Gamow-Teller Transitions in *p*-, *sd*-, and *pf*-shell Nuclei

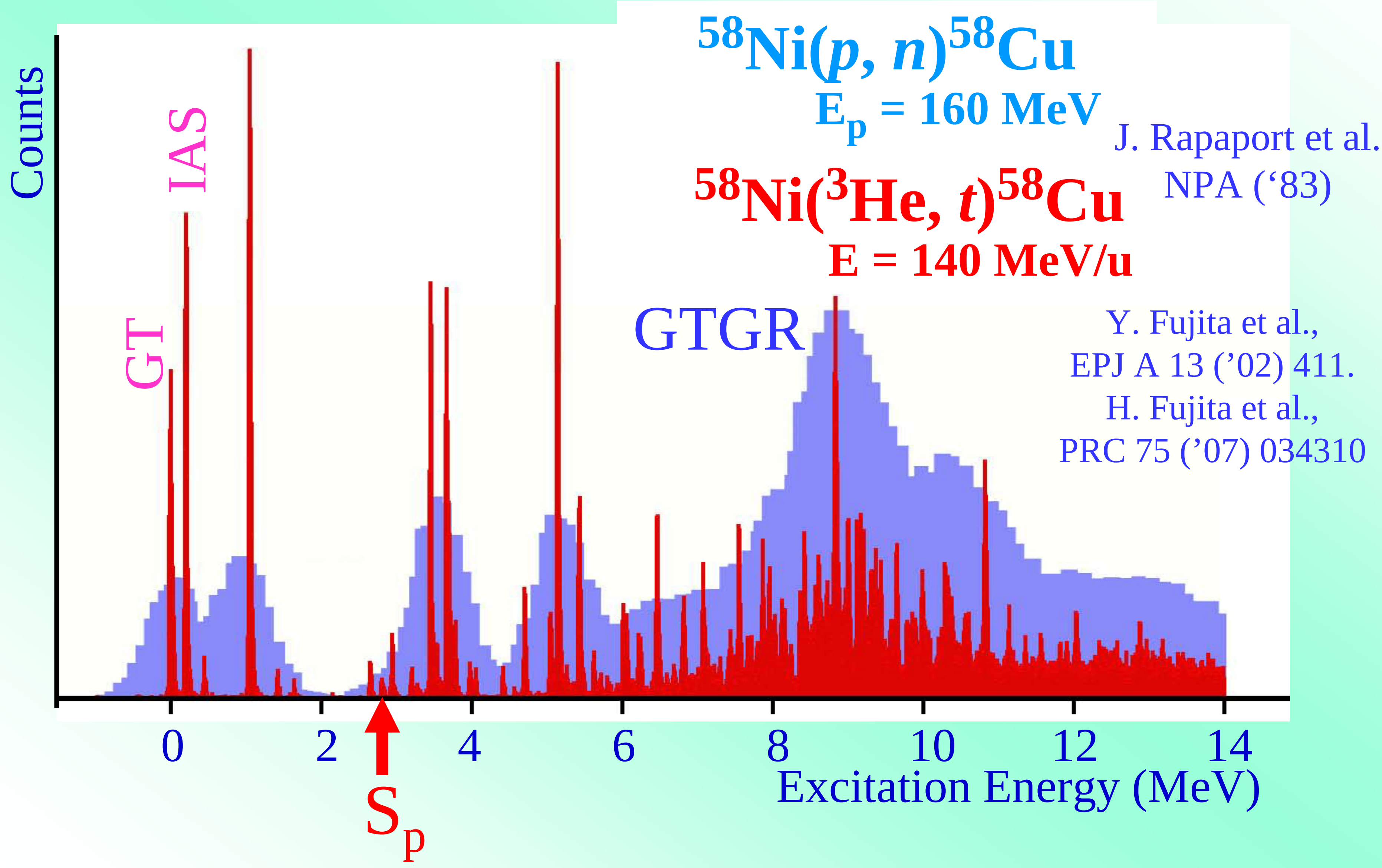
Yoshitaka FUJITA
RCNP & Dept. Phys., Osaka Univ.

Hirschegg 2013: Astrophysics & Nuclear Structure
Hirschegg, Kleinwalsertal, Jan. 26 – Feb. 1, 2013

GT : Important weak response, simple $\sigma\tau$ operator

- ✧Representing "Spin Isospin" response of nuclei.
  They are unique quantum numbers in Atomic Nuclei.
- ✧Good Probe to study the Key Part of the Nuclear Structure.
- ✧Astrophysical Interest.
- ✧Studied by β decay and Charge-Exchange reactions

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



Properties of GT transitions

Caused by the **στ** operator : a simple operator !

1) |i> and |f> states should have similar spatial shapes.
   - there is no space-type operator -

2) **σ** operator: states with $j_>$ and $j_<$ configurations are connected.

3) **τ** operatpr: isospin quantum number T plays an important role (isospin selection rule)

Selection Rules

$|\Delta J|=0, 1$

$|\Delta T|=0, 1$

➔ 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 state

(^{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 = $\frac{1}{t_{1/2}} = f\,\frac{\lambda^2}{K}\,B(\mathrm{GT})$

B(GT) : reduced GT transition strength

∝ (matrix element)^2 = |<f|στ|i>|^2

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

= reaction mechanism

⊗ operator

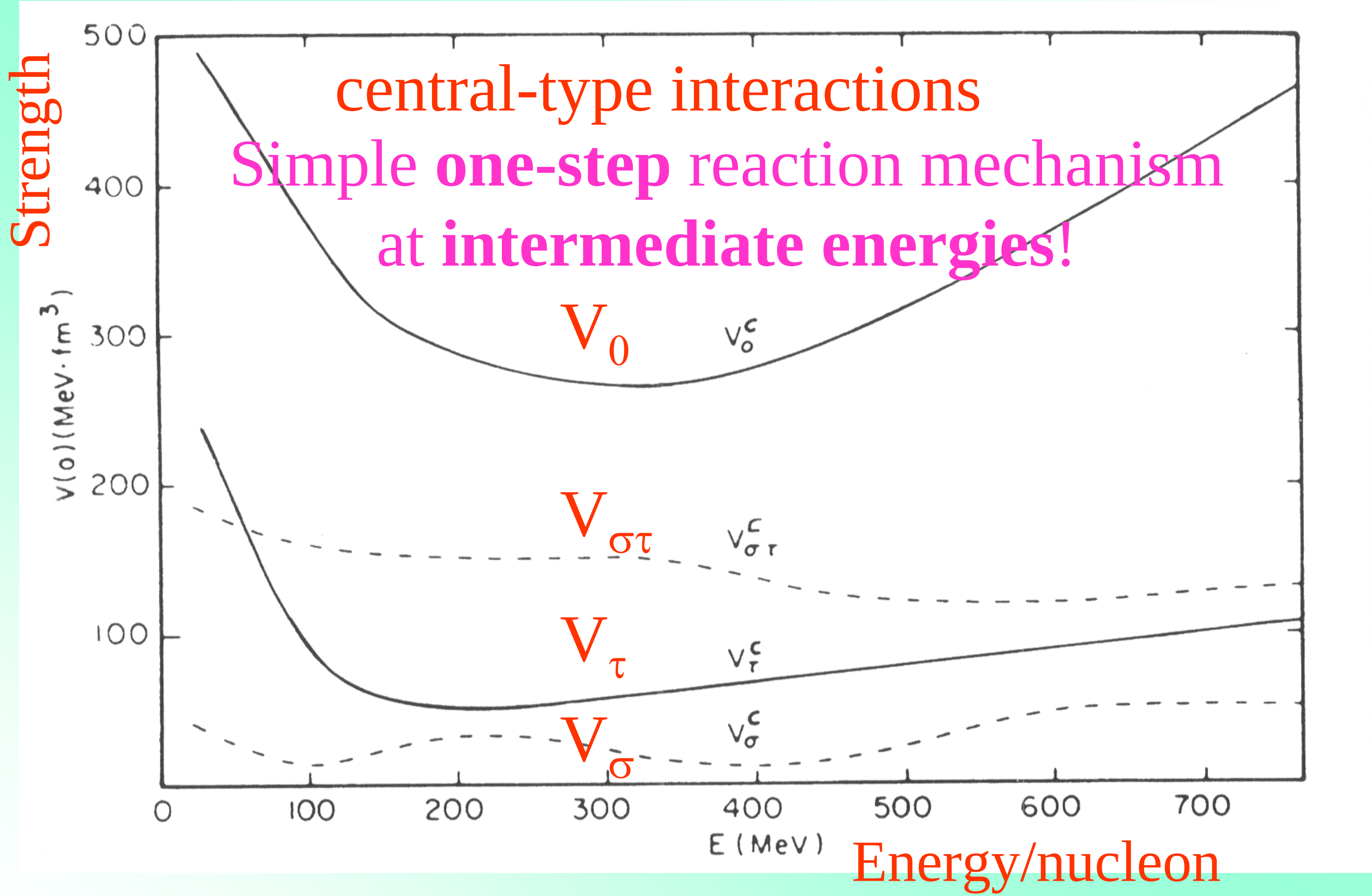
⊗ structure

=(matrix element)^2

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

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

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

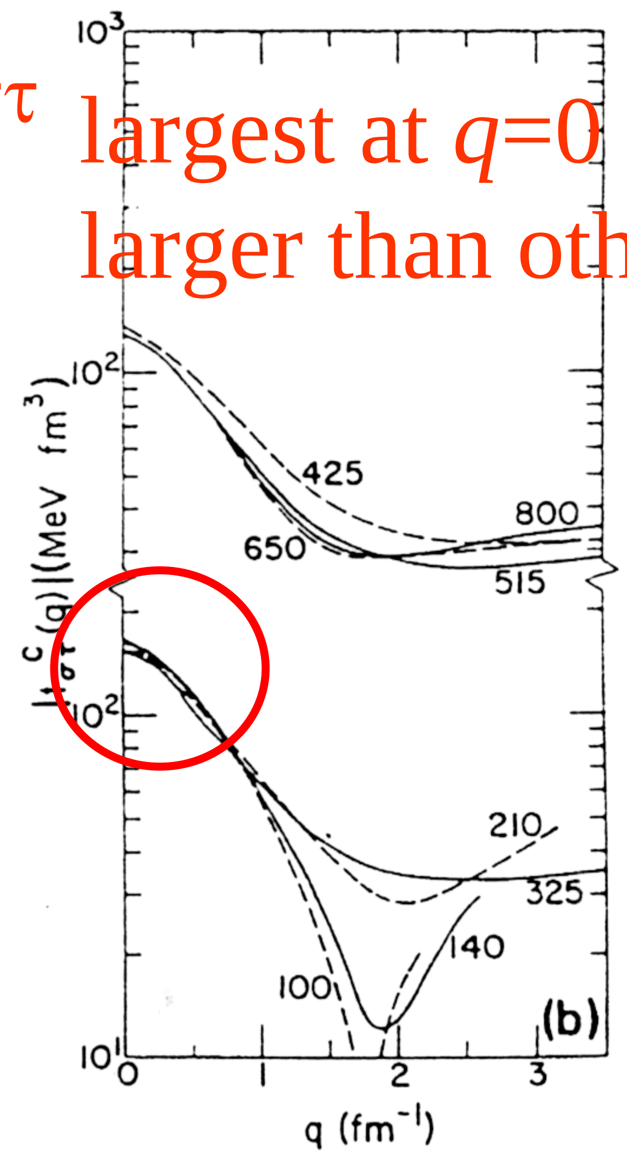


Love & Franey PRC 24 ('81) 1073

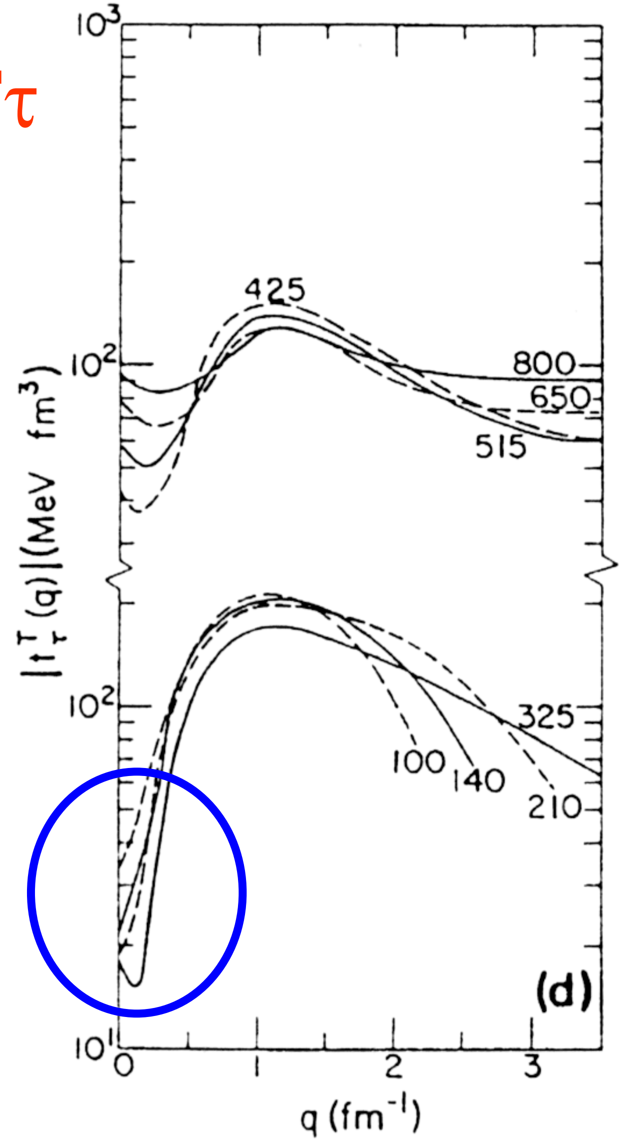
N.-N. Int. : στ & Tensor-τ *q*-dependence

στ largest at *q*=0 !

larger than others !



