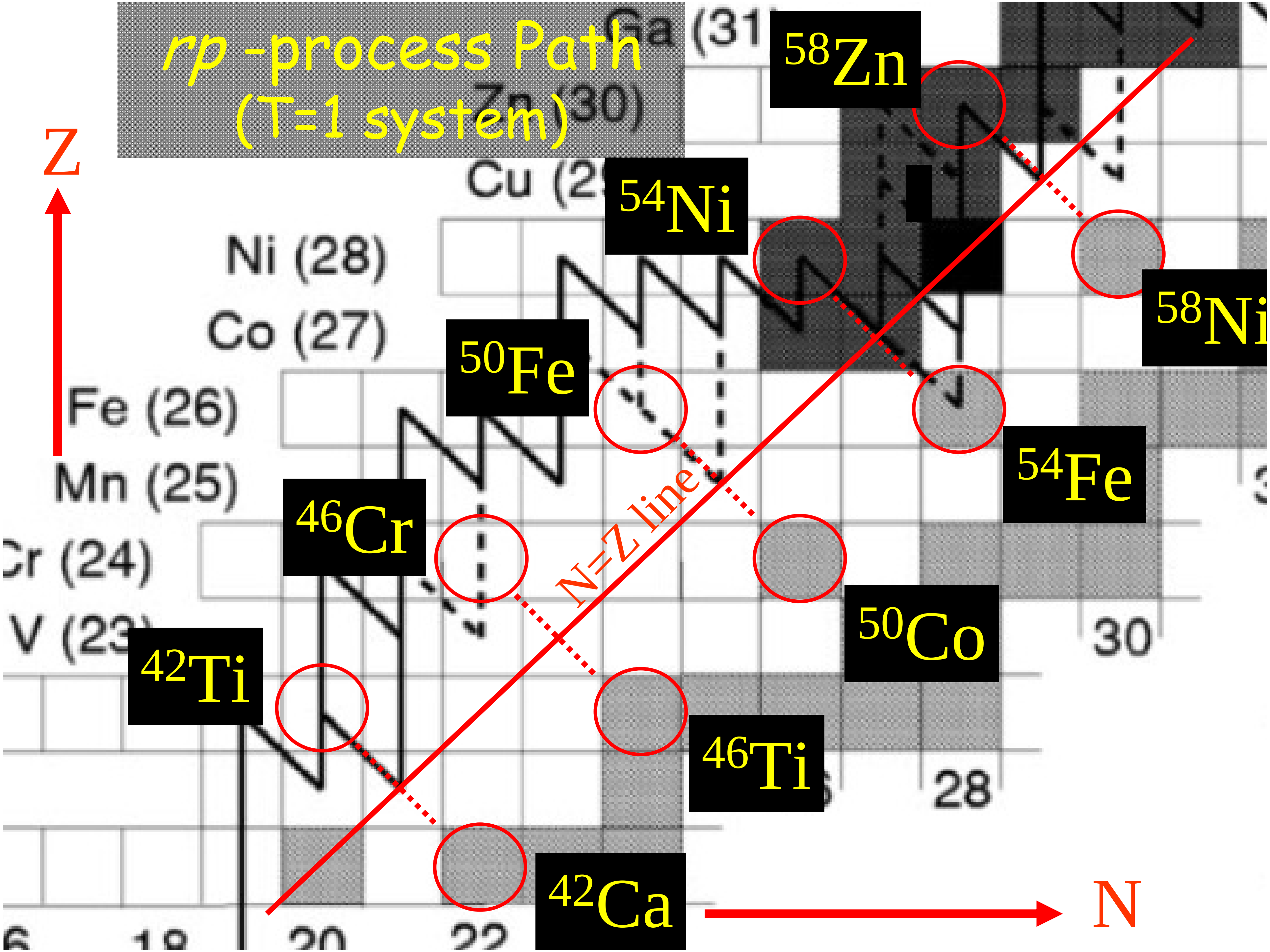


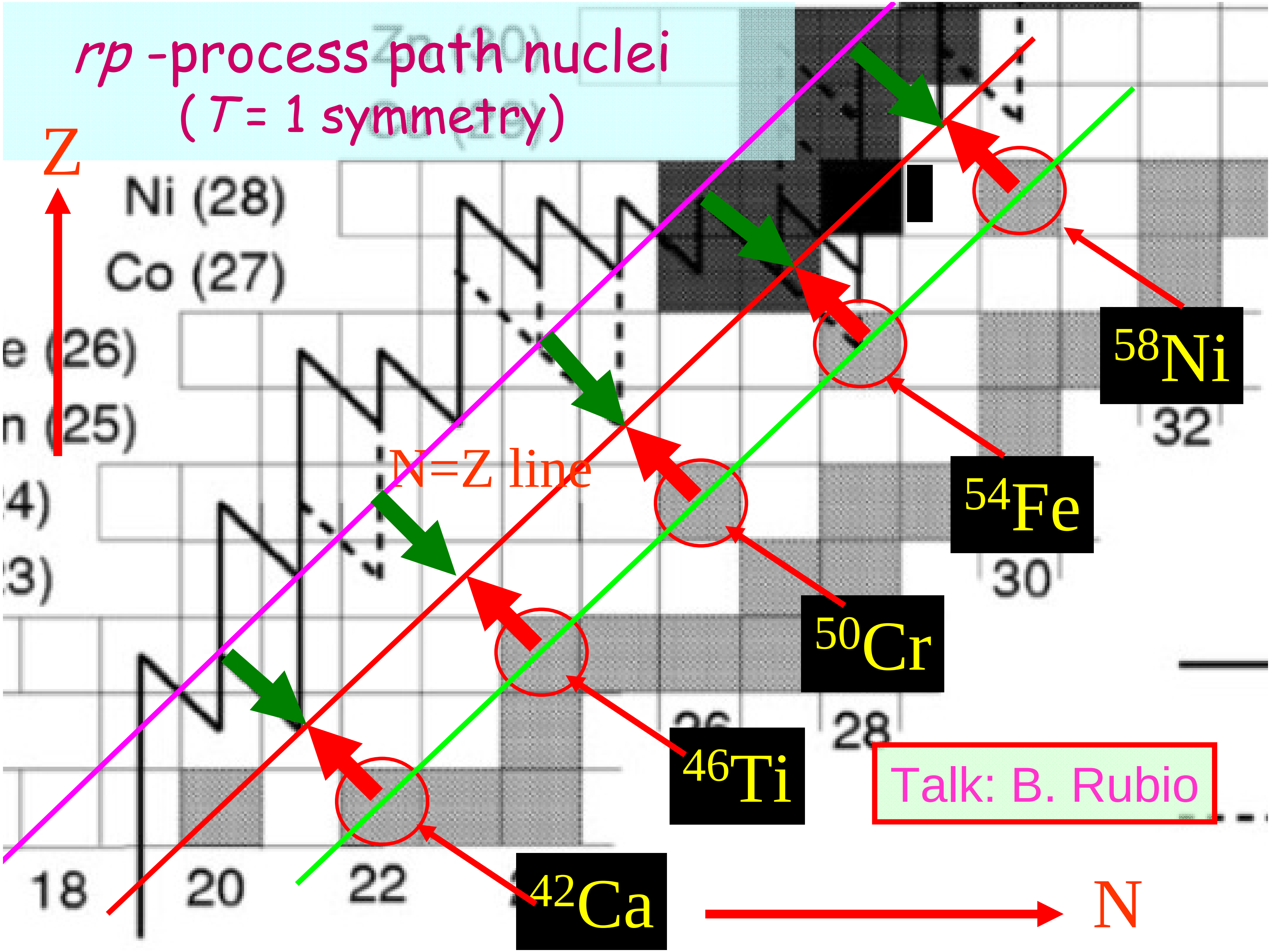
Talk by S. Orrigo: ^{48}Fe, ^{52}Ni, ^{56}Zn β decay

**GT transitions in each nucleus are UNIQUE !

- *pf*-shell nuclei -

rp-process Path (T=1 system)

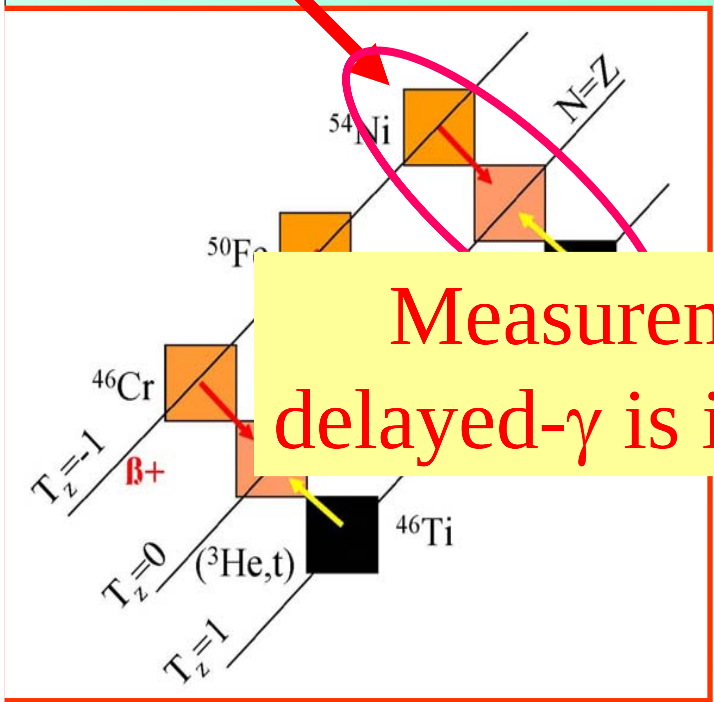


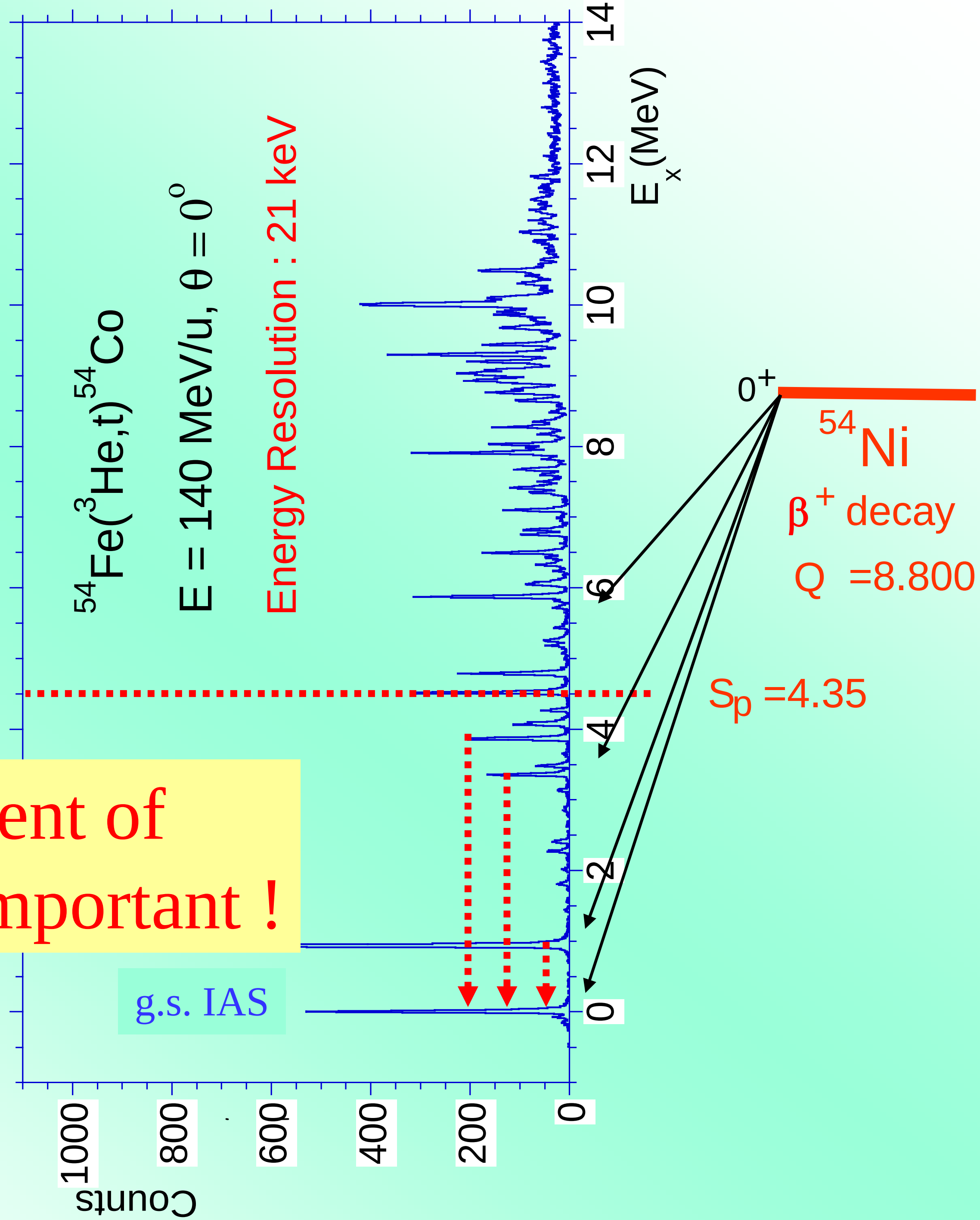


rp -process path nuclei
(*T* = 1 symmetry)
Z
Ni (28)
Co (27)
e (26)
n (25)
4)
3)
N=Z line
^{58}Ni
^{54}Fe
^{50}Cr
^{46}Ti
^{42}Ca
32
30
28
18
20
22
Talk: B. Rubio
N