Tτ



Love & Franey PRC 24 ('81) 1073

β-decay & Nuclear Reaction

*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 = |<f|στ|i>|^2

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

= reaction mechanism

⊗ operator

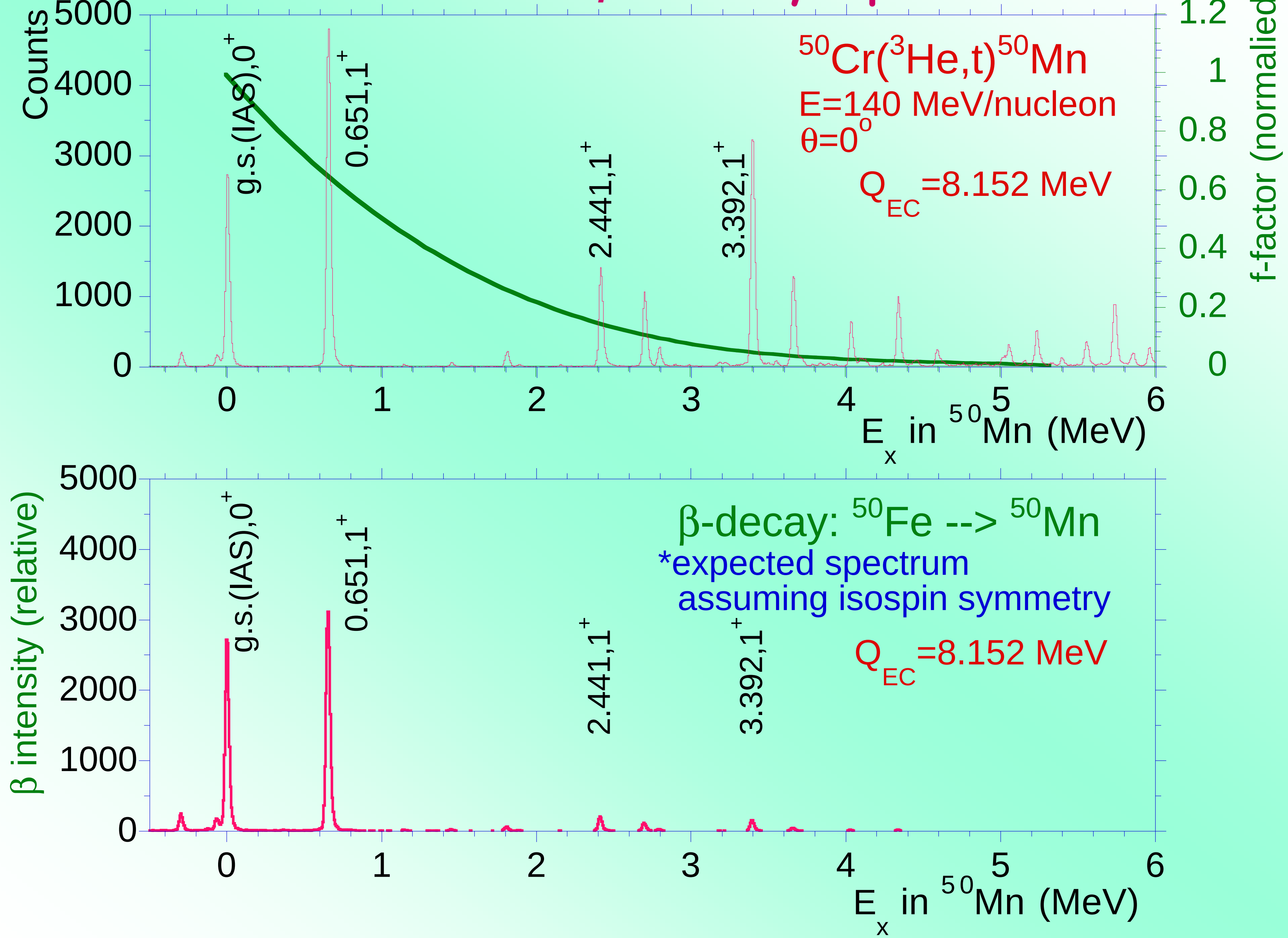
⊗ structure

=(matrix element)^2

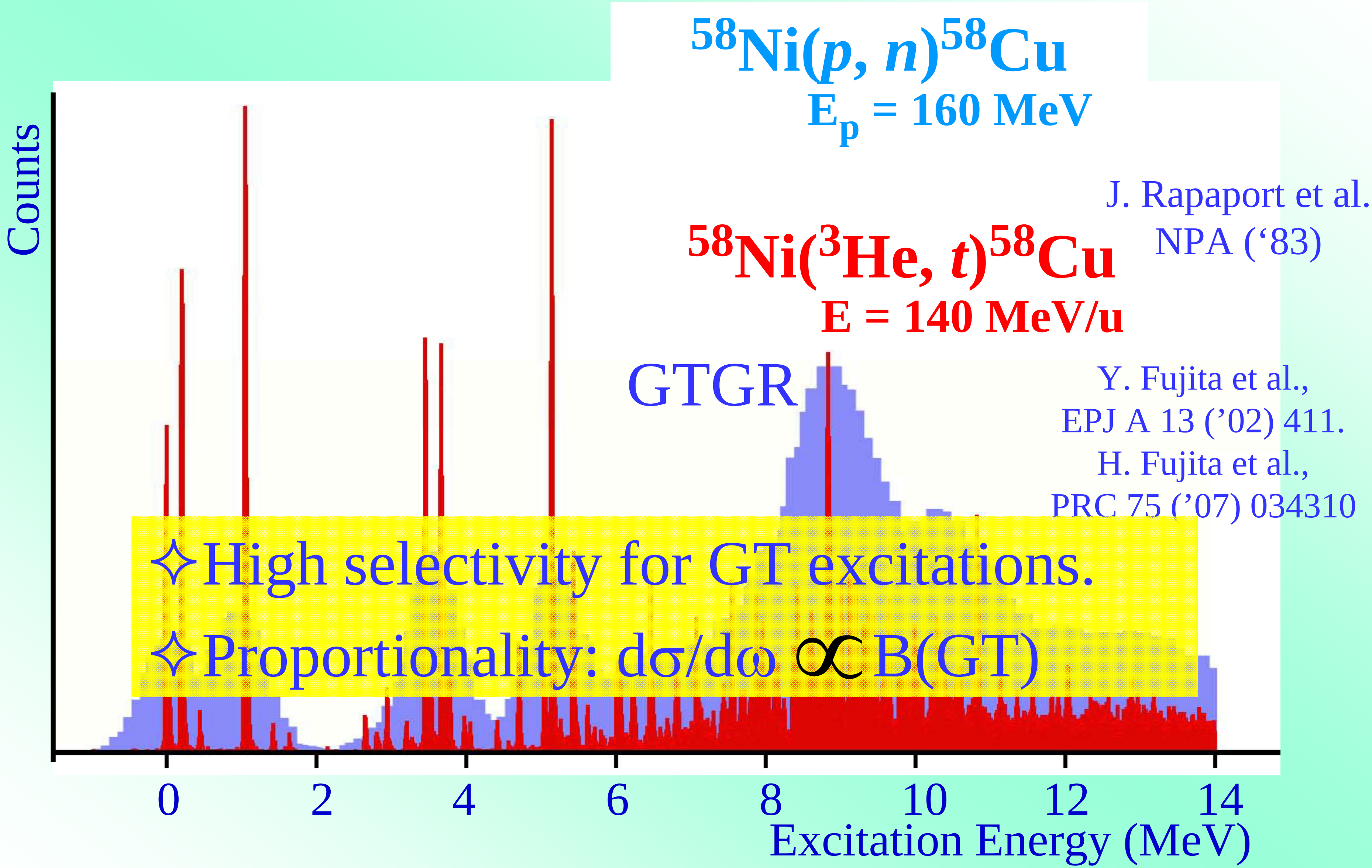
*At intermediate energies (100 < E_{in} < 500 MeV)

→ dσ/dω(q=0) : proportional to B(GT)

Simulation of β-decay spectrum



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



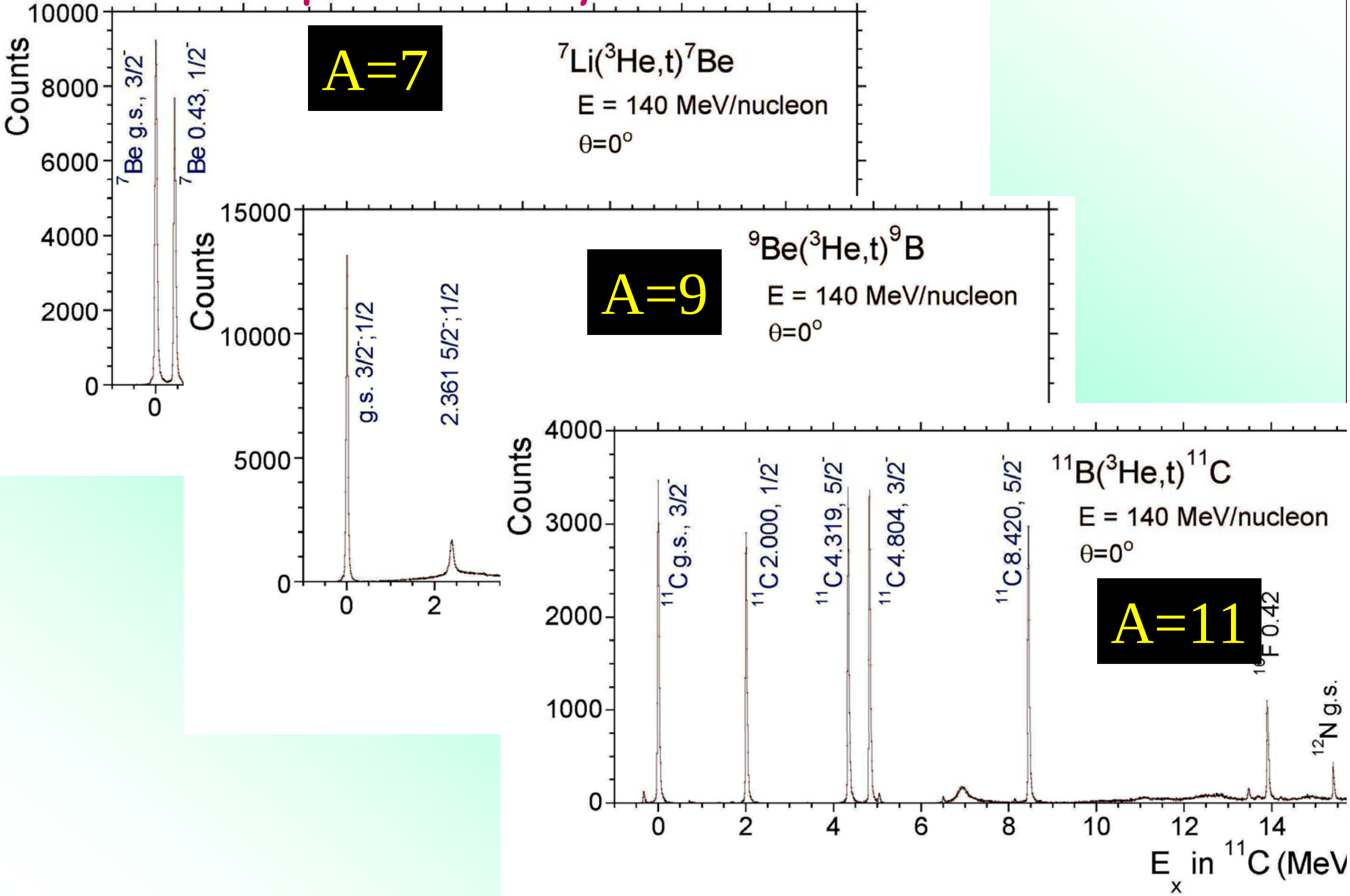
✧High selectivity for GT excitations.

✧Proportionality: $d\sigma/d\omega \propto B(GT)$

**GT transitions in each nucleus are UNIQUE !

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

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



Relationship: Decay and Width

Heisenberg's Uncertainty Priciple

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

$$\Delta t \cdot \Delta E \approx \hbar$$

Width $\Gamma = \Delta E$

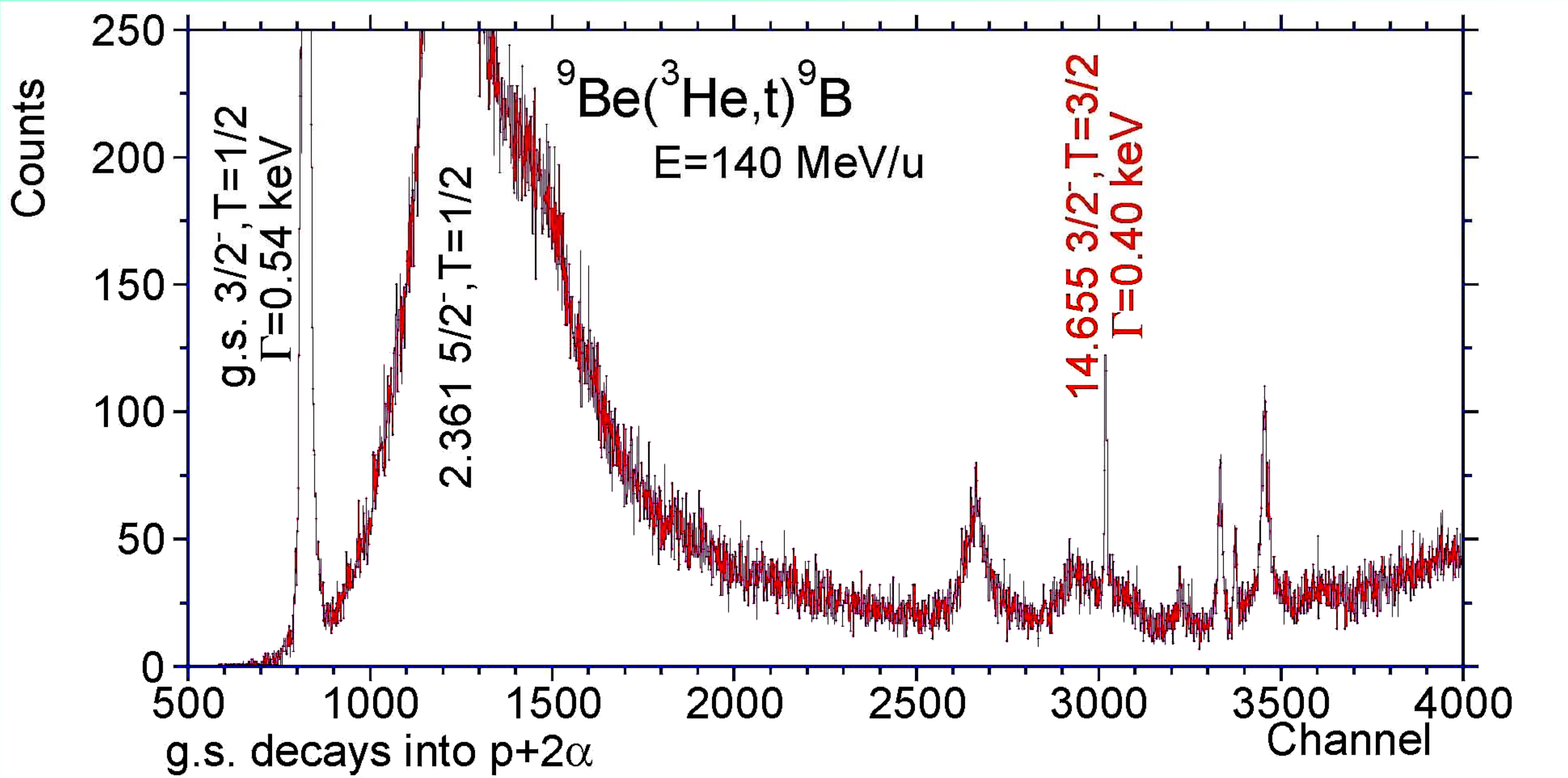
*if: Decay is Fast,

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)