^{54}Ni β-decay measurement

- at GSI
  (FRS facility)
- RISING
  (stopped beam campaign)



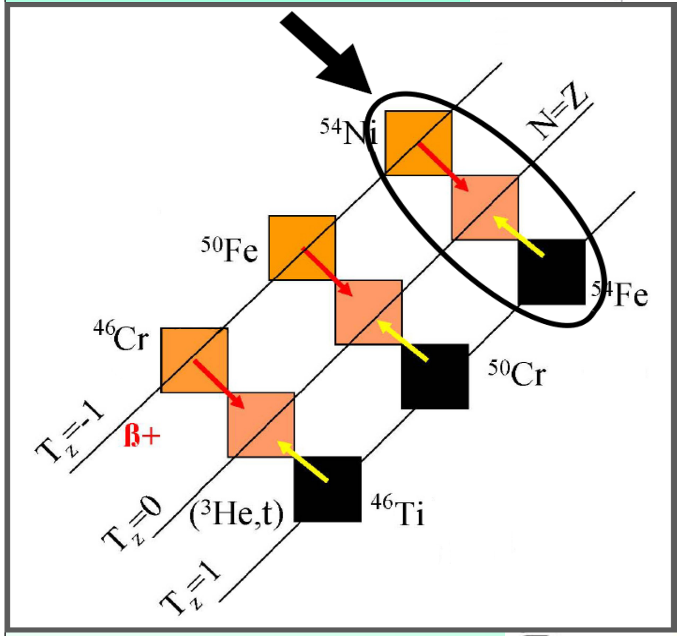


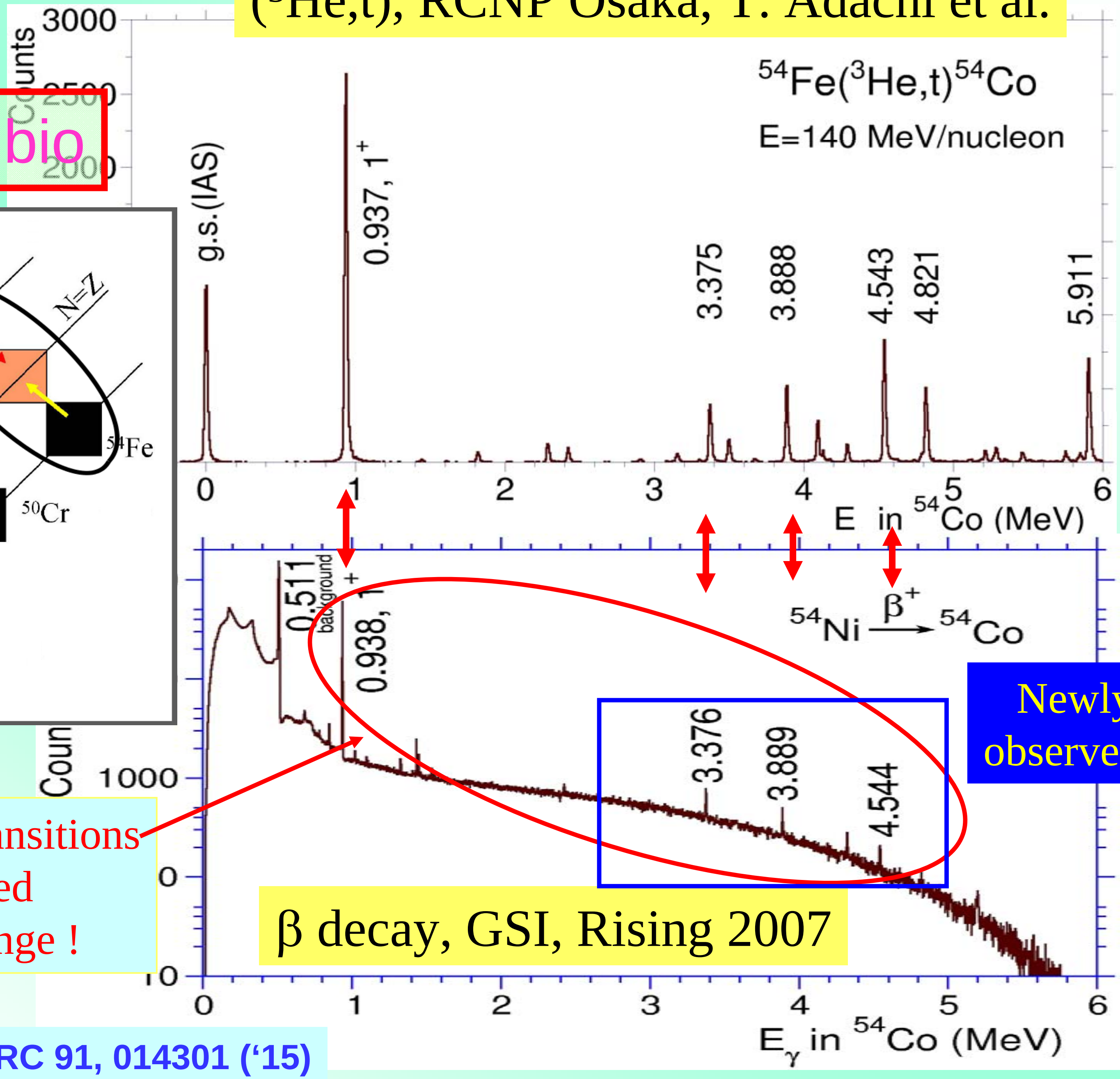
Measurement of delayed-γ is important !

GSI RISING set up

(³He,t), RCNP Osaka, T. Adachi et al.

Talk: B. Rubio





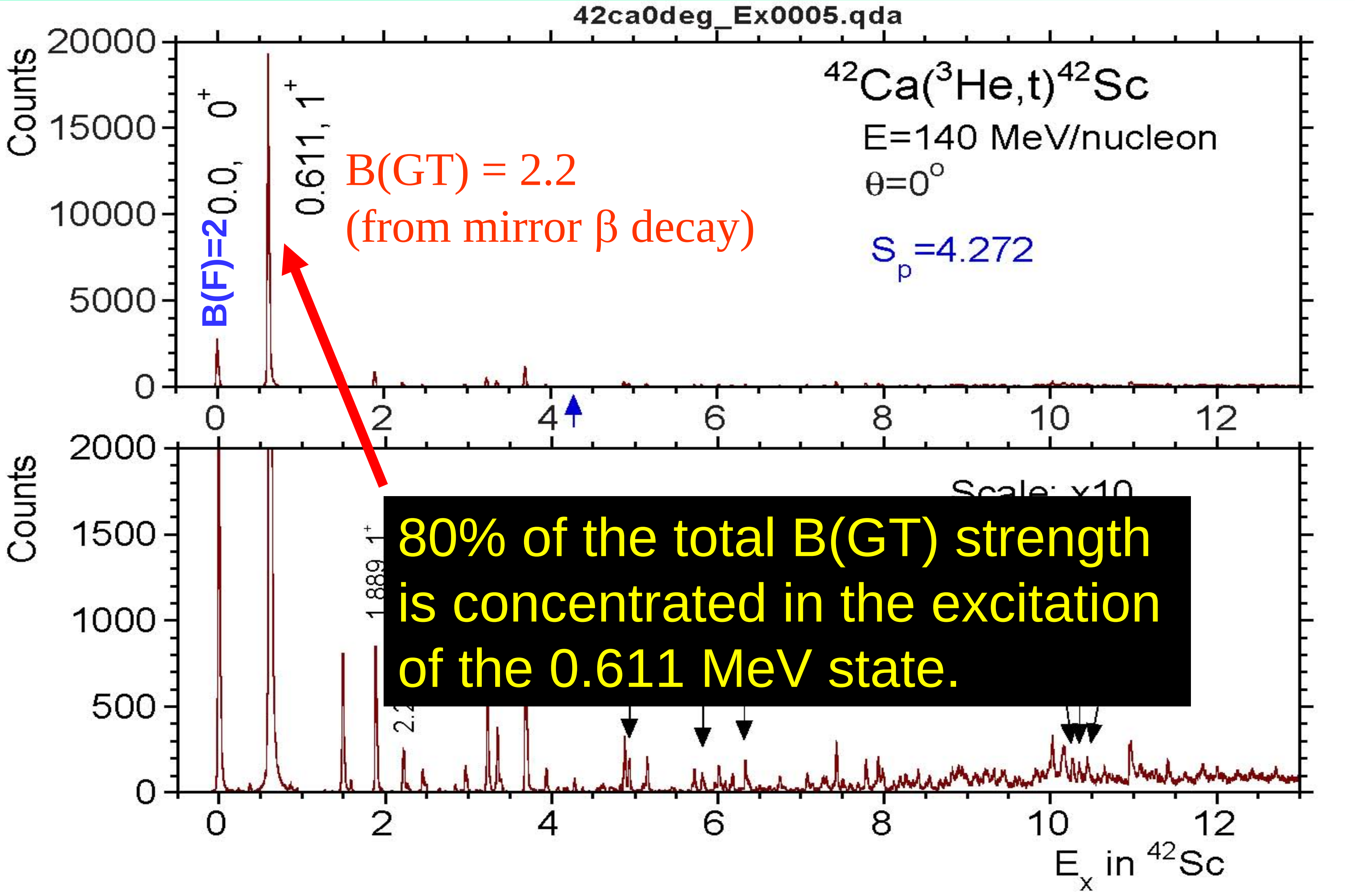
Newly observed !

Corresponding Transitions were observed in a wide E_x range !

β decay, GSI, Rising 2007

F. Molina et al., PRC 91, 014301 ('15)

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



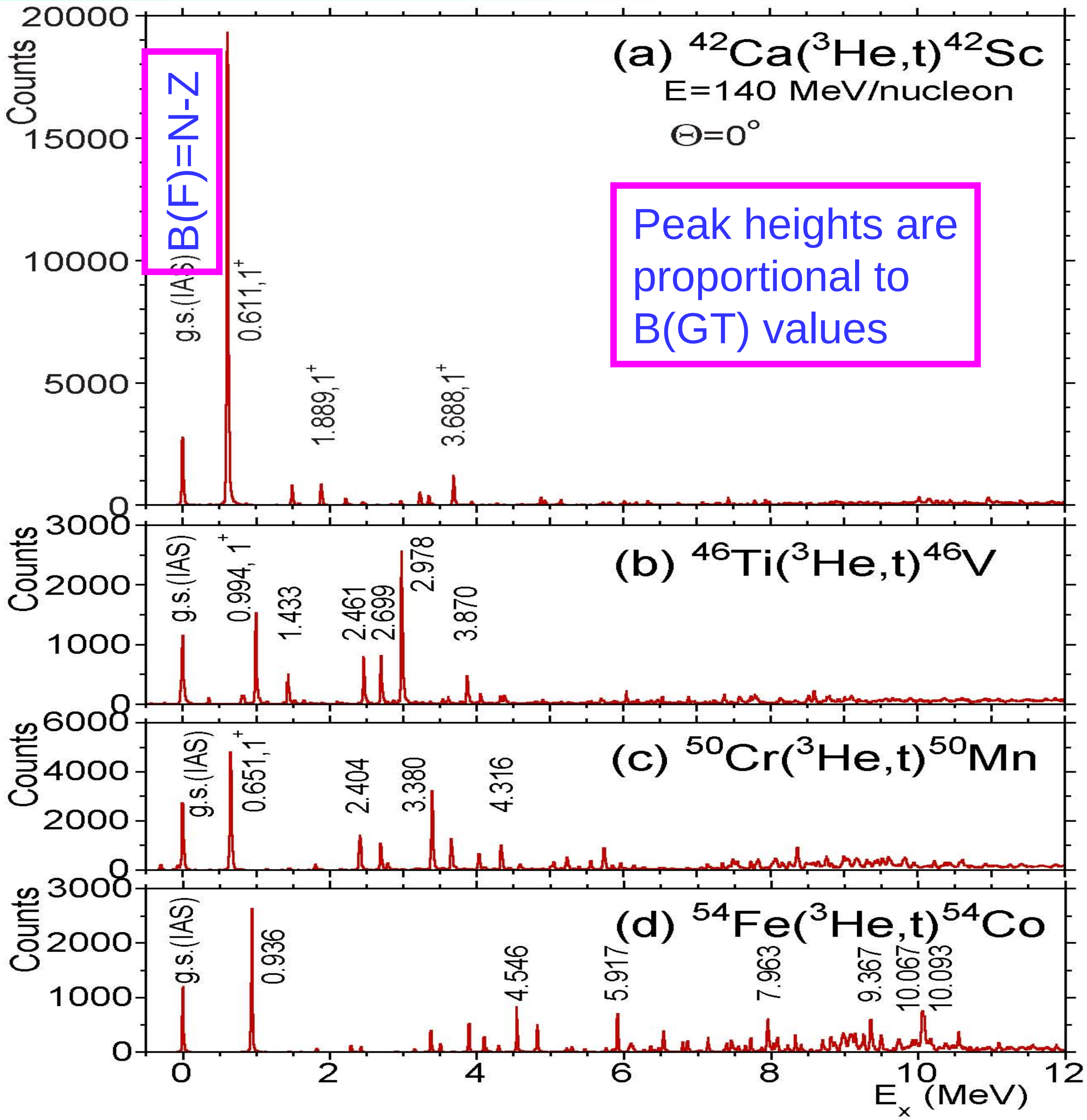
GT states in A=42-54 T_z=0 nuclei

Y. Fujita et al.
PRL 2014
PRC 2015

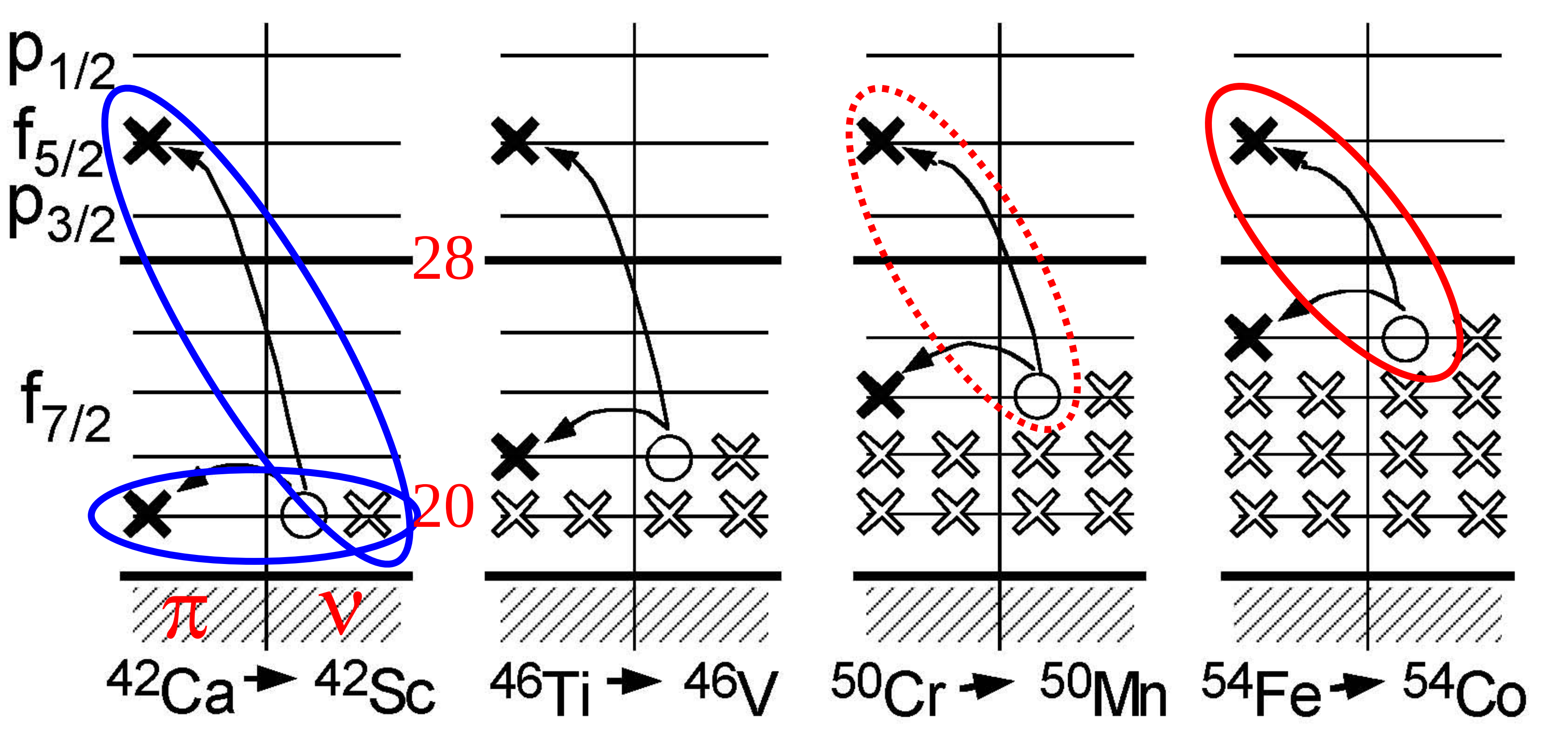
T. Adachi et al.
PRC 2006

Y. Fujita et al.
PRL 2005

T. Adachi et al.
PRC 2012



SM Configurations of GT transitions



particle-hole configuration
+ IV-type int.
= REPULSIVE

Role of Residual Int. (repulsive)

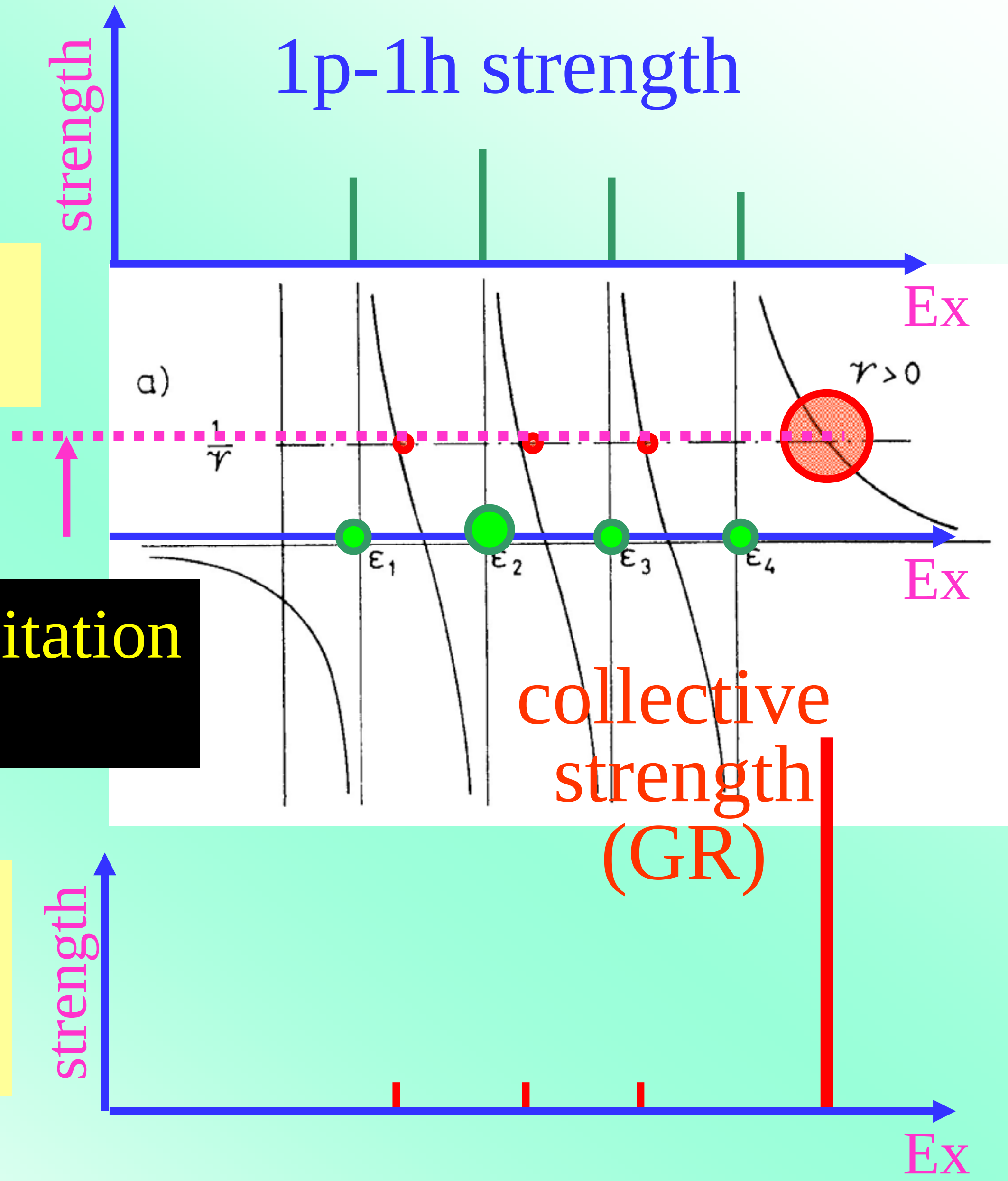
Single particle-hole strength distribution

Graphical solution of the RPA dispersive eigen-equation

positive = repulsive

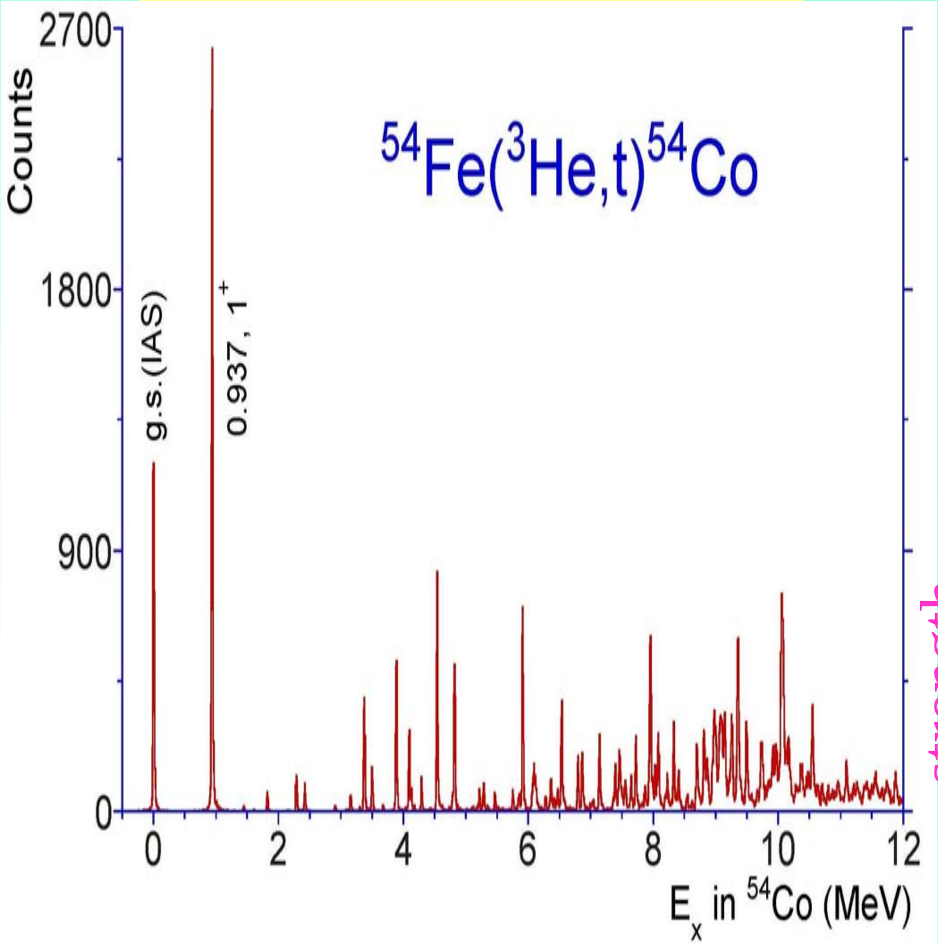
p-h configuration + IV excitation = repulsive