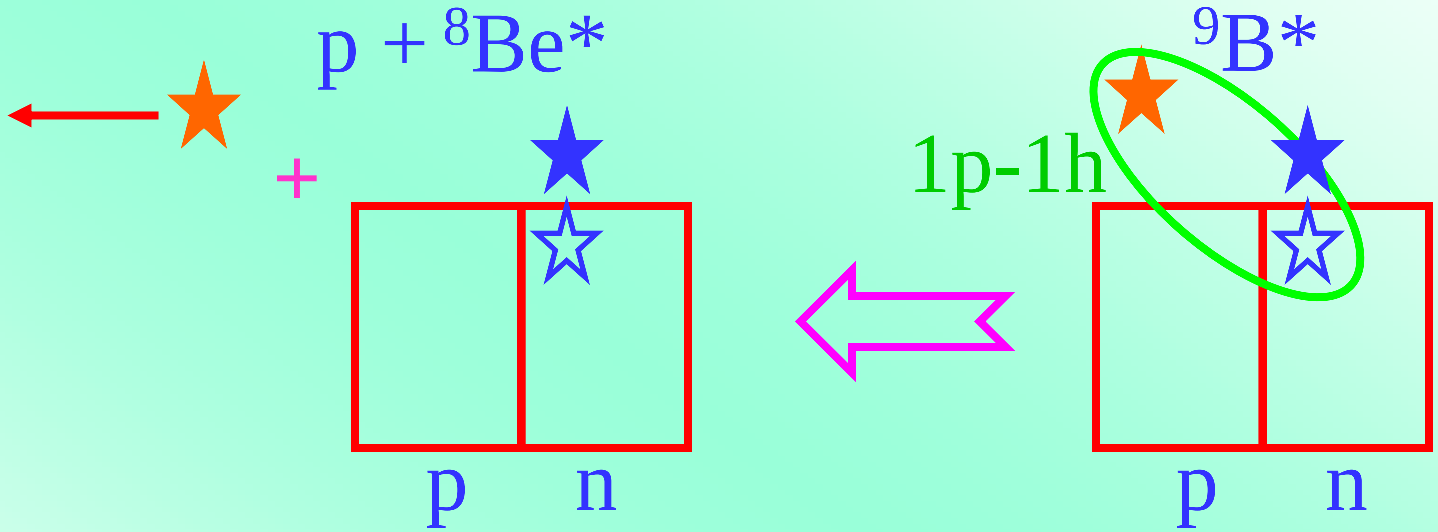
$^{9}Be(^{3}He,t)^{9}B$ spectrum (II)



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

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

Isospin Selection Rule : in *p*-decay of ^{9}B



T_z : -1/2 + 0 = -1/2

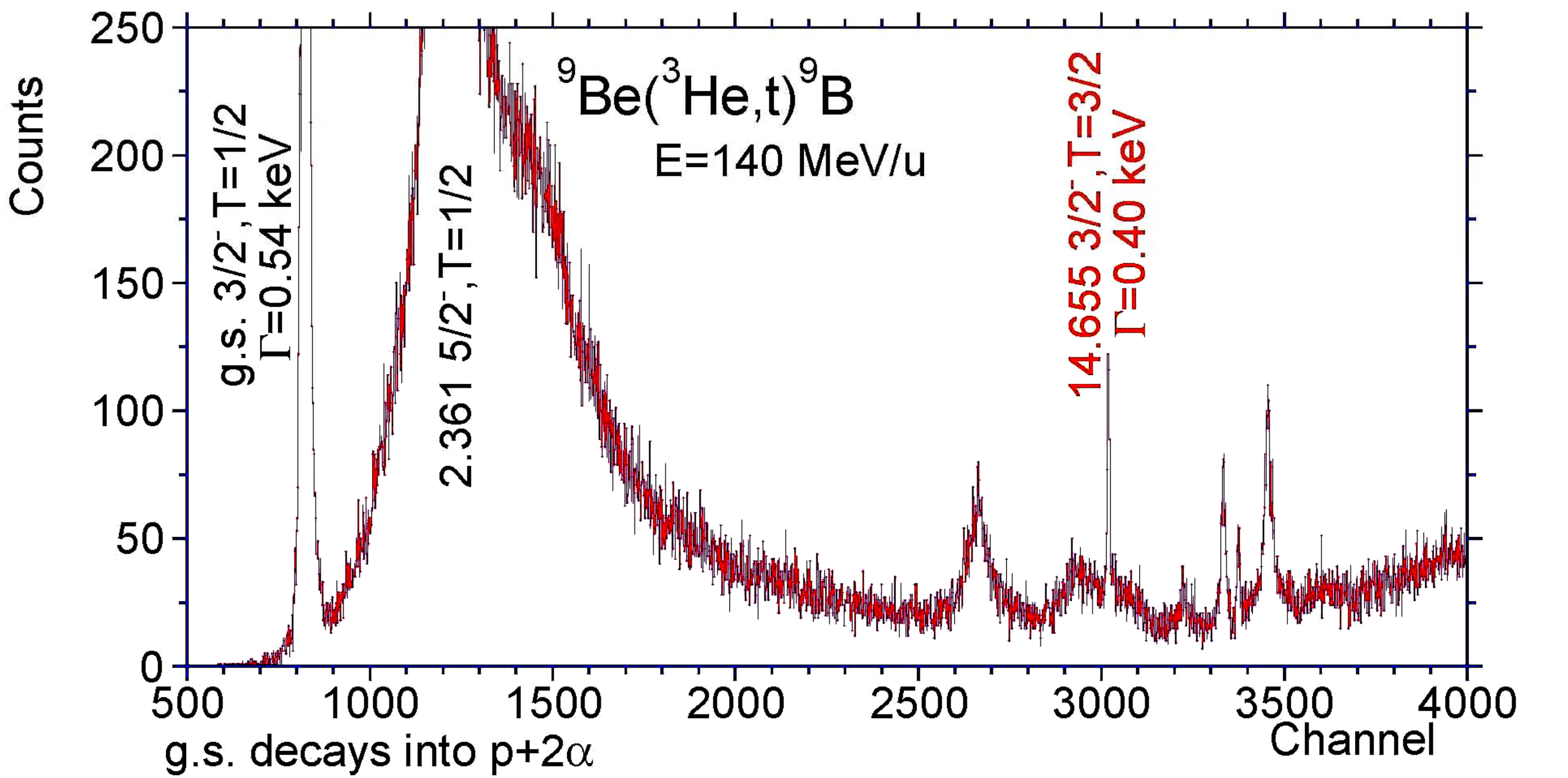
T : 1/2 + 0 (low lying) **= 1/2**

T : 1/2 + 1 (higher Ex) **= 1/2 & 3/2**

*T=1 state in ^{8}Be is only above E_x=16.6 MeV

Therefore, ***p***-decay of T=3/2 states is forbidden!

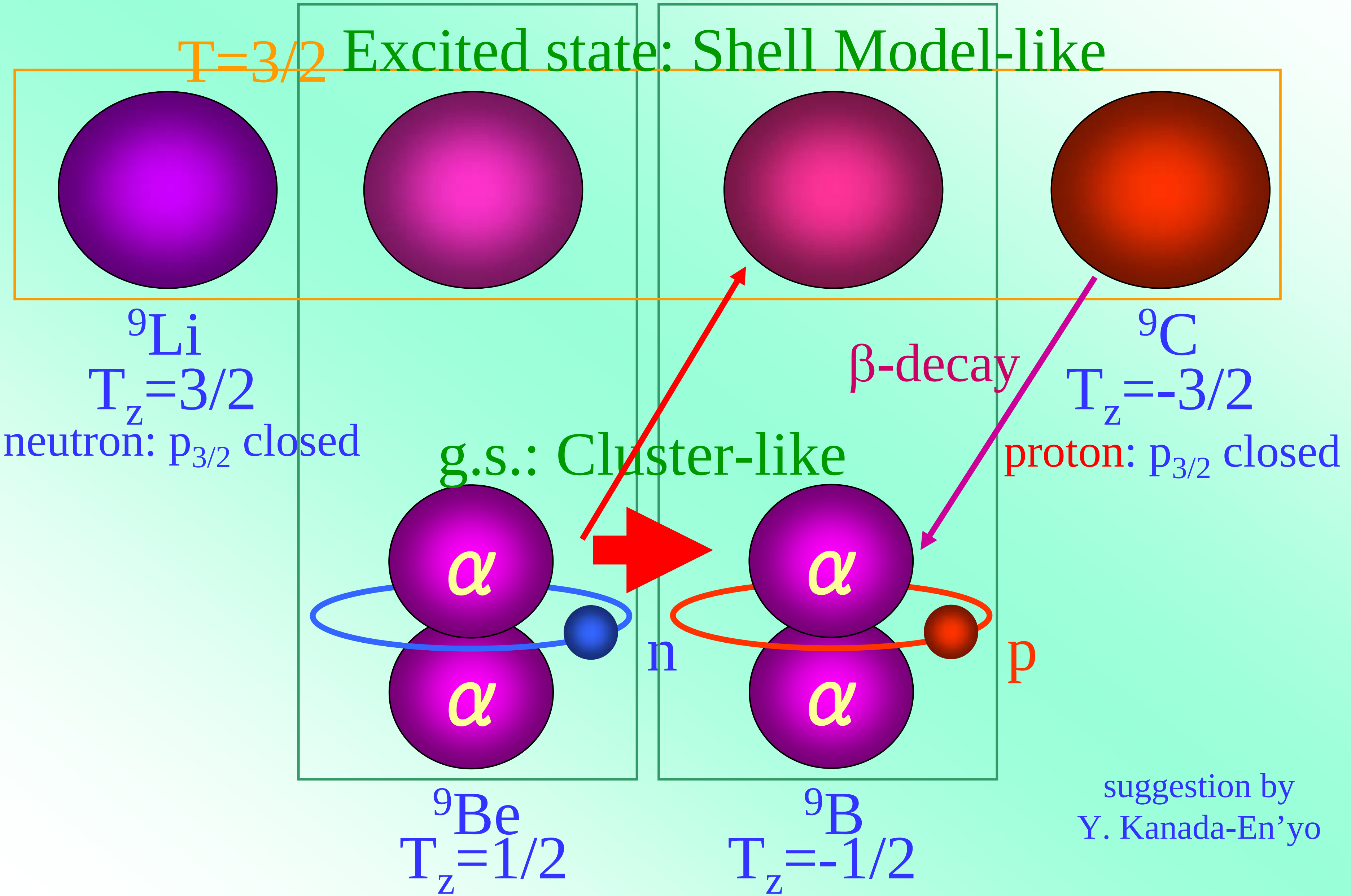
$^9Be(^3He,t)^9B$ spectrum (III)