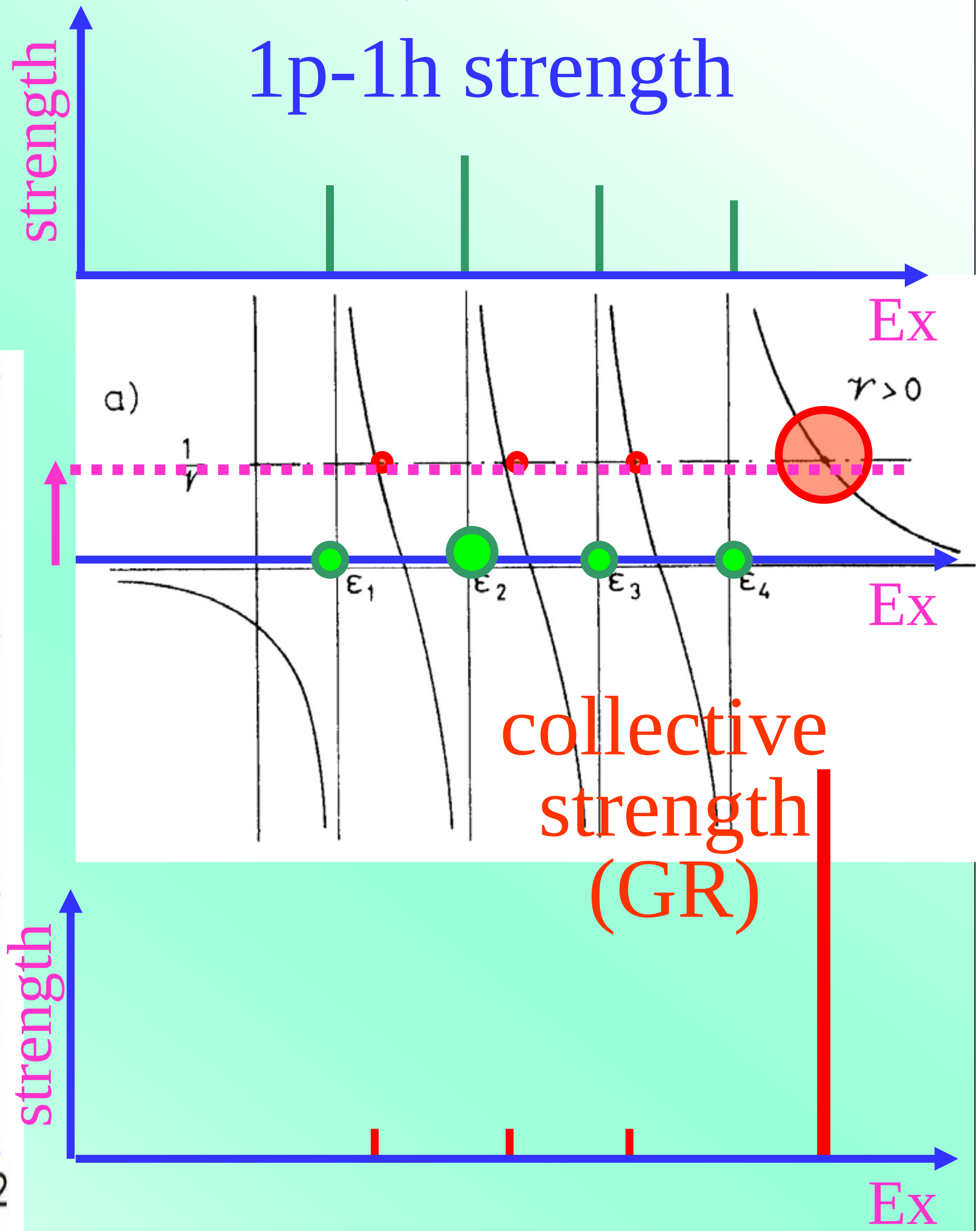
Collective excitation formed by the repulsive residual interaction



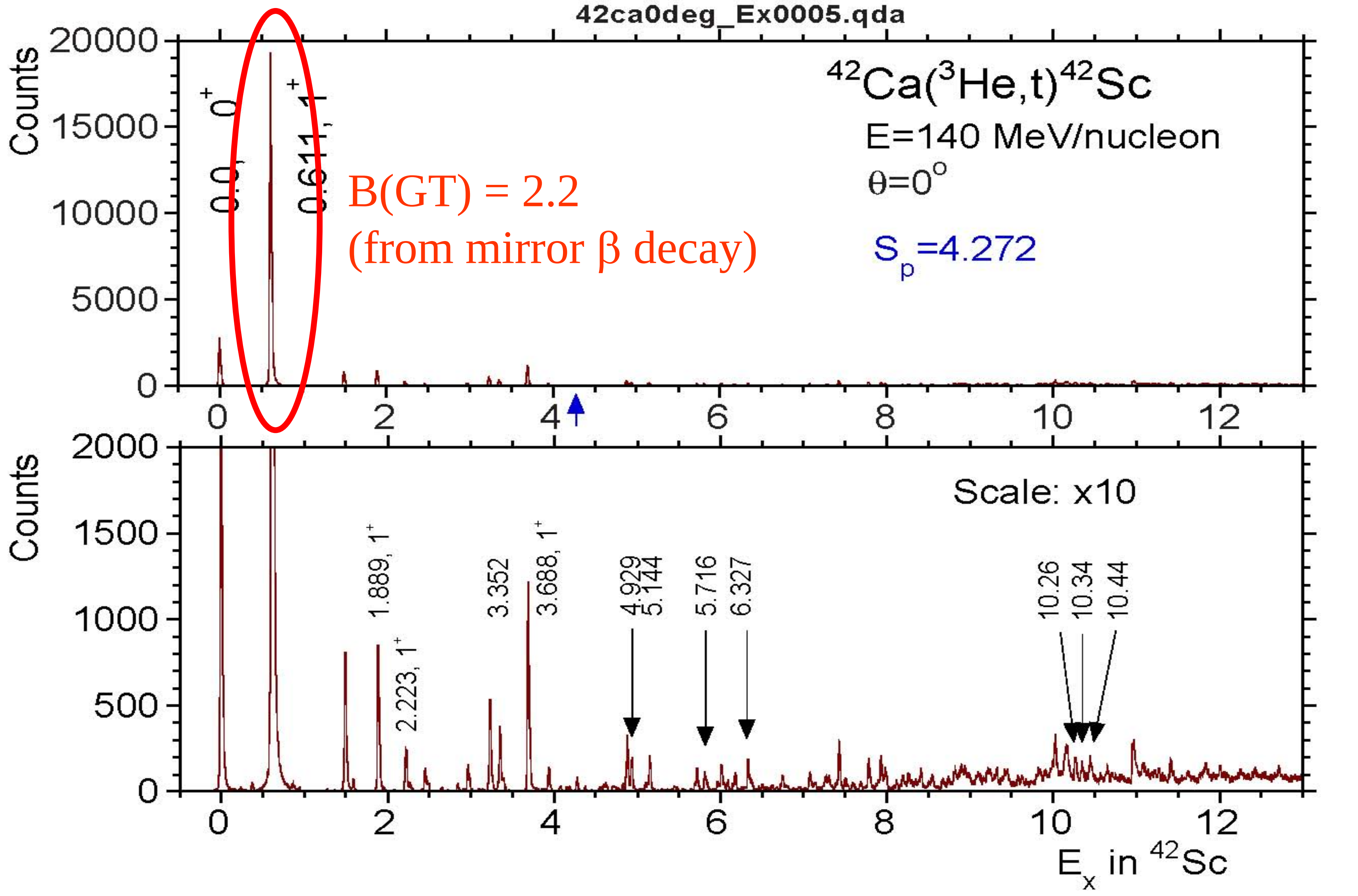
Role of Residual Int. (repulsive)