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

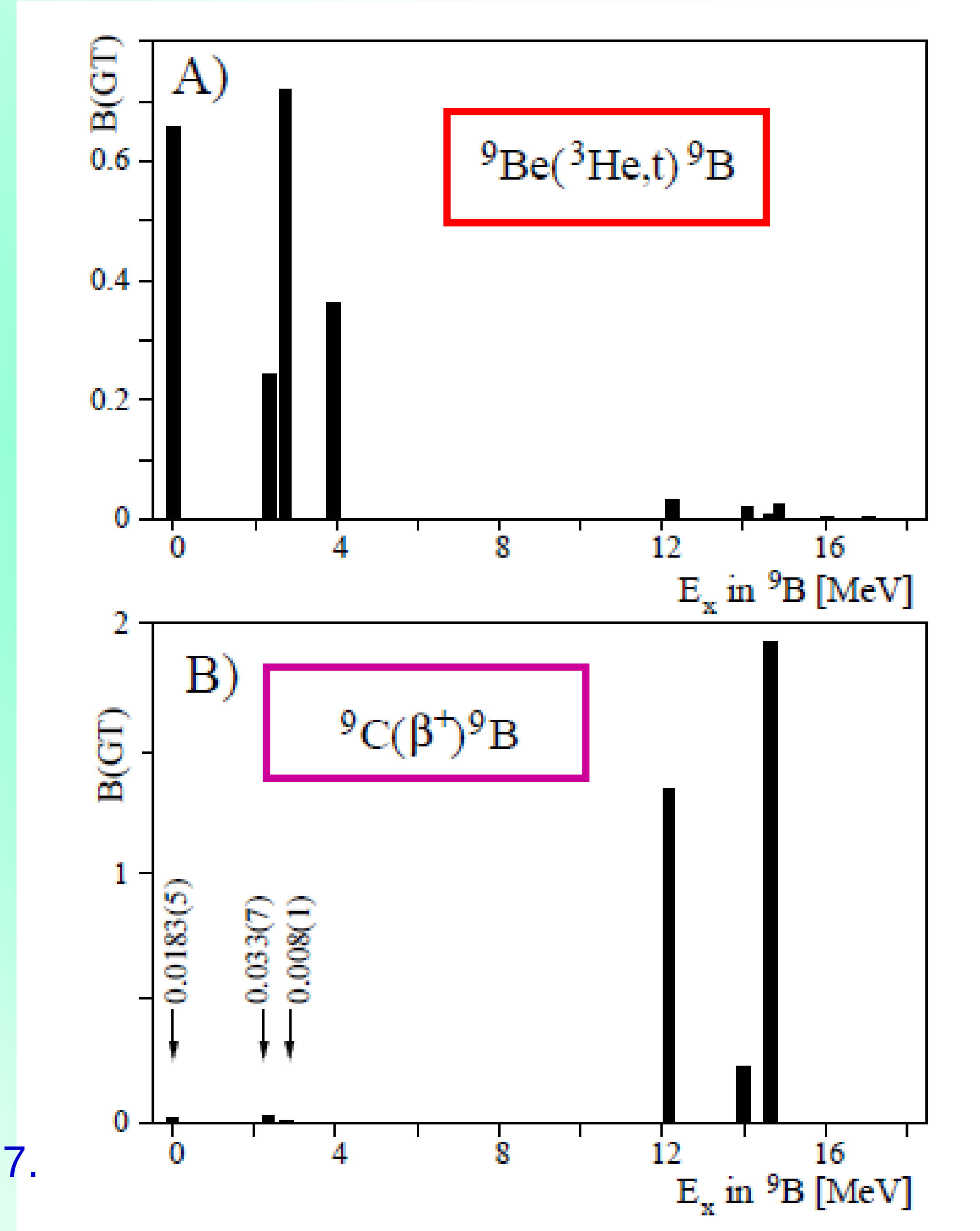


suggestion by
Y. Kanada-En'yo

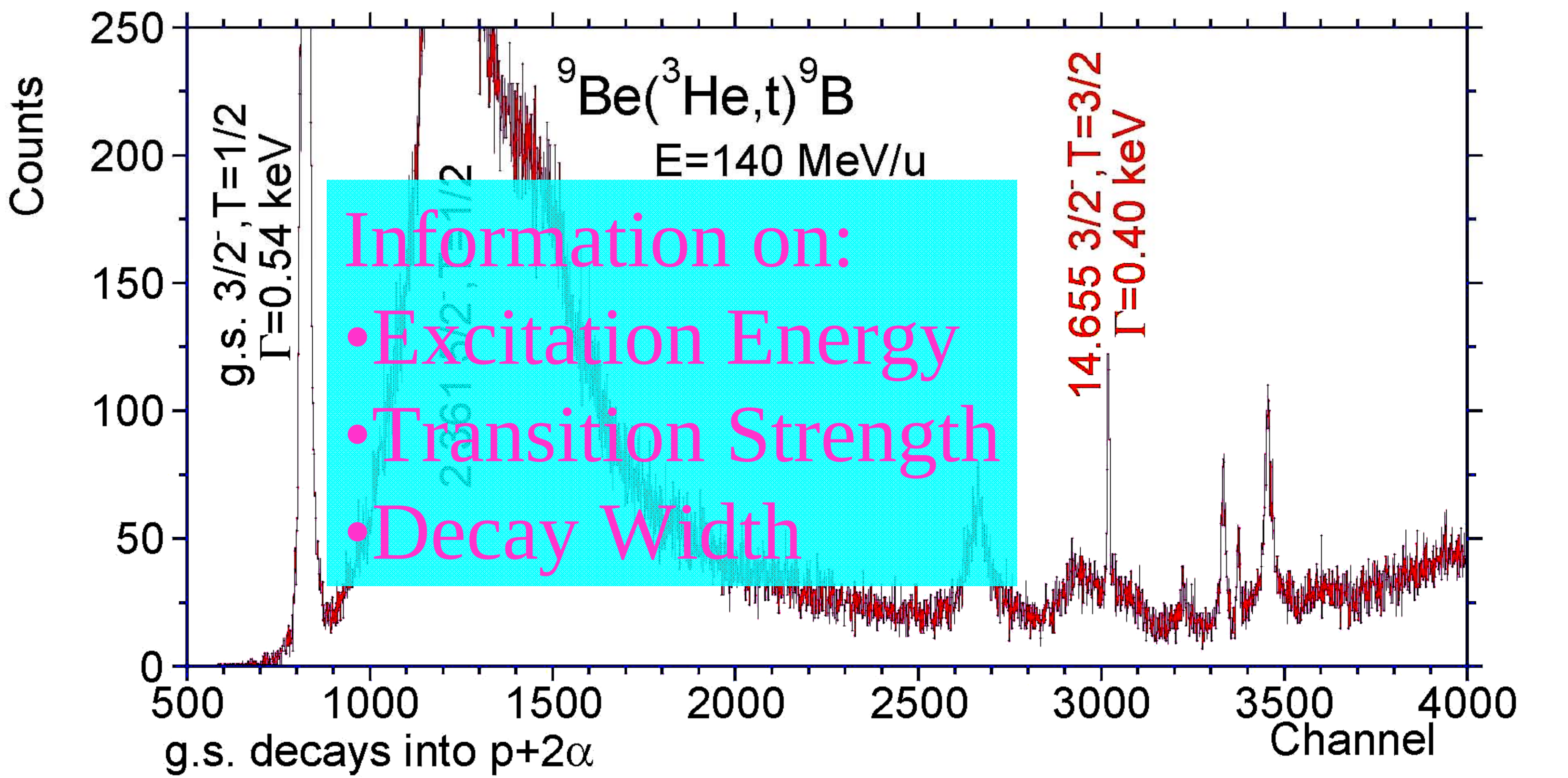
β-decay and (^{3}He,t) results

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.



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

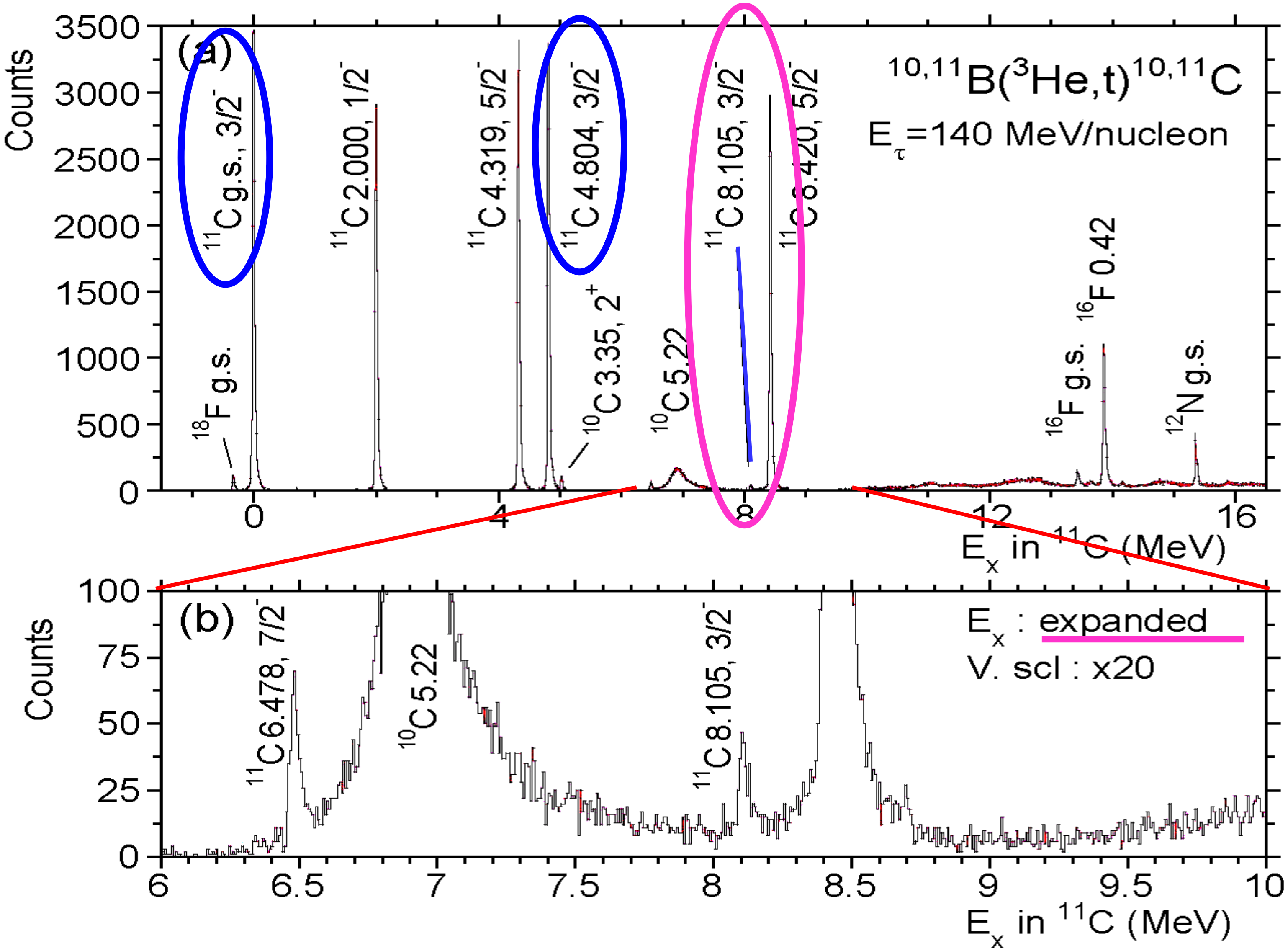


14.7 MeV T=3/2 state is very weak!

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

GT transitions to $J^\pi = 3/2^-$ states: J^π allowed

Why $3/2^-_3$ so weak!



Y. Fujita et al., PRC 70 (2004) 011206(R)

1. Introduction

11B→11C: **GT** transition strengths

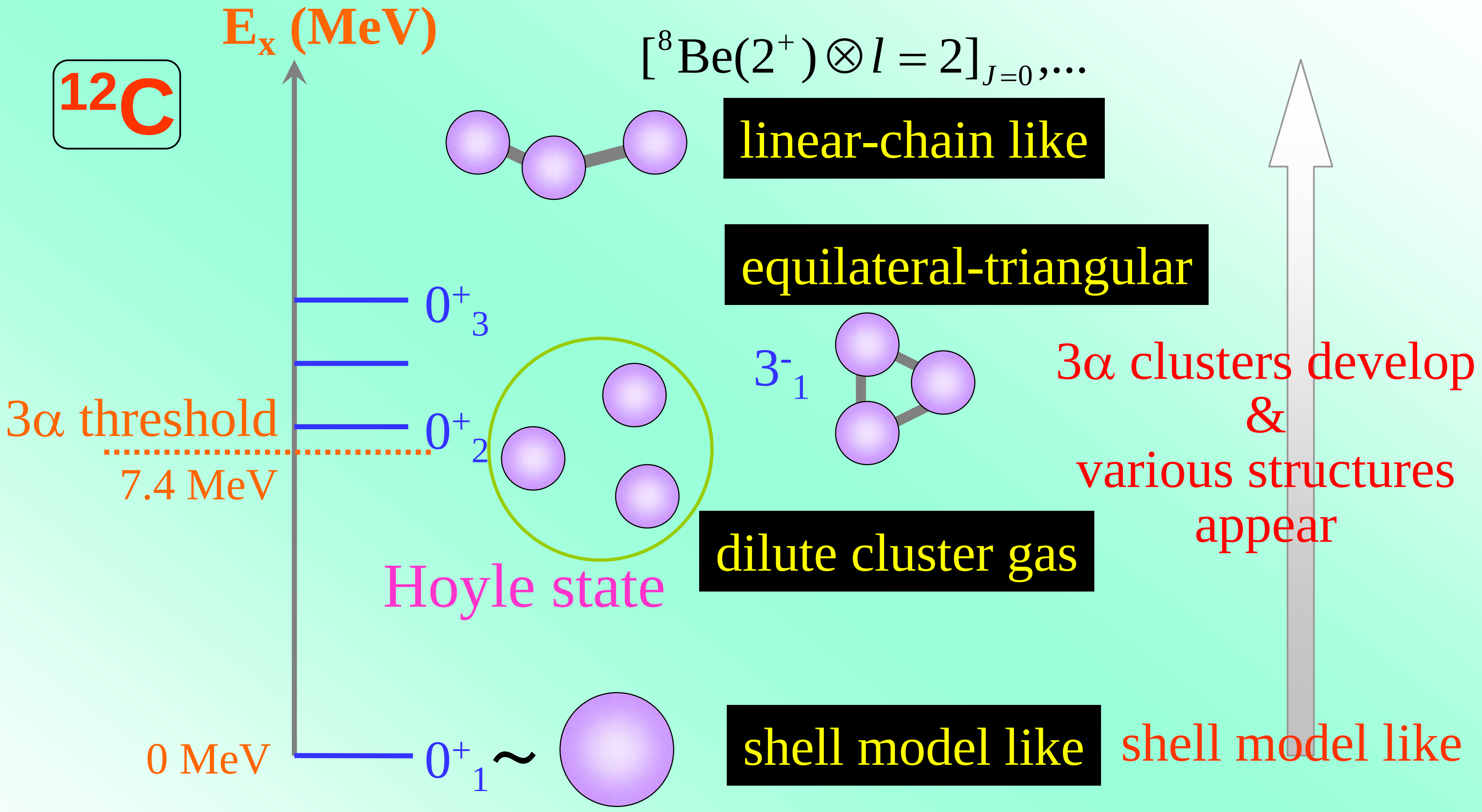
by Y. Kanada-En'yo

Y. Fujita, et al. PRC 70, 011306(R)(2004).
charge exchange reaction: $^{11}B(3He,t)^{11}C$

Experiment				no-core shell-model With TNI	
			B(GT)		
E_x (MeV)	$2J^{\pi}$	(p,n)[a]	$(^3He,t)$	E_x (MeV)	B(GT)
0.0	3^-	0.345(8)[b]	0.345(8)[b]	0.0	0.315
2.000	1^-	0.399(32)	0.440(22)	0.525	0.591
4.319	5^-	0.961(60)[c]	0.526(27)	3.584	0.517
4.804	3^-		0.525(27)	3.852	0.741
8.105	3^-	0.444(10)[d]	0.005(2)[e]		
8.420	5^-		0.461(23)	8.943	0.625

small B(GT).
missing of $3/2^-_3$ in theoretical calculations.

Shell-model-like and Cluster structures in ^{12}C

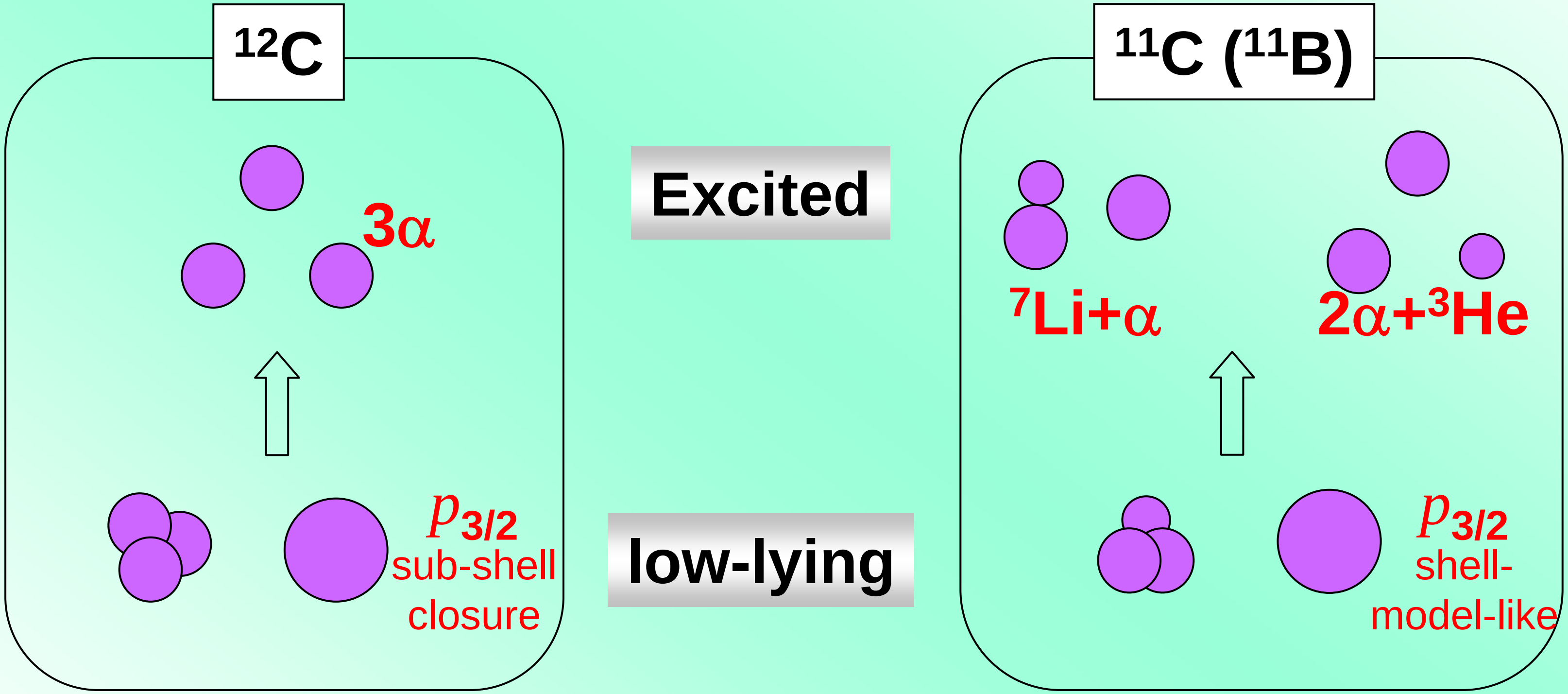


E. Uegaki, et al. Prog. Theor. Phys. **57**, 1262 (1977)
M. Kamimura, et al. J. Phys. Soc. Jpn. **44** (1978), 225.
A. Tohsaki, et al. Phys. Rev. Lett. **87**, 192501 (2001)
Y. Kanada-En'yo, Prog. Theor. Phys. **117**, 655 (2007) etc

by Suhara & En'yo '08

Coexistence of shell-model and cluster states

by Y. Kanada-En'yo
PRC ('07)



β-decay & Nuclear Reaction

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

$B(\mathrm{GT})$: reduced GT transition strength

$\propto$ (matrix element)^2

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

= reaction mechanism

⊗ operator

⊗ structure

=(matrix element)^2

A simple reaction mechanism should be achieved !