Collective excitation formed by the repulsive residual interaction

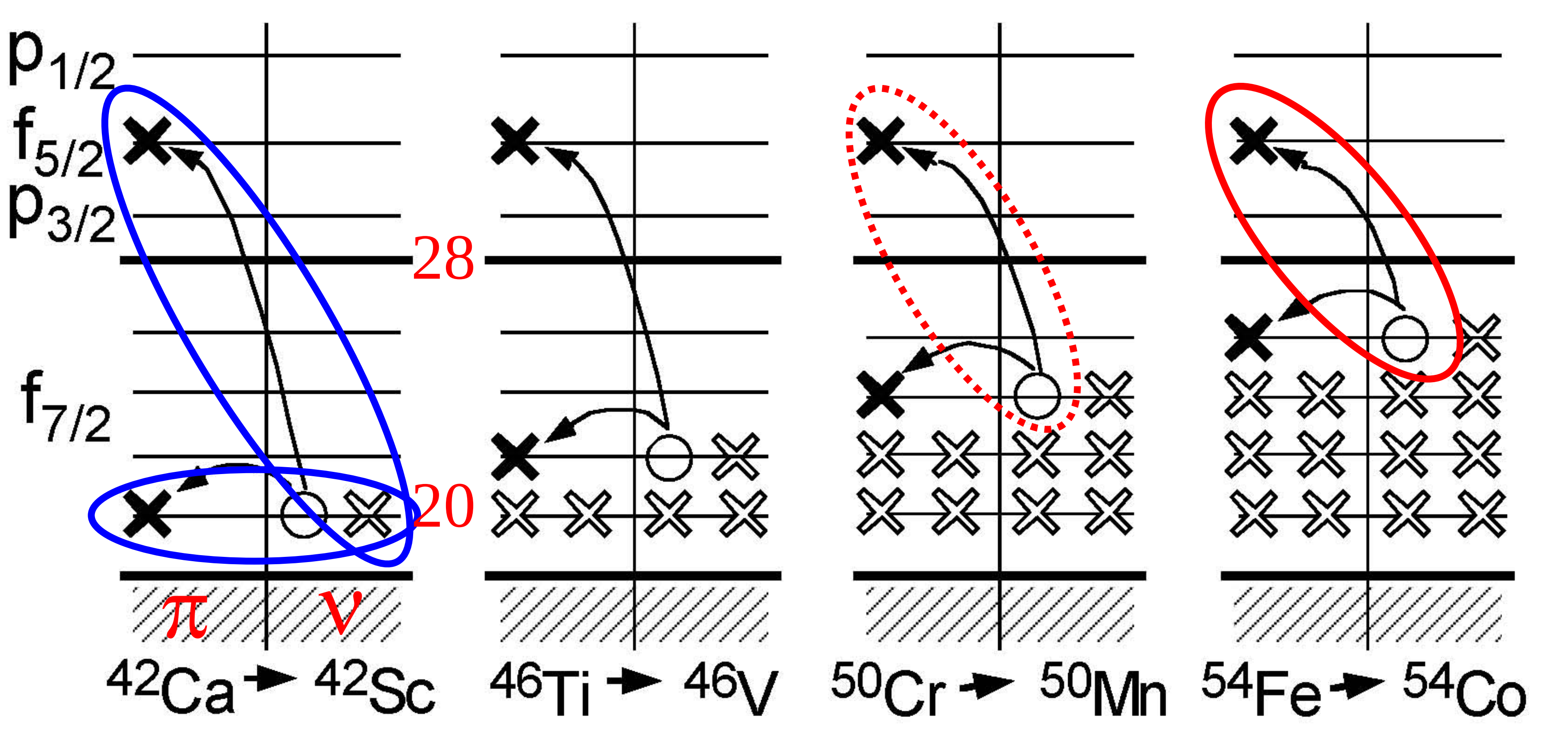




$^{42}Ca(^3He,t)^{42}Sc$ in 2 scales



SM Configurations of GT transitions

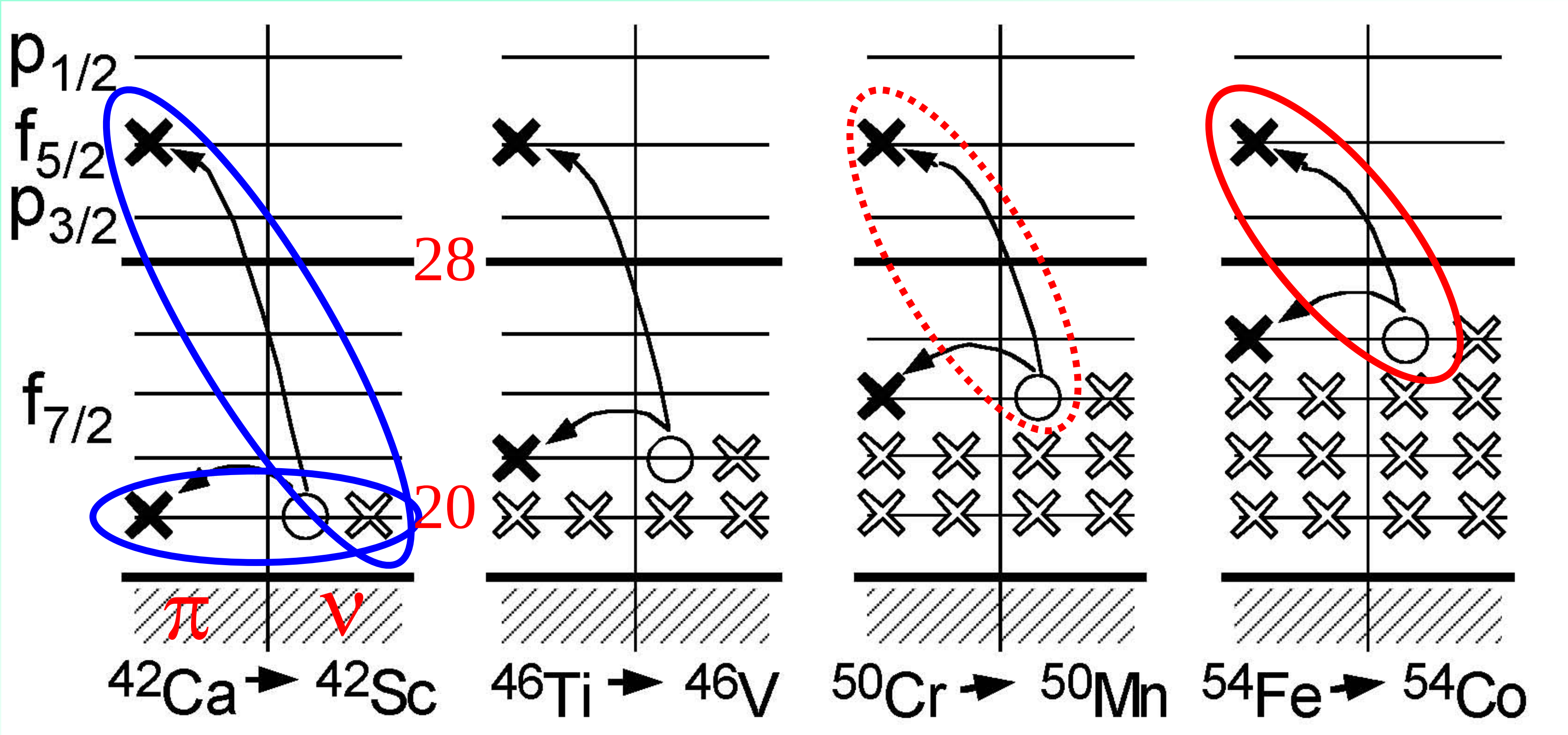


π-p - ν-p configurations
sensitive to IS pairing int.
➔attractive
(spin-triplet, IS int. is stronger
than spin-singlet, IV int.)

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

by Engel, Bertsch, Macchiavelli

SM Configurations of GT transitions



particle-particle int. (attractive)

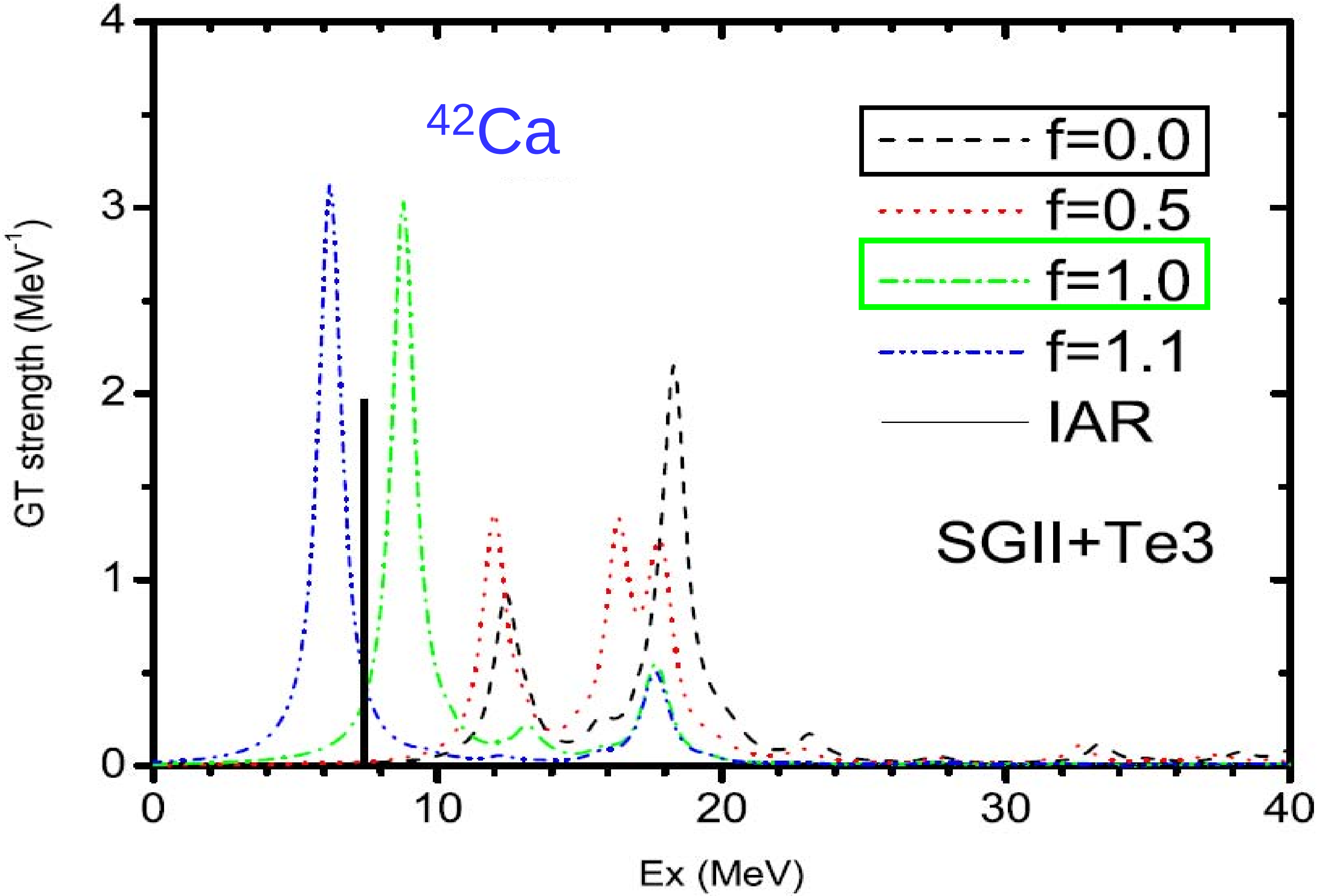
(IS p-n int. is attractive)

particle-hole int. (repulsive)

Isoscalar interaction
can play Important roles !

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

Bai, Sagawa, Colo et al., PRC 90 (2014) 054335



$^{42}Ca \rightarrow {}^{42}Sc$ (Q-value)

QRPA cal. including IS int.

Bai, Sagawa, Colo et al., PRC 90 (2014) 054335

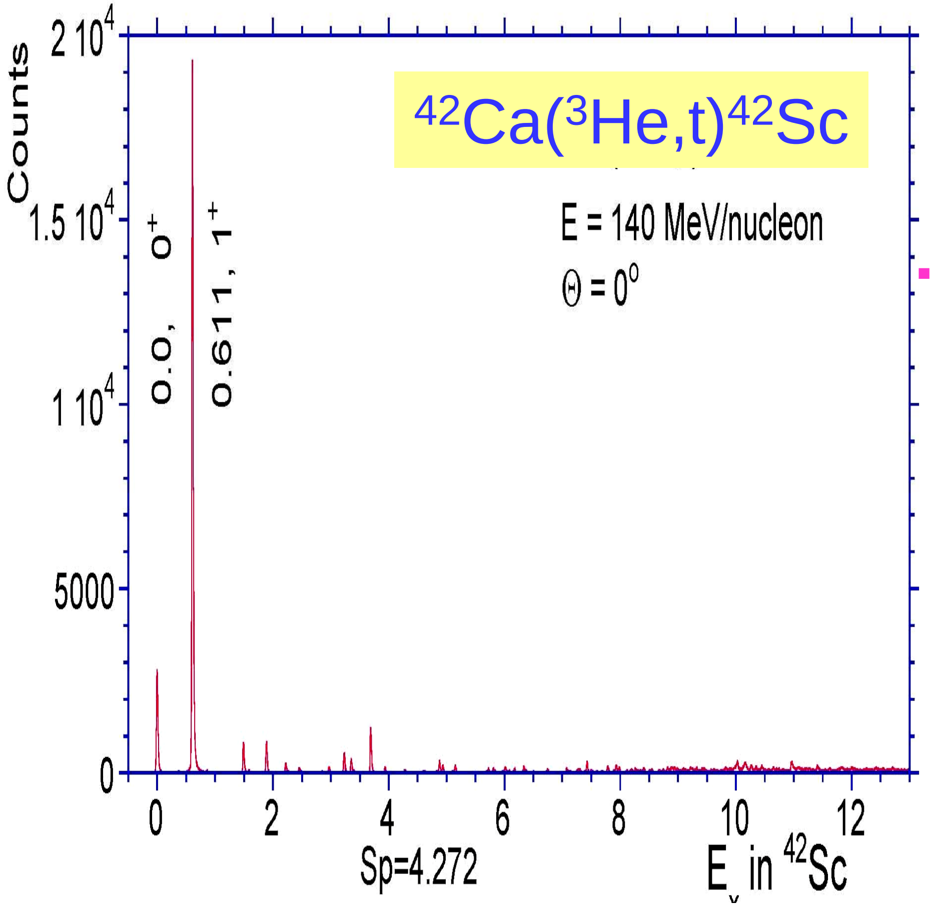
f	Bnp			
0	1. 34			
	neutron	proton	(Xupvn+Yunvp)	(Xupvn+Yunvp)*<p||GT||n>
	1f7/2	1f7/2	0. 427	1. 3689
0. 5	2. 051			
	1f7/2	1f7/2	0. 432	1. 384
1	4. 75			
	1f5/2	1f7/2	0. 053	0. 2158
	1f7/2	1f5/2	0. 129	0. 474
	1f7/2	1f7/2	0. 33	1. 059