➡ we have to go to high incoming energy

Study of Weak Response of Nuclei

by means of

Strong Interaction !

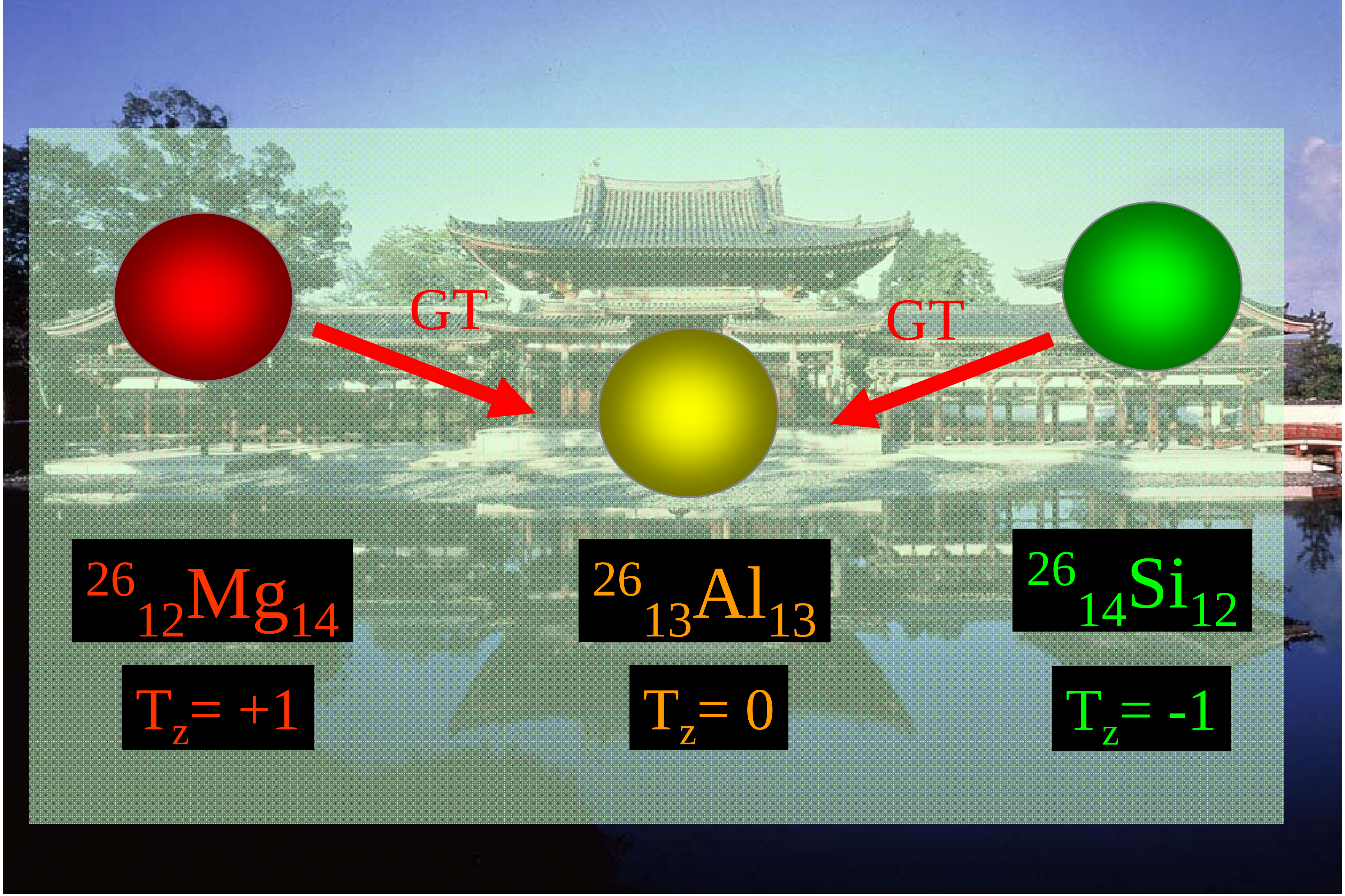
using β-decay as a reference

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

by means of
Isospin Symmetry


T=1 Isospin Symmetry
Byodoin-temple,
Uji, Kyoto

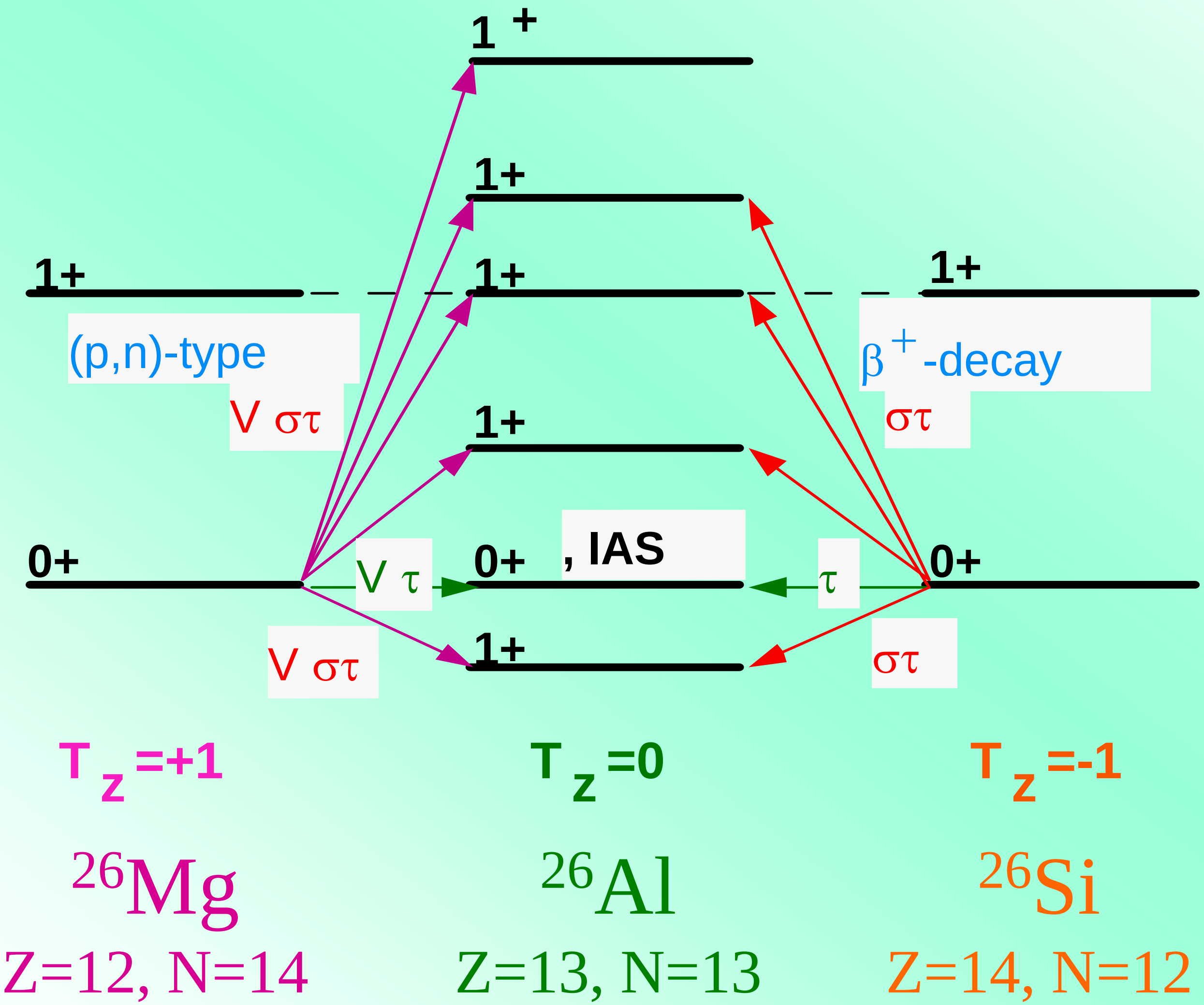
T=1 Isospin Symmetry



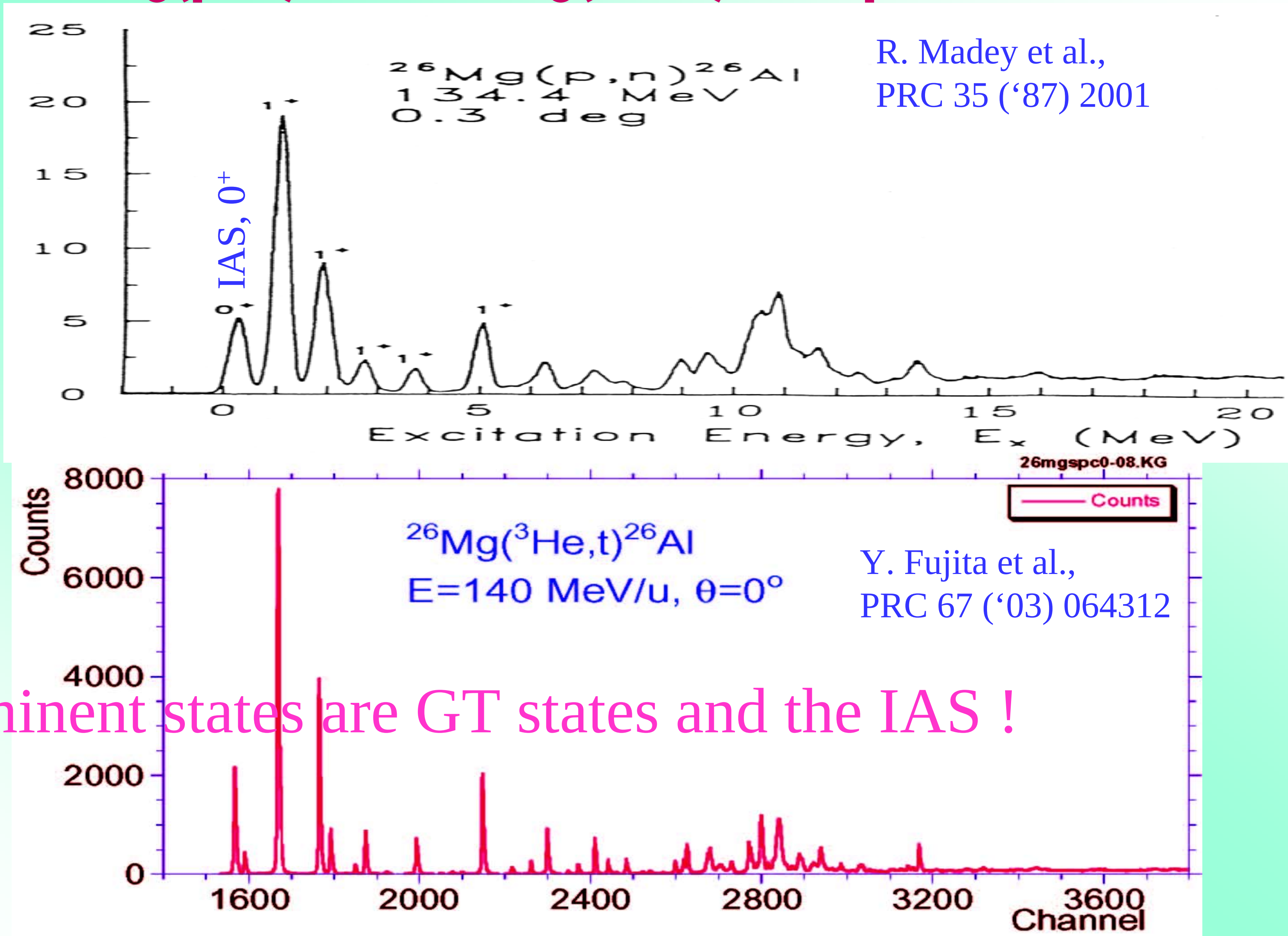
T=1 symmetry : Structures & Transitions

$T_z=+1$ → $T_z=0$ ← $T_z=-1$

(in isospin symmetry space*)

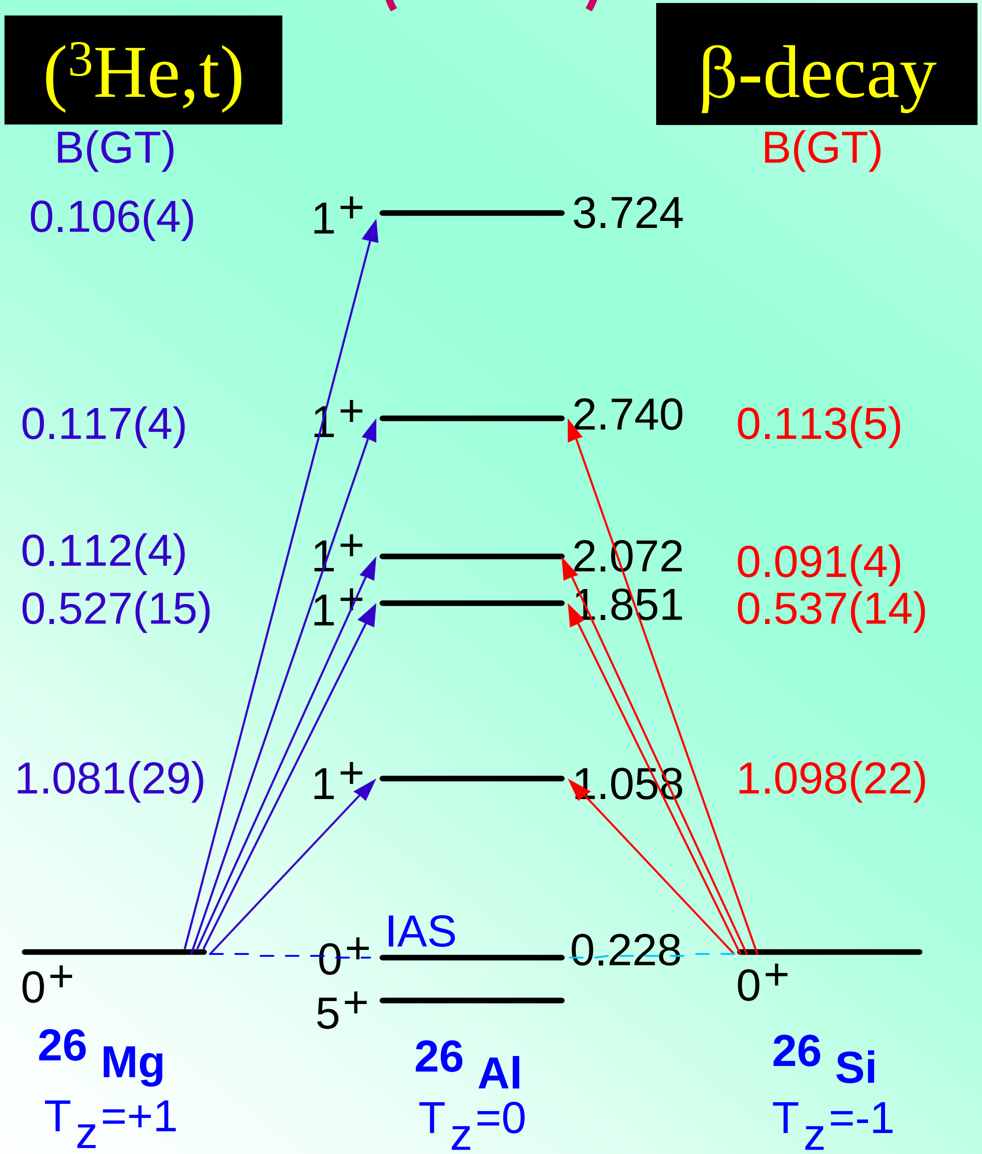


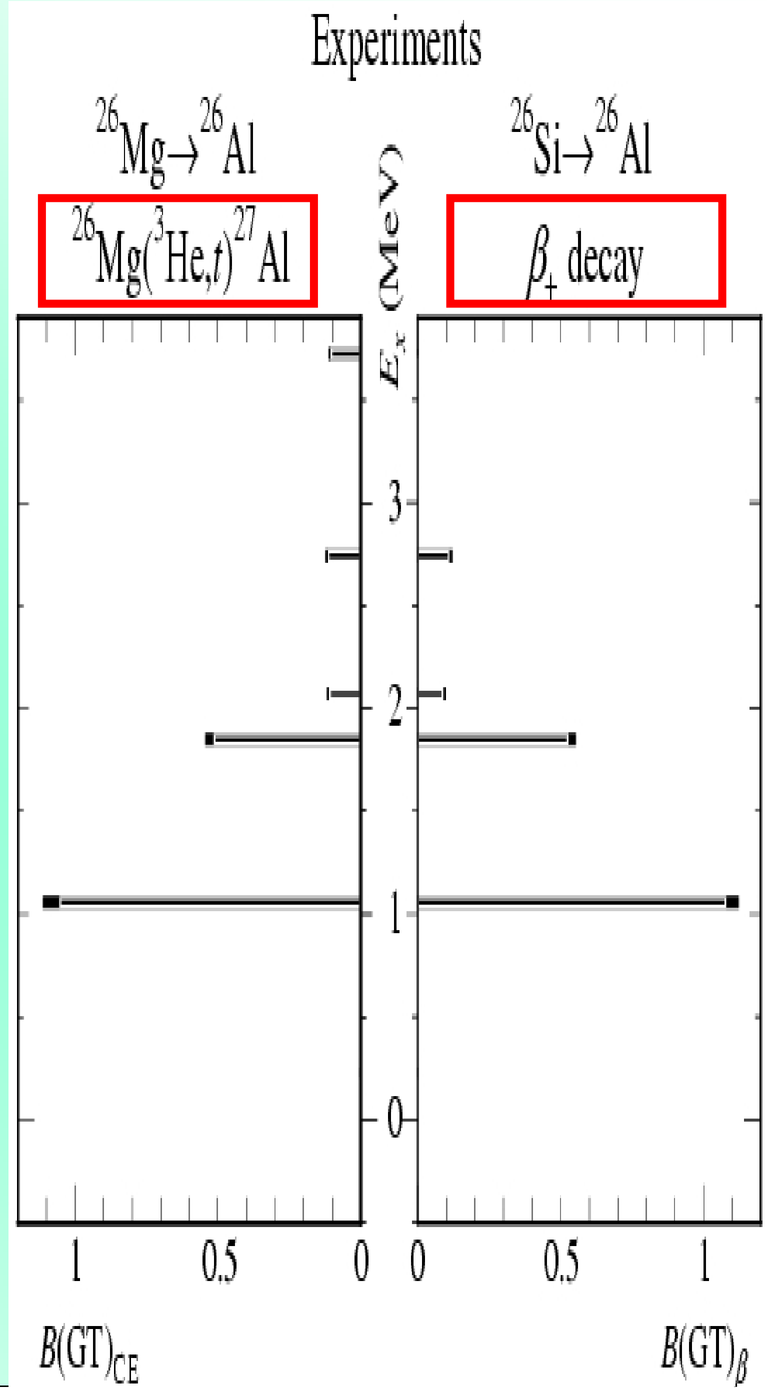
$^{26}Mg(p, n)^{26}Al$ & $^{26}Mg(^{3}He,t)^{26}Al$ spectra



Prominent states are GT states and the IAS !

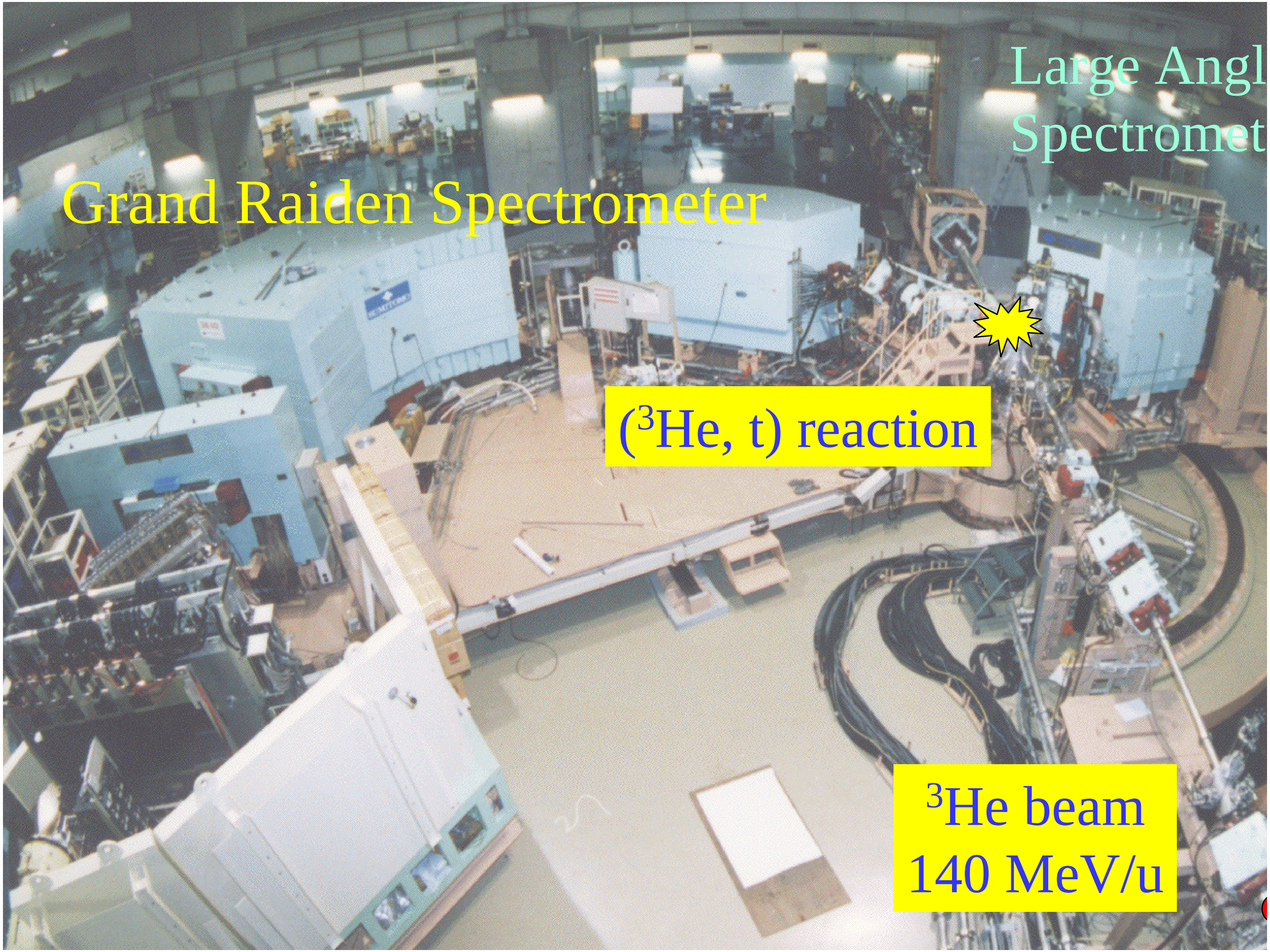
B(GT) values from Symmetry Transitions (A=26)





Y. Fujita et al., PRC 67 ('03) 064312

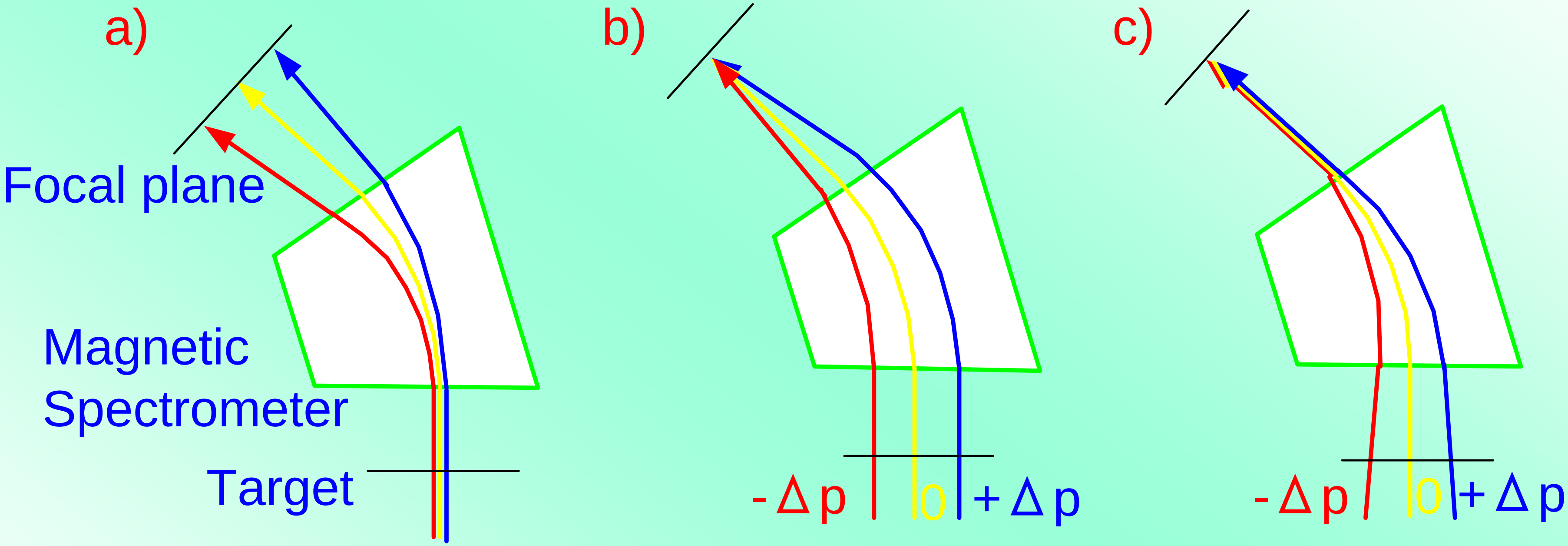

RCNP (Osaka) Ring Cyclotron
SUMITOMO
Good quality ^{3}He beam (140 MeV/nucleon)


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

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

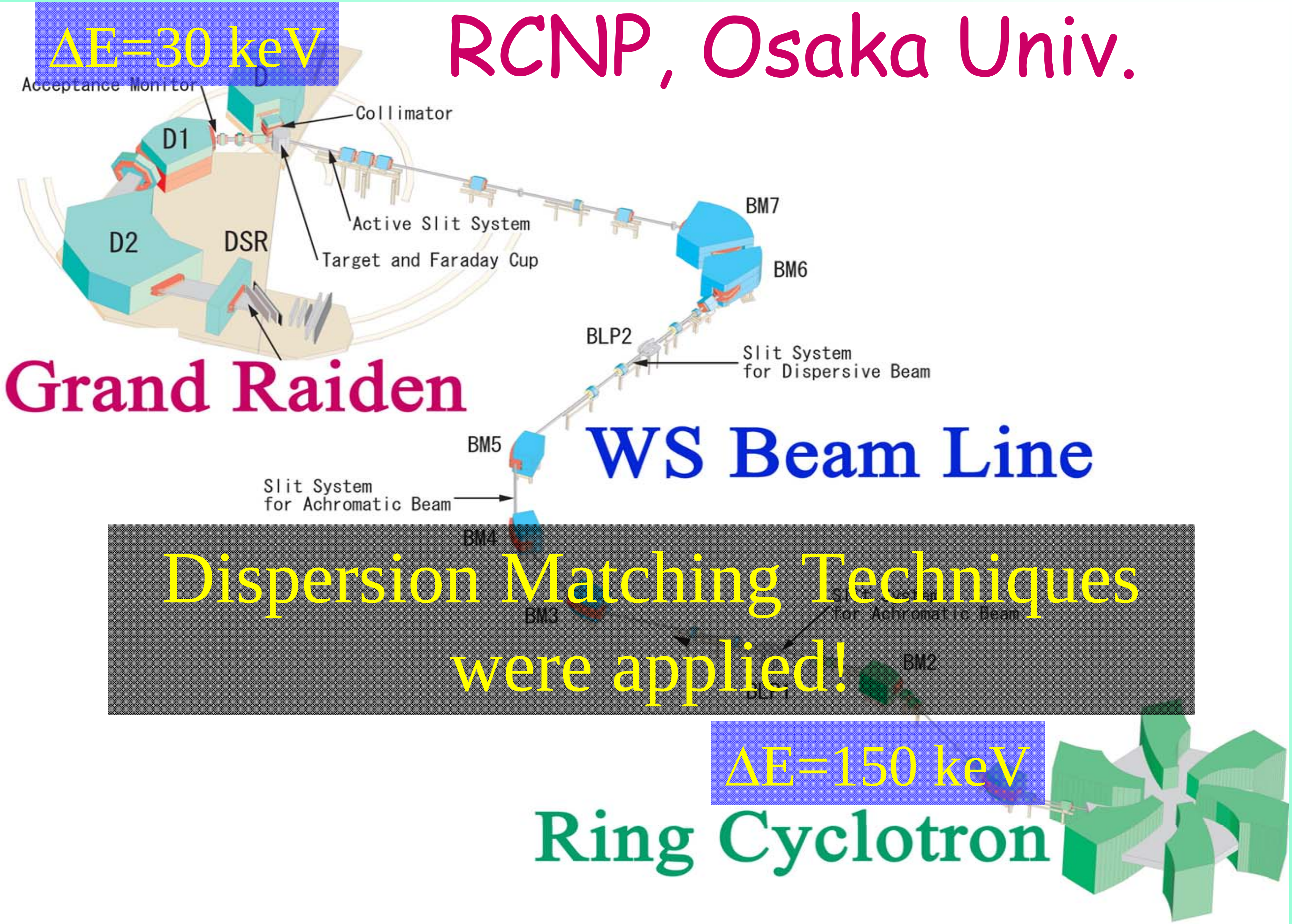
Horiz. angle resolution

$\Delta\theta_{sc} > 15$mrad

Angular dispersion matching

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

RCNP, Osaka Univ.