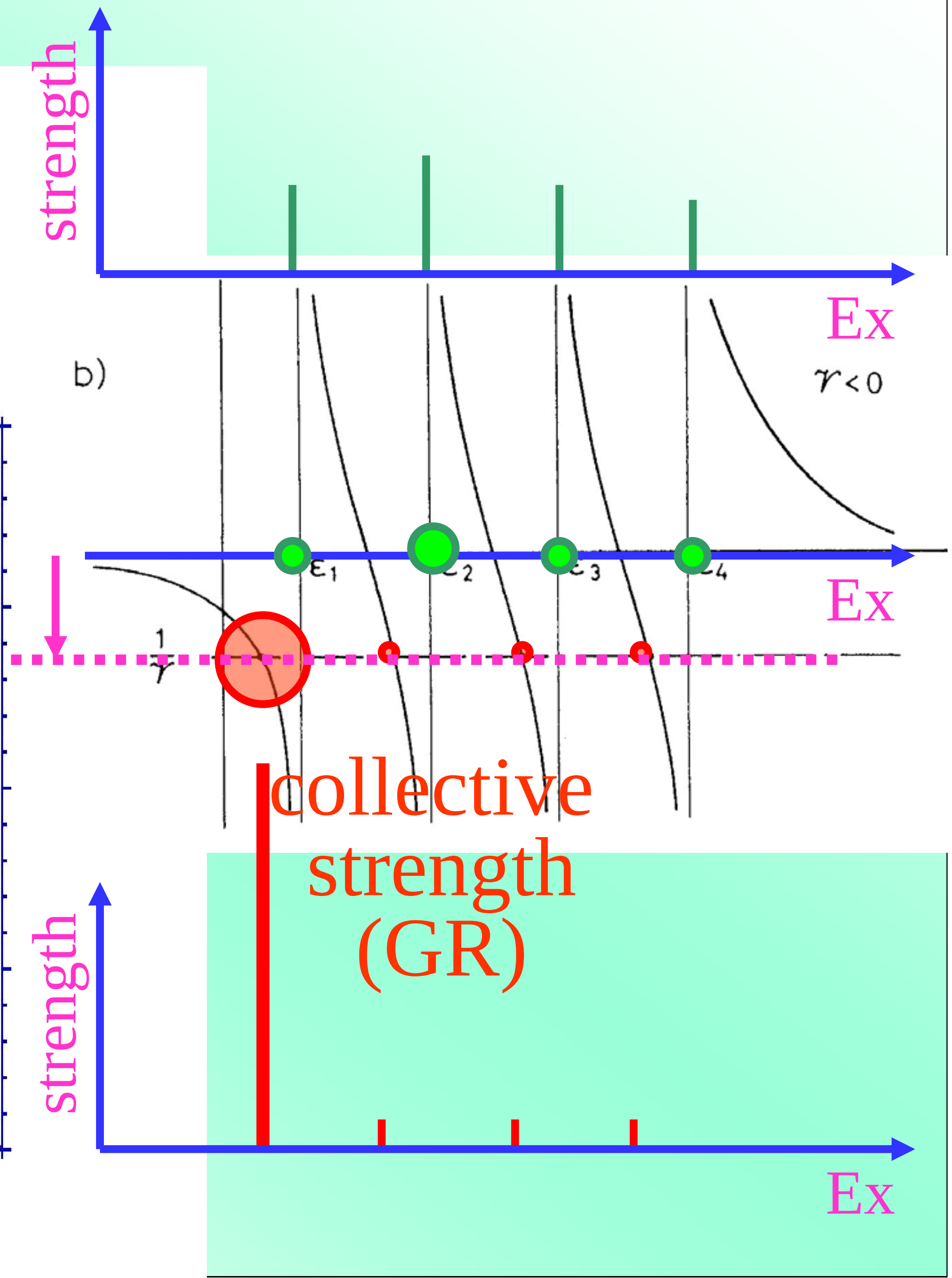
Configurations are in phase!

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

Role of Residual Int. (attractive)

Collective excitation formed by the attractive IS residual interaction





42Ca→42Sc:
Shell Model Cal.: Transition Matrix Elements

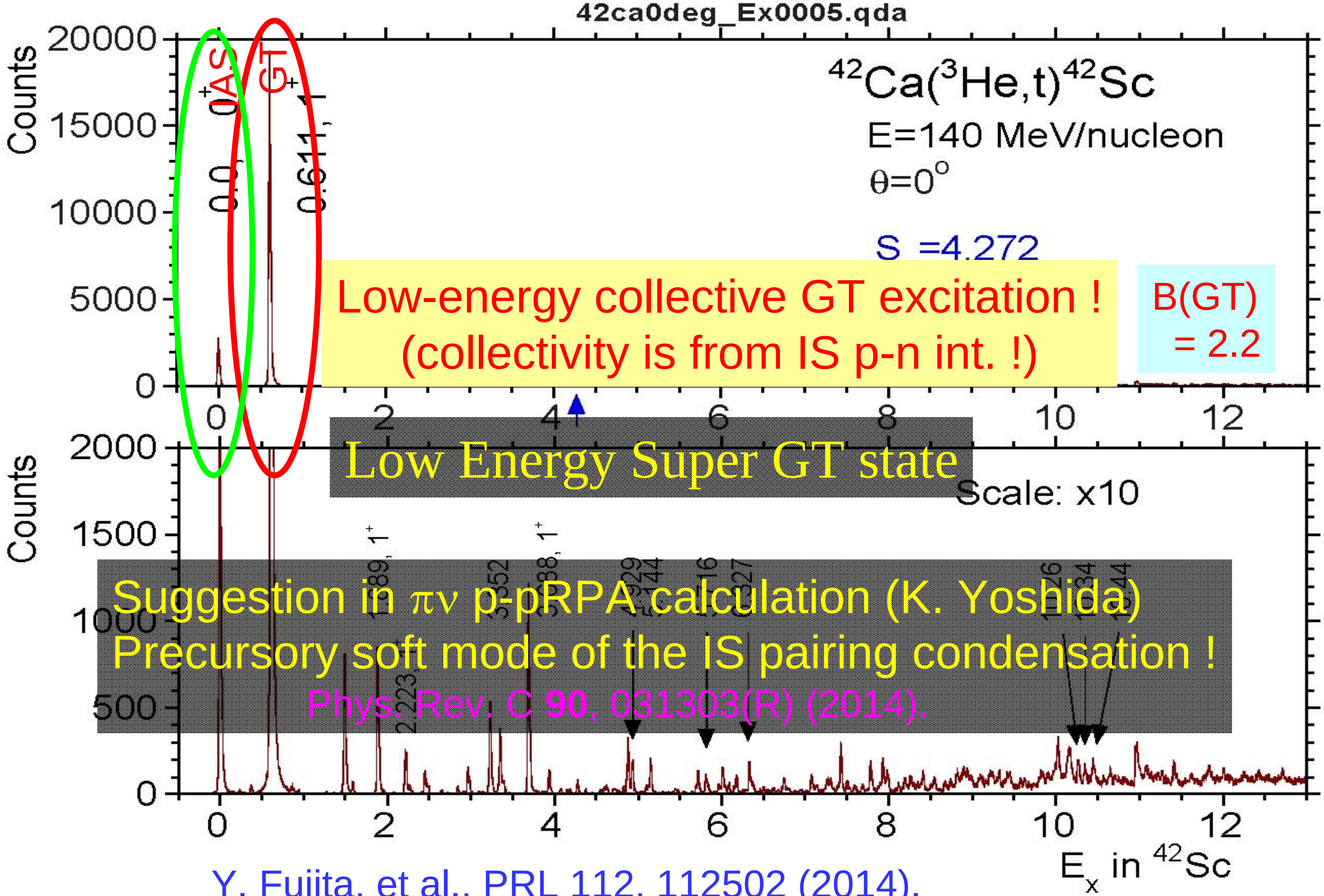
TABLE VI. Results of the *pf*-shell SM calculation using the GXPF1J interaction. The matrix elements *M*(GT) of GT transitions exciting individual $J^{\pi} = 1^{+}$ GT states in ^{42}Sc from the g.s. of ^{42}Ca are shown for each configuration. The results are shown for all excited GT states predicted 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 !**

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



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

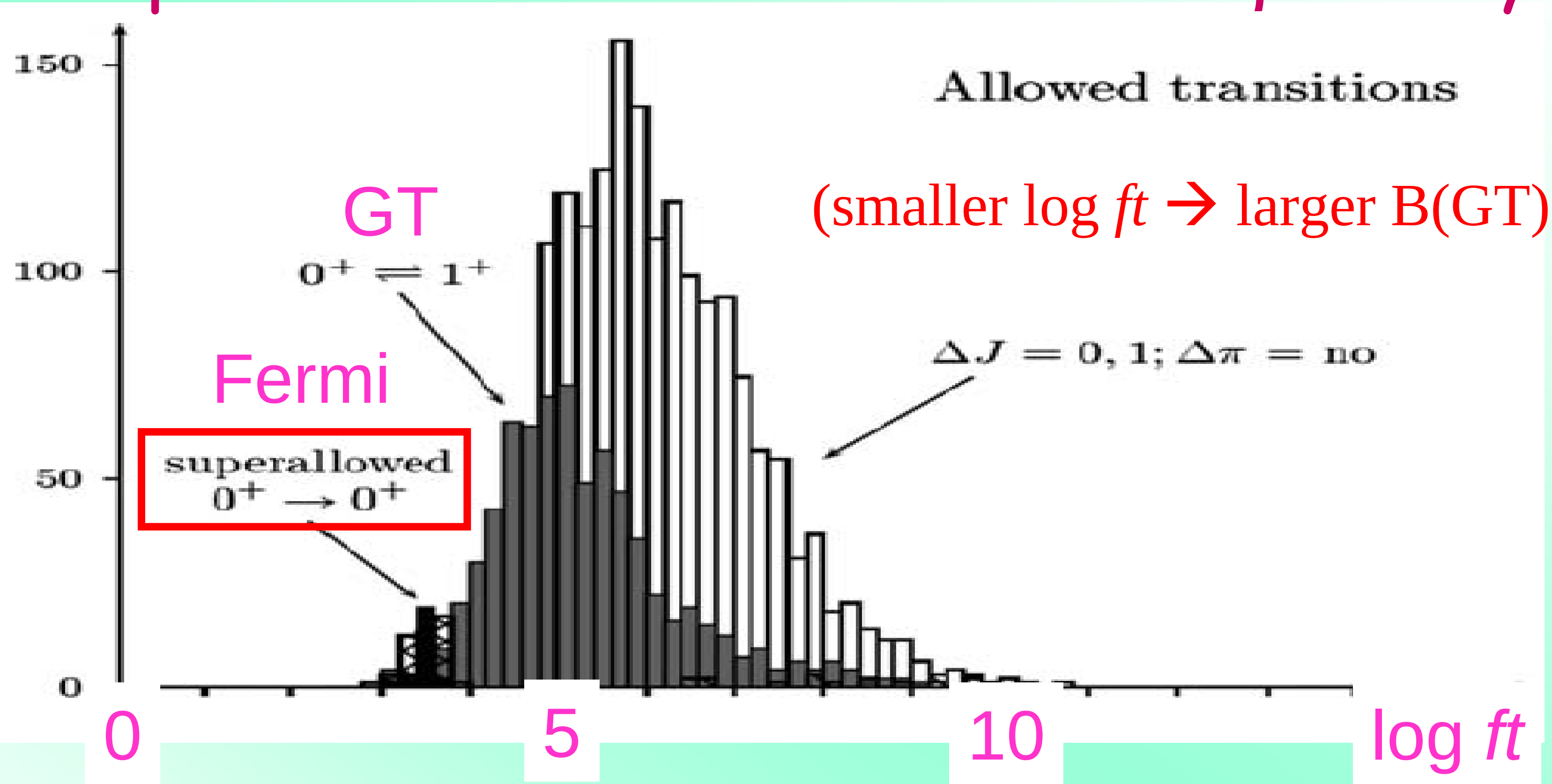
B(GT) = 2.2

Low Energy Super GT state

Suggestion in πν p-pRPA calculation (K. Yoshida)
Precursory soft mode of the IS pairing condensation !
Phys. Rev. C **90**, 031303(R) (2014).

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

Super-allowed GT transitions in β decay



^{6}He, 0^+ → ^{6}Li, 1^+ log *ft* = 2.9

^{18}Ne, 0^+ → ^{18}F, 1^+ log *ft* = 3.1

^{42}Ti, 0^+ → ^{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.

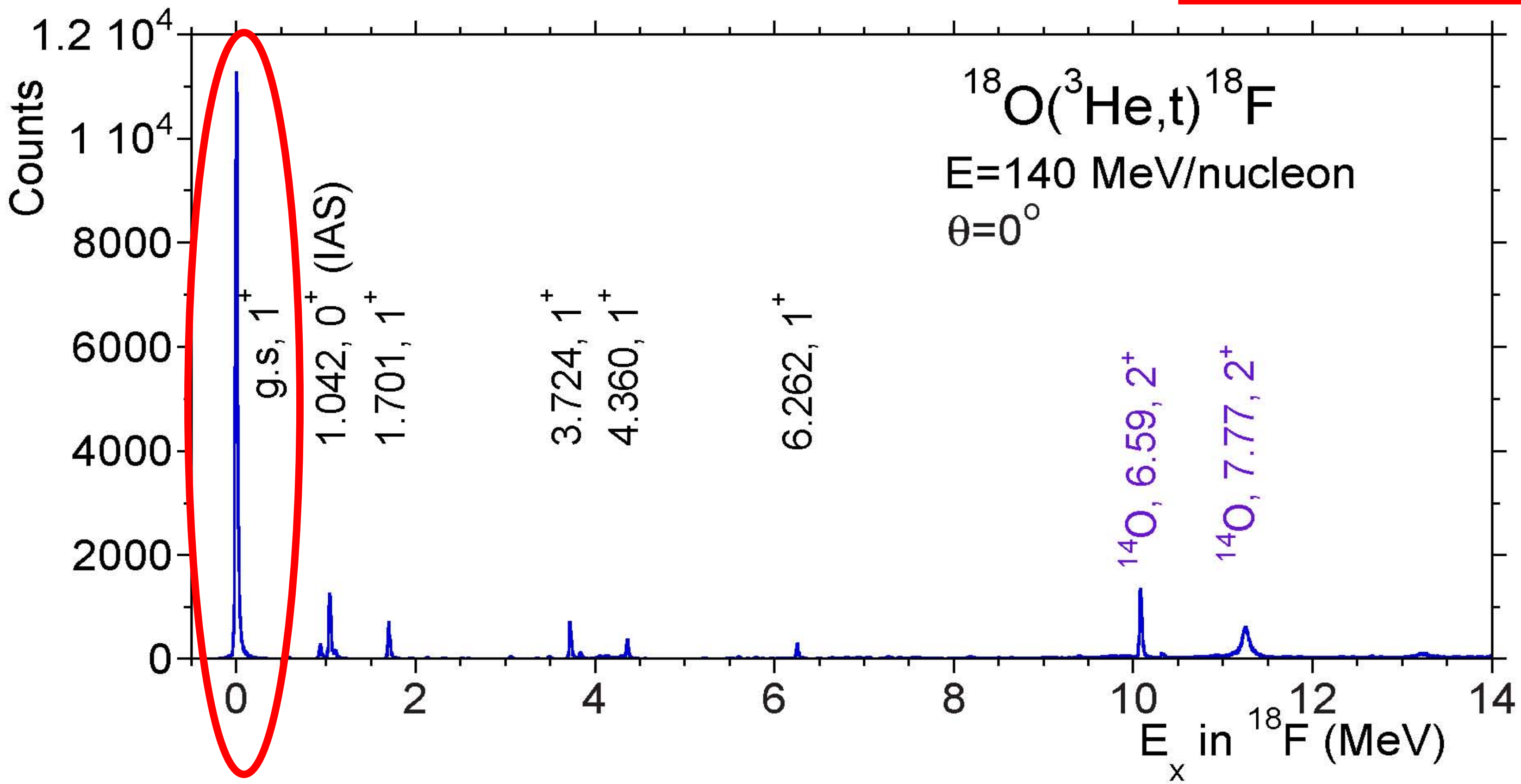
→ attractive IS residual int. restores the symmetry !

→ 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 !

$^{18}O(^{3}He,t)^{18}F$ at 0°

Talk: H. Fujita

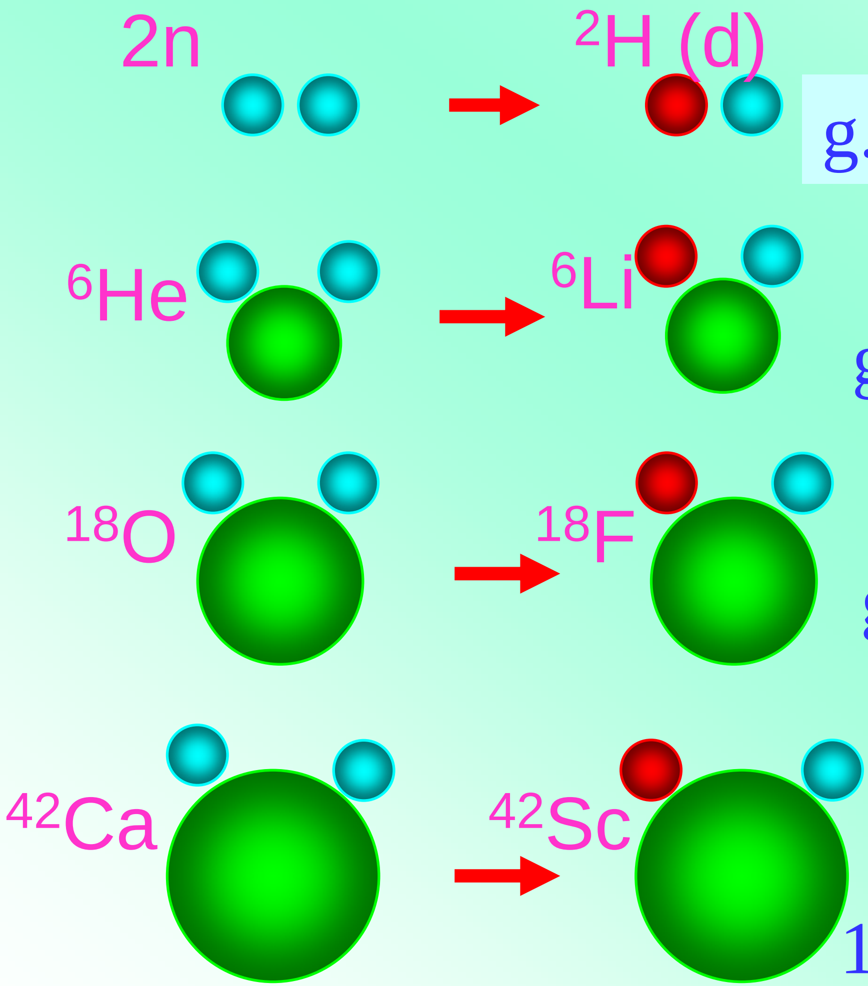


Low-energy collective GT excitation: B(GT)=3.1

Low Energy Super GT state

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

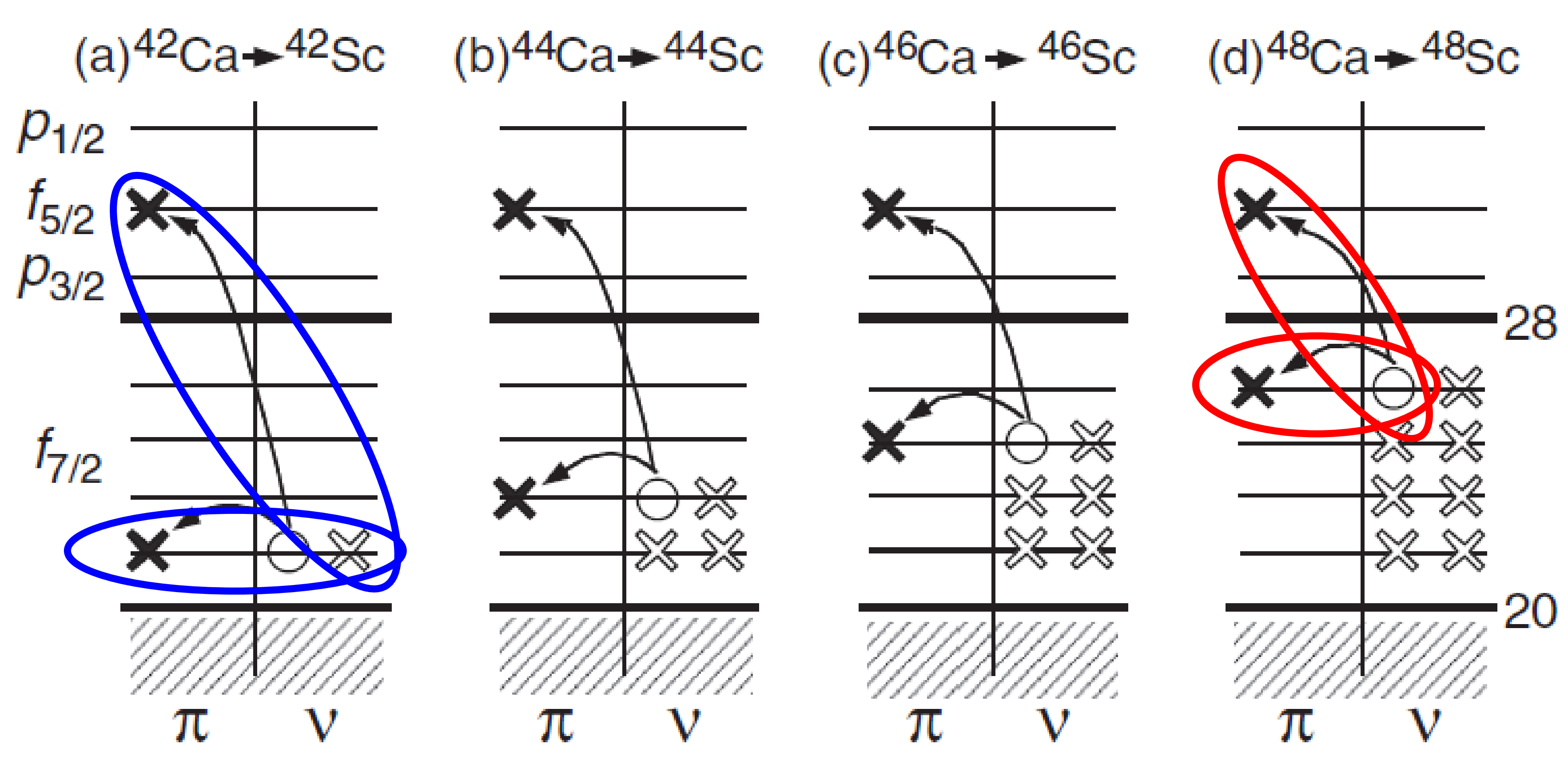
B(GT) = 2.17 Smaller !

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

***from *p-p* to *p-h* configuration

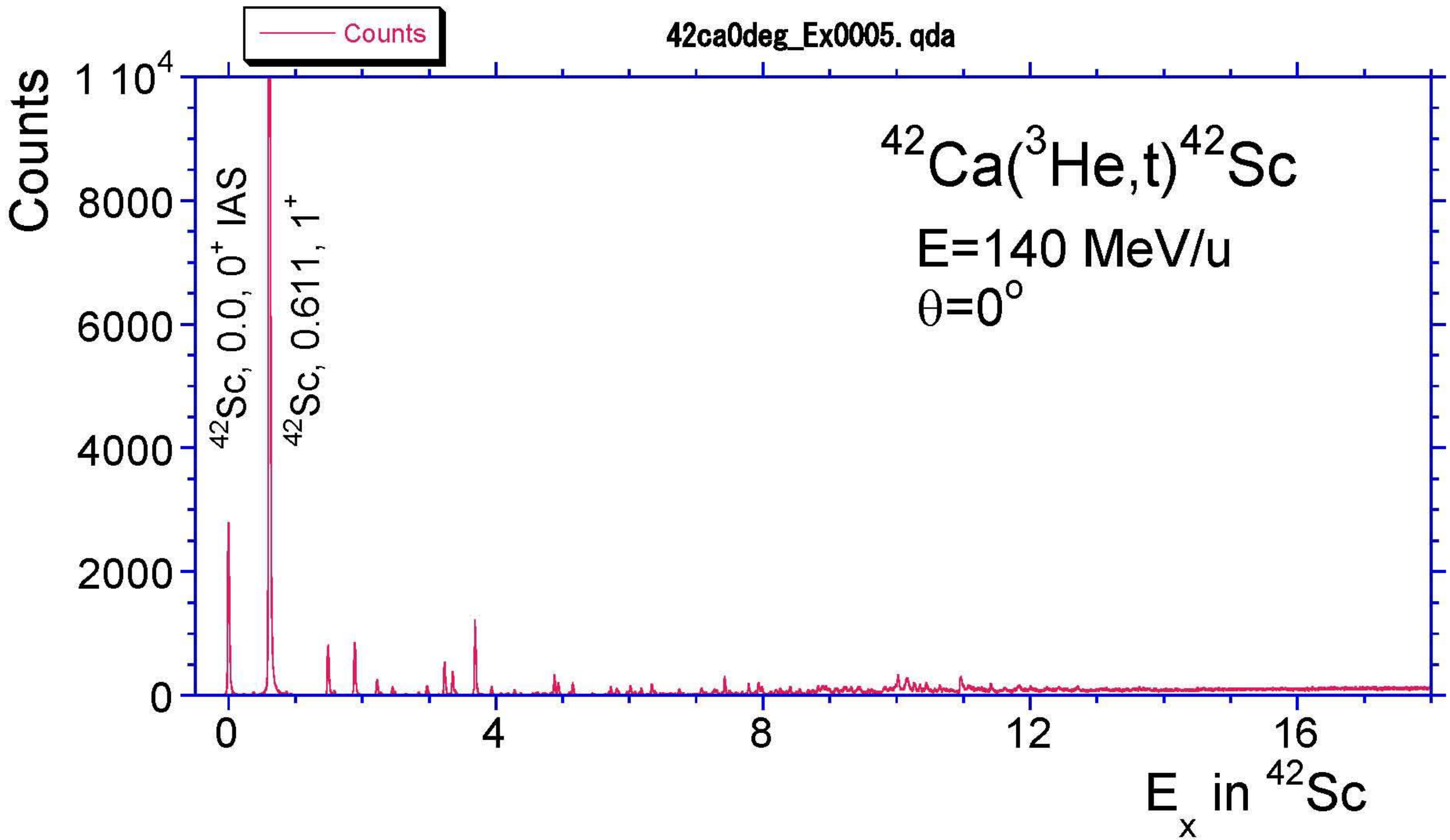
LESGT stae → GTR structure
in A= 42 to 48 Ca isotopes