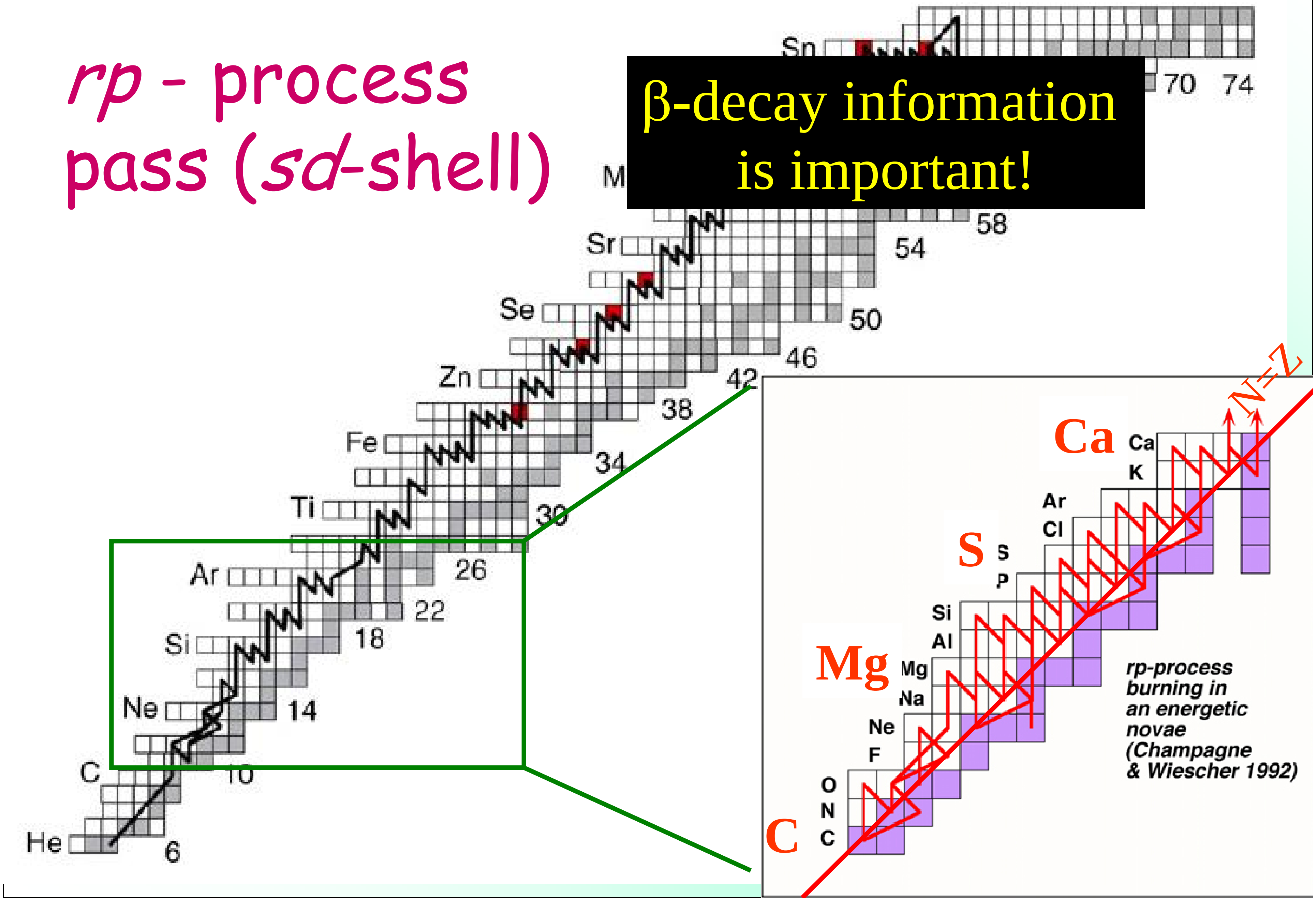


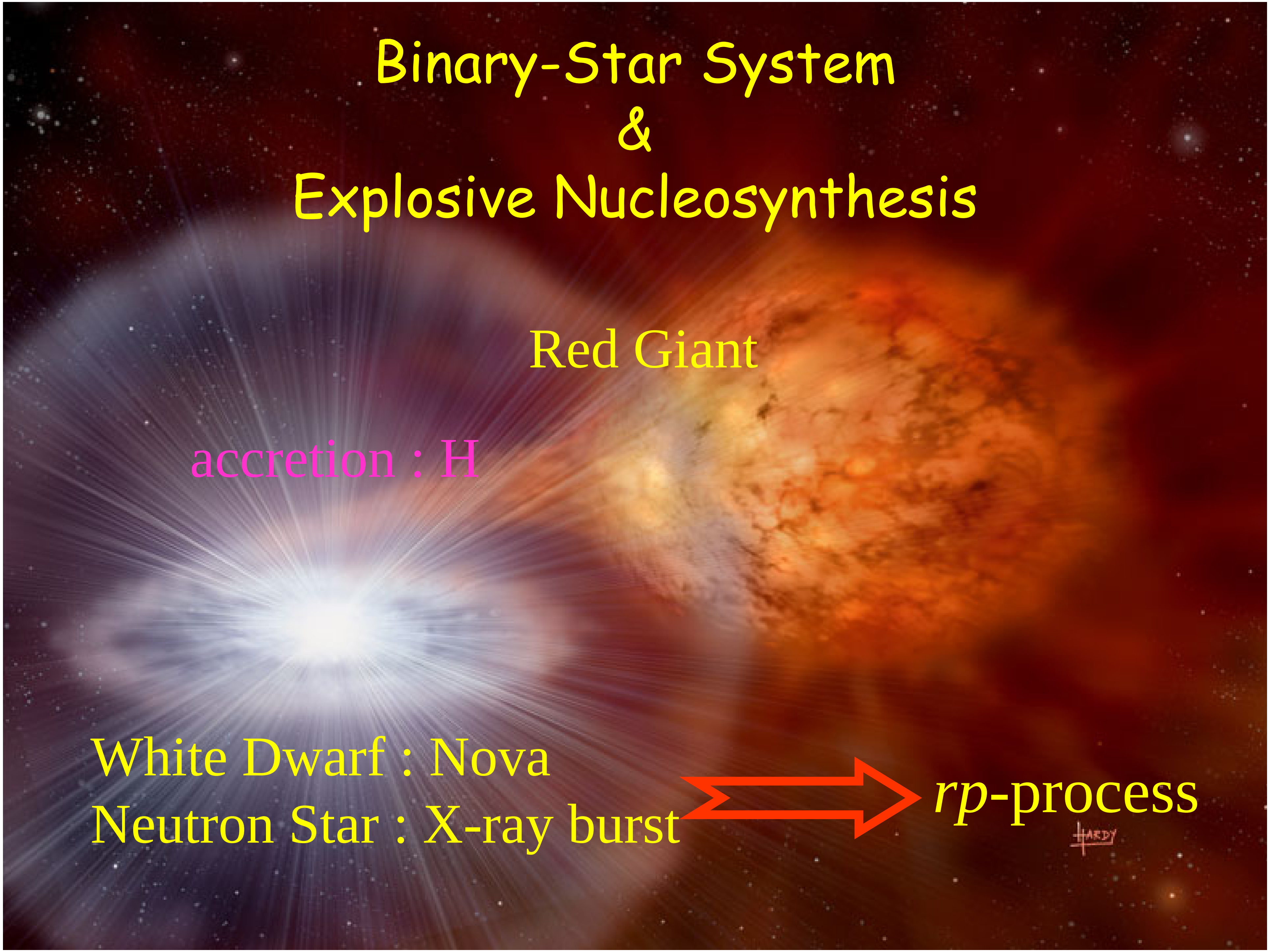
**GT transitions in each nucleus are UNIQUE !

M. Wiescher et al. / Progress in Particle and Nuclear Physics 59 (2007) 51–65

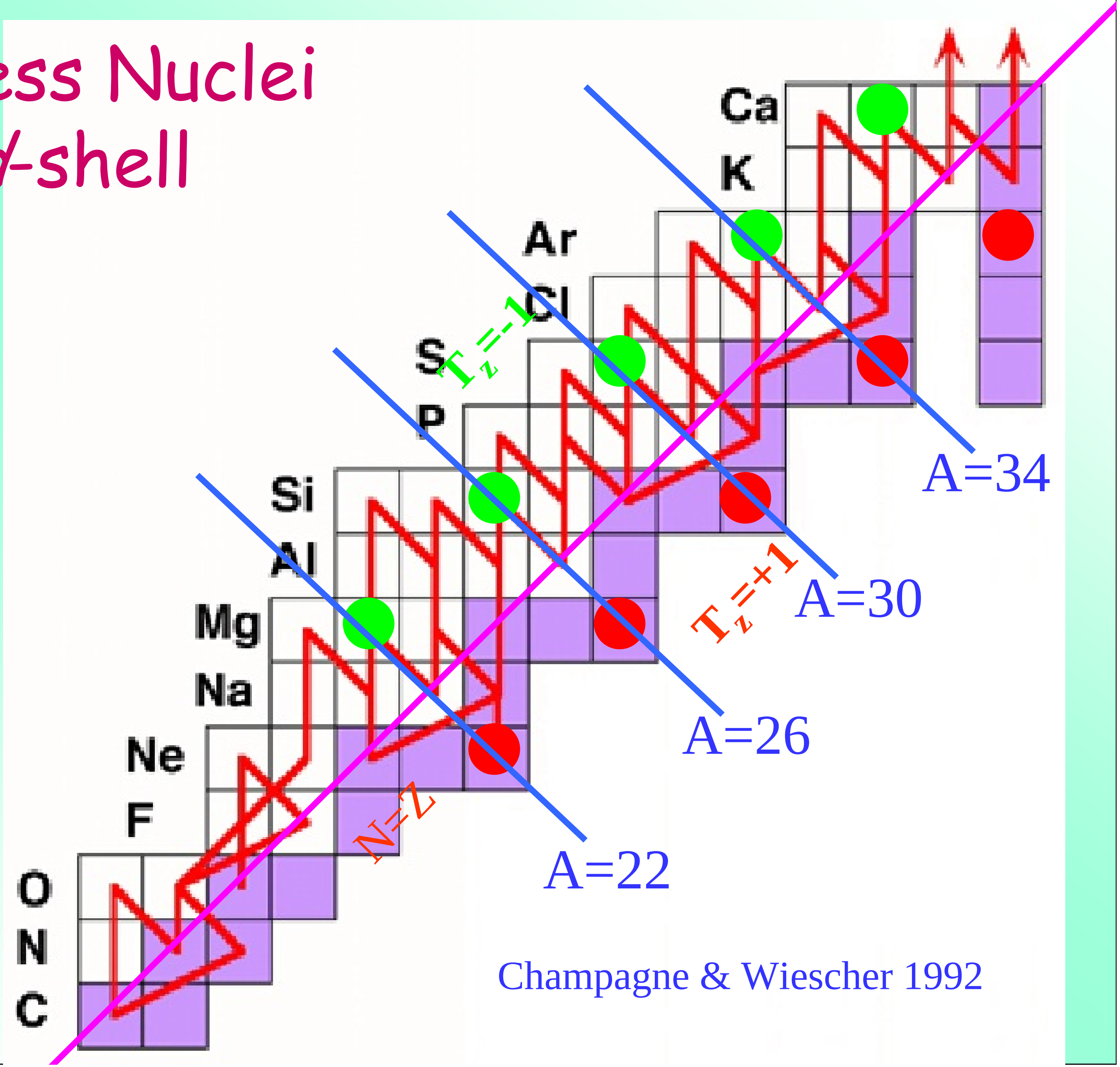
rp - process pass (*sd*-shell)

β-decay information is important!



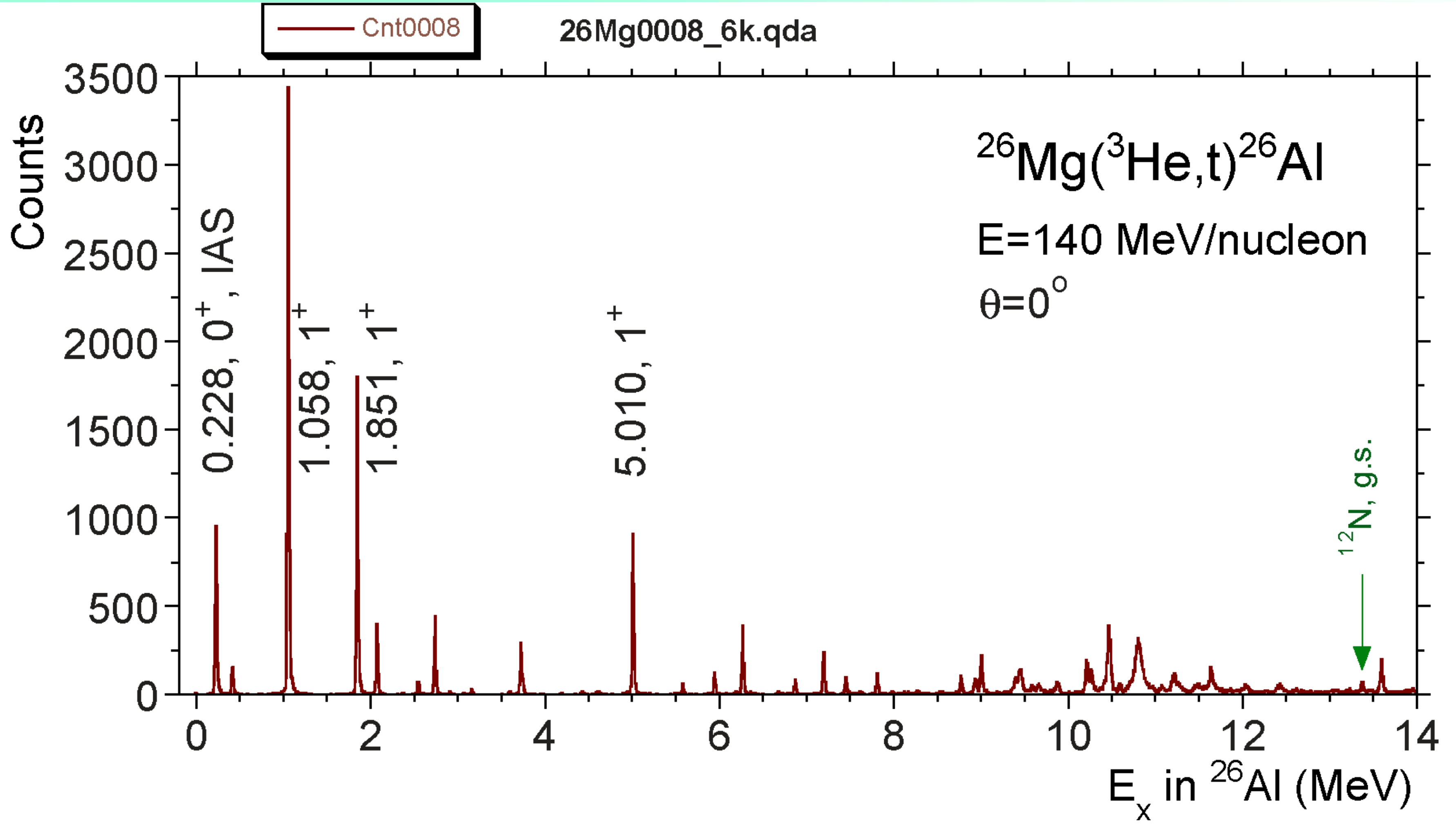

Binary-Star System
&
Explosive Nucleosynthesis
Red Giant
accretion : H
White Dwarf : Nova
Neutron Star : X-ray burst
rp-process
HARDY