GT Configurations in Sc isotopes

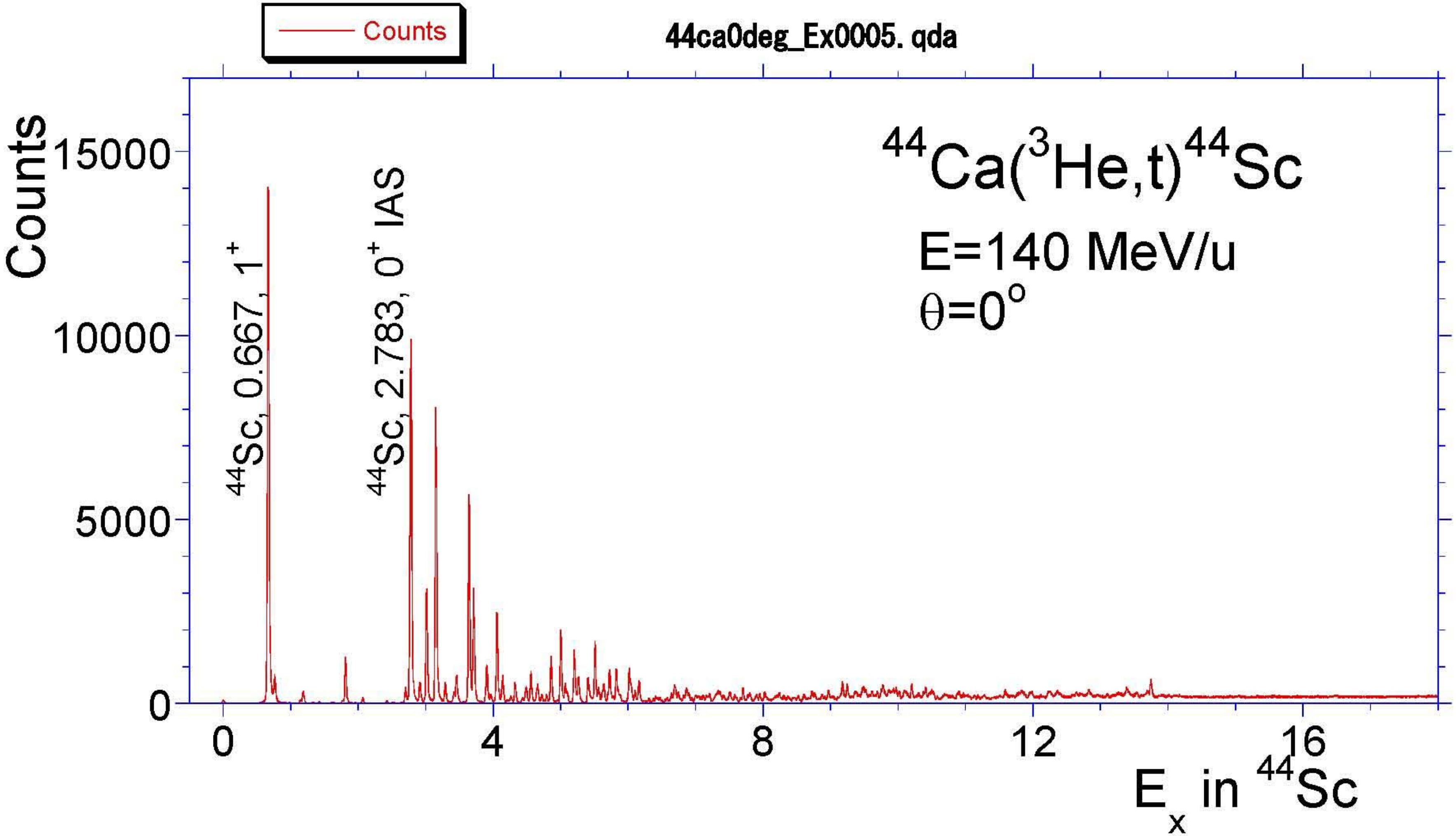


particle-particle int. (attractive) → particle-hole int. (repulsive)

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

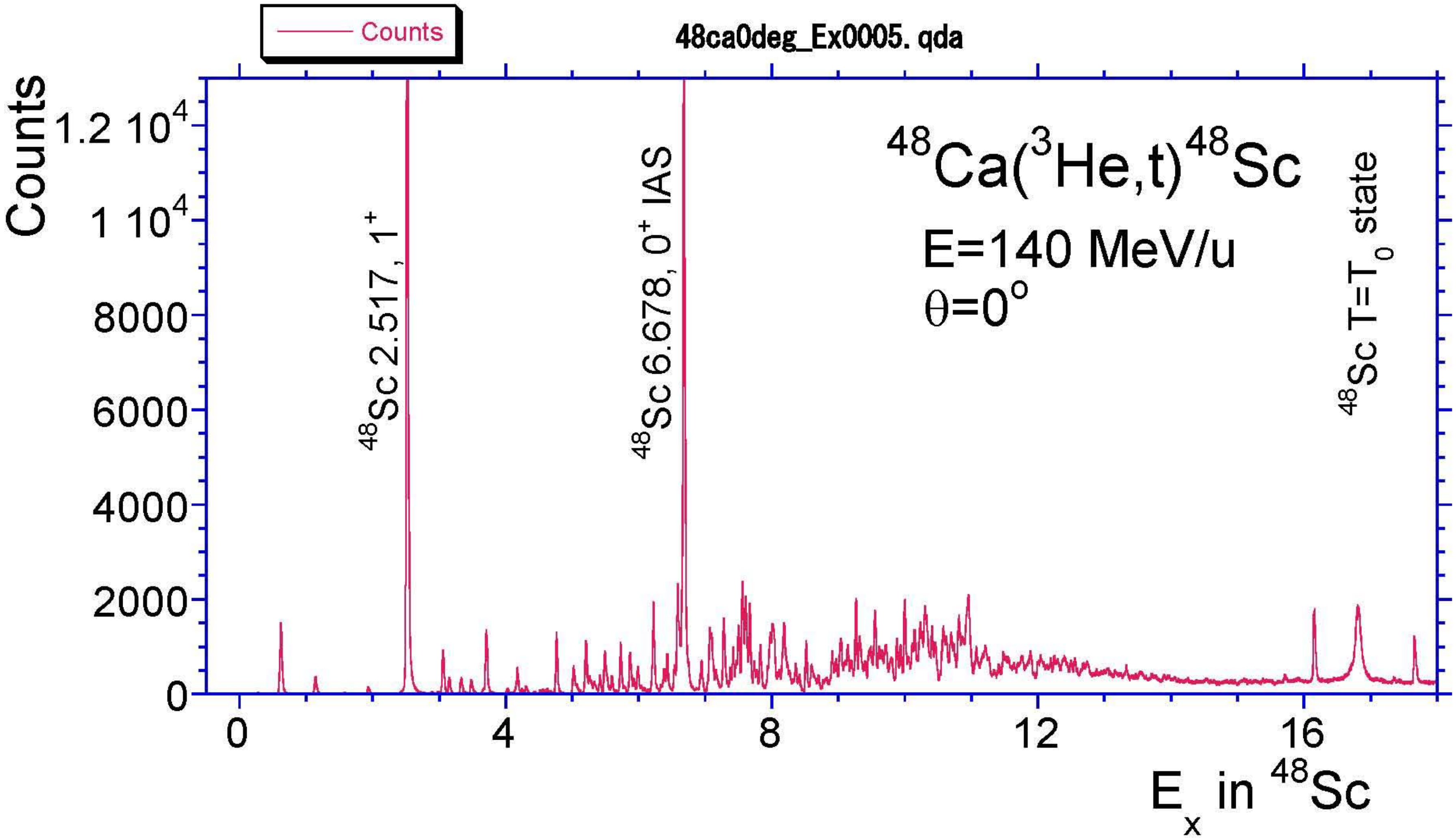


$^{44}Ca(^{3}He,t)^{44}Sc$



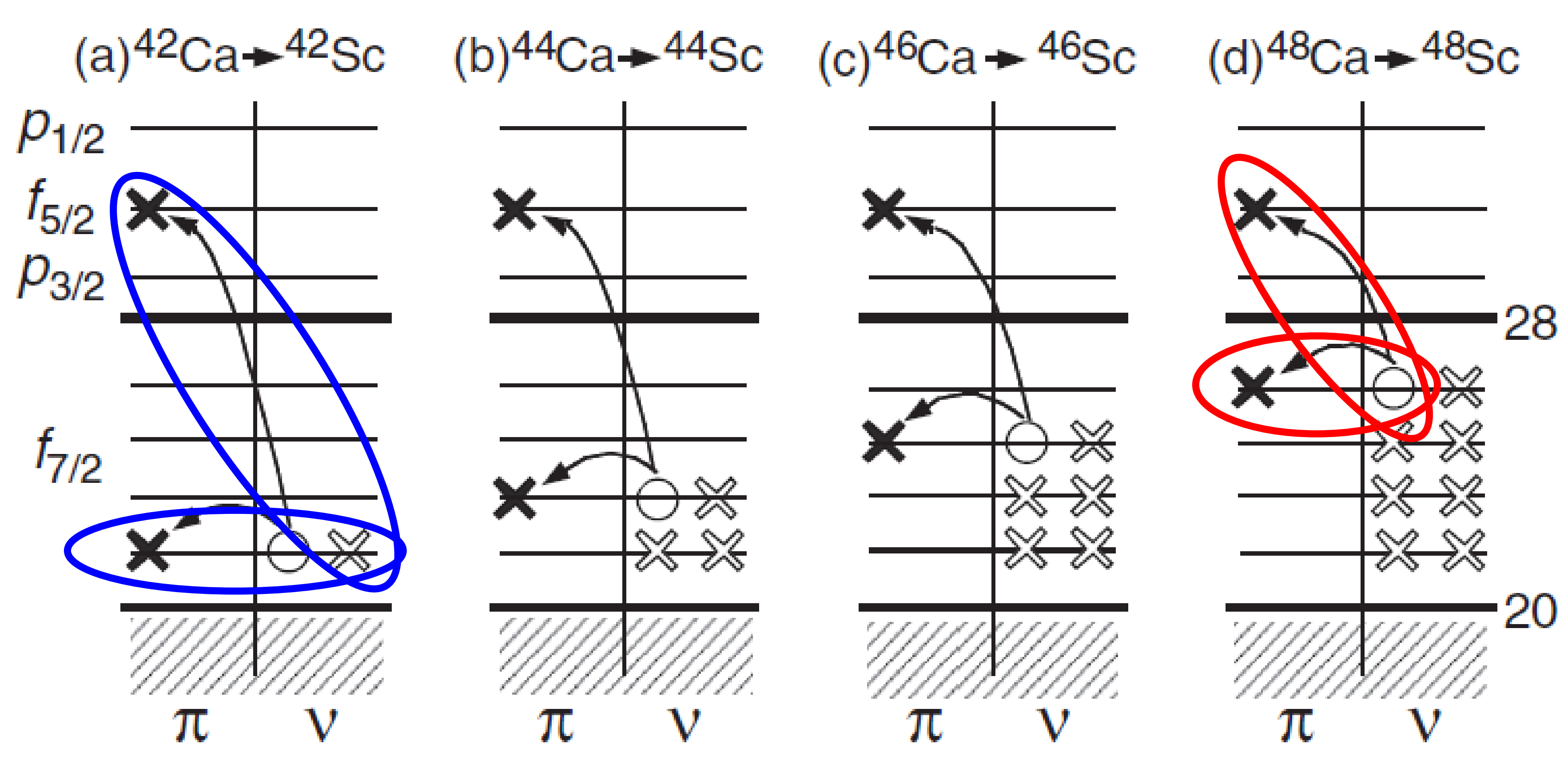
Y. Fujita et al., PRC 88, 014308 (2013)

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



H.F analysis

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 !

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

Mirror β decays and Isospin Symmetry

* Giving the Absolute GT strength

→ GT transitions in each nucleus are UNIQUE !
→ Low-energy Super GT state (LESGT state)
→ Assuming T-symmetry → GT in unstable nuclei !

We can learn a lot by the comparison of analogous GT transitions !

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
Milano : theory
Osaka University (Japan) : (p, p'), (^{3}He, t), theory
RIKEN : β decay, 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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Review

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

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