rp-Process Nuclei in *sd*-shell

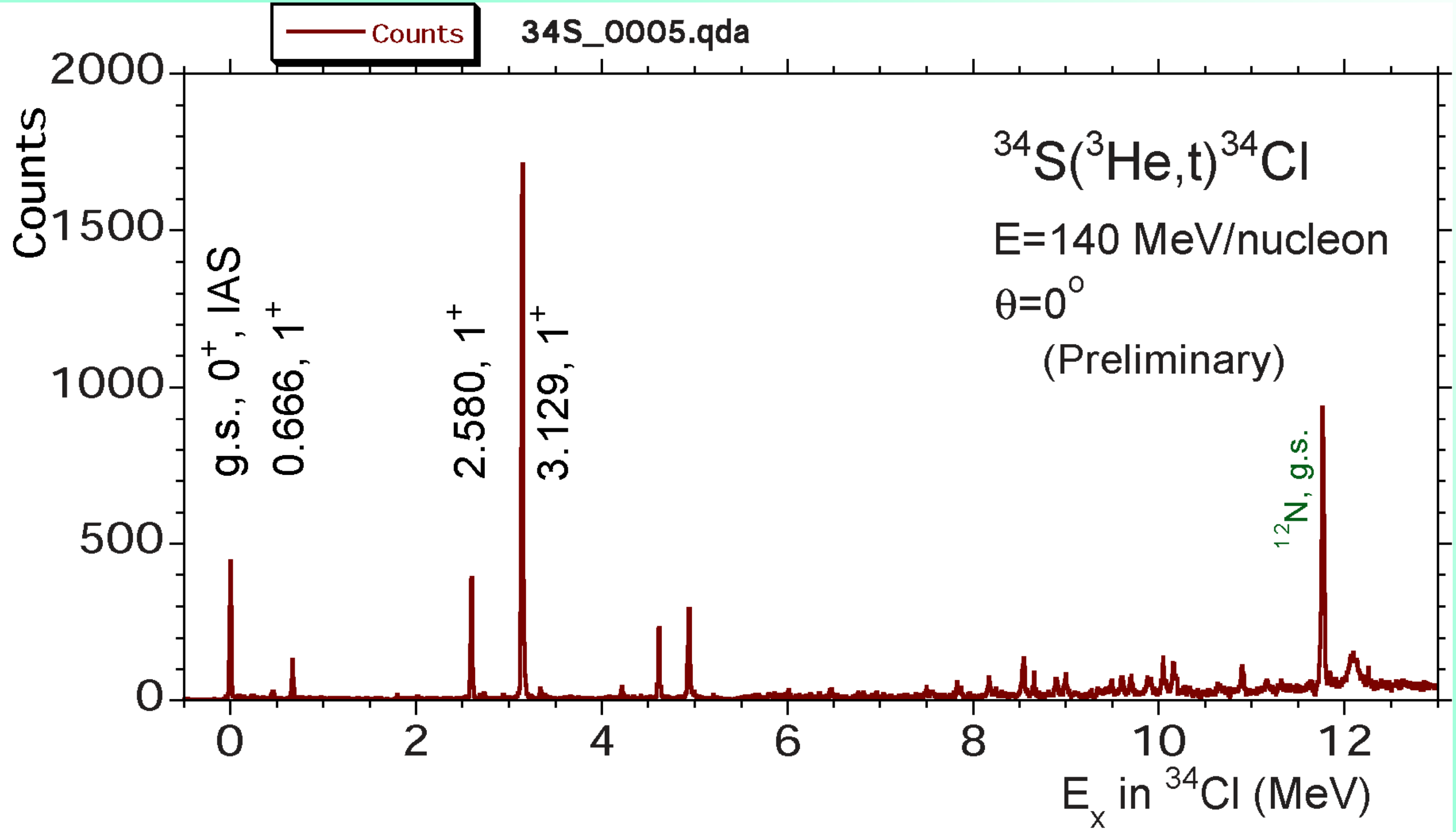


Champagne & Wiescher 1992

$^{26}Mg(^{3}He,t)^{26}Al$

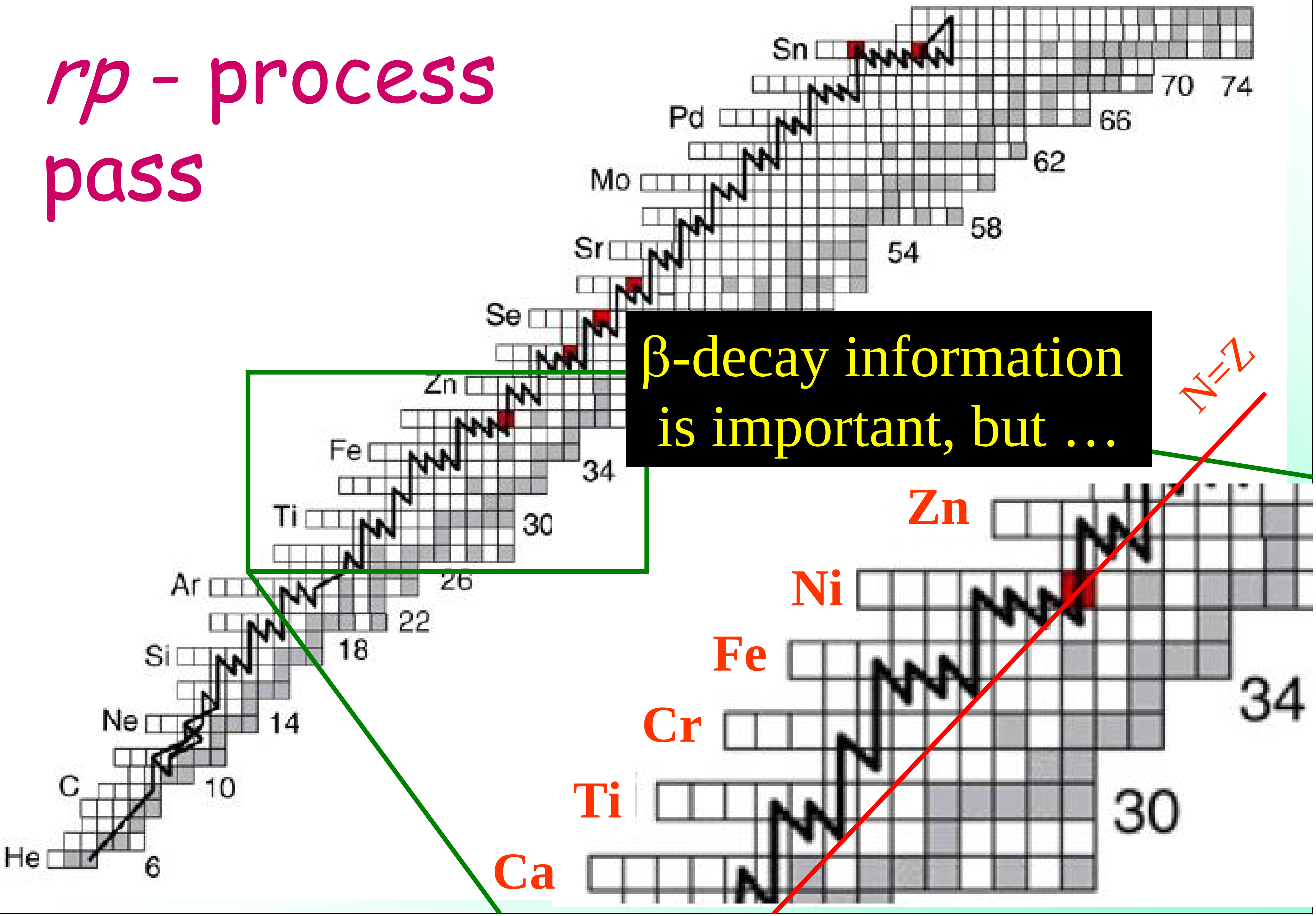


$^{34}S(^{3}He,t)^{34}Cl$

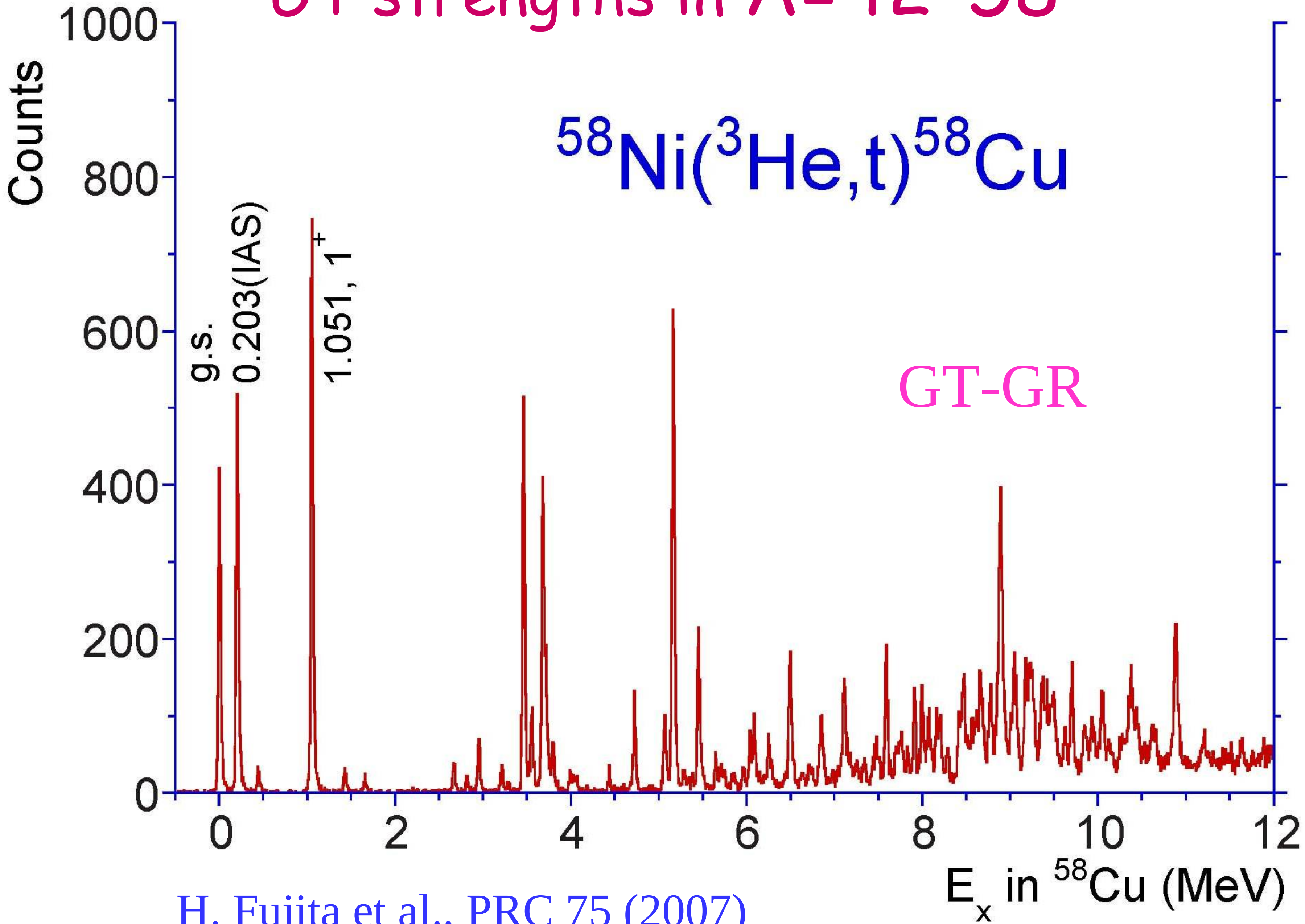


M. Wiescher et al. / Progress in Particle and Nuclear Physics 59 (2007) 51–65

rp - process pass

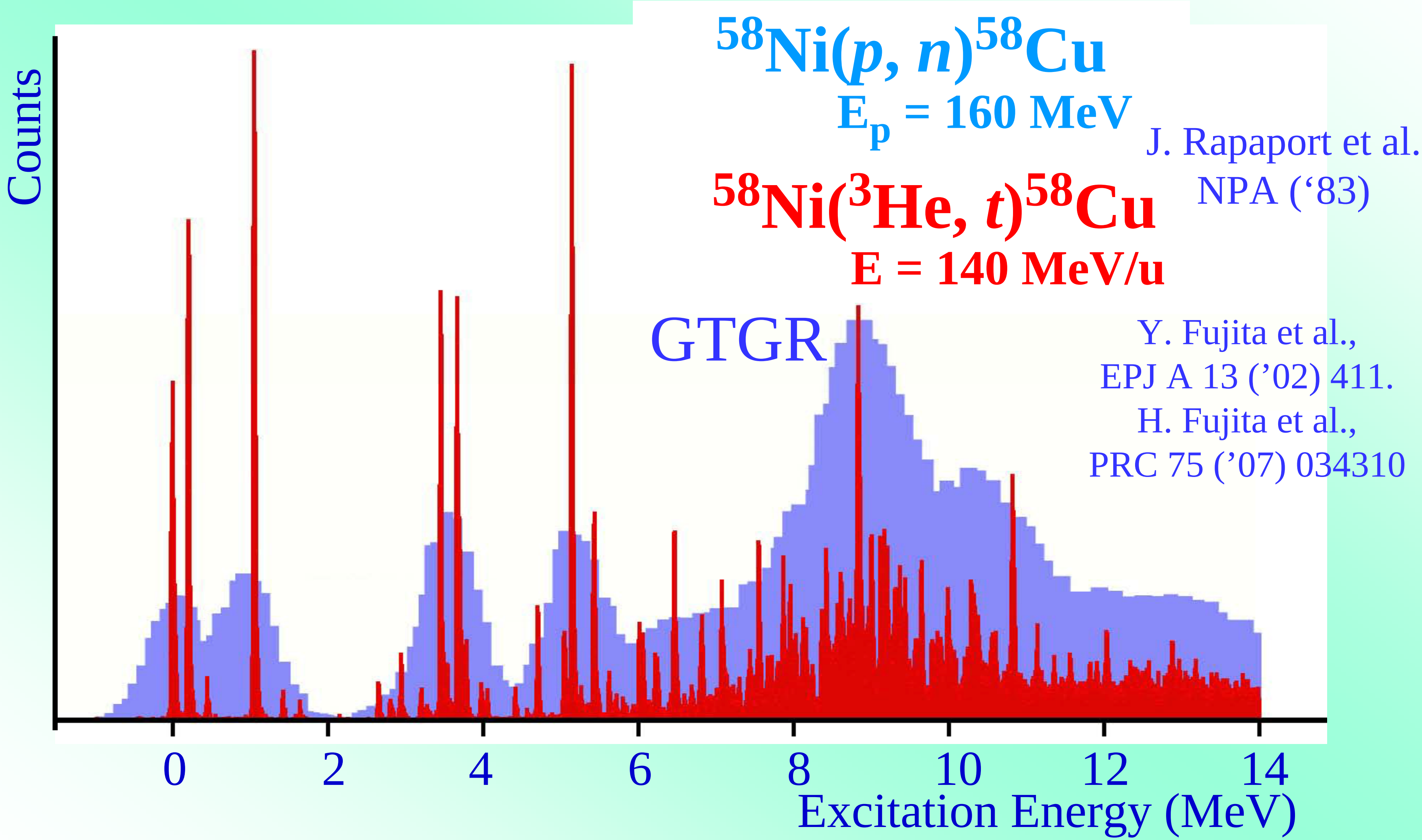


GT strengths in A=42-58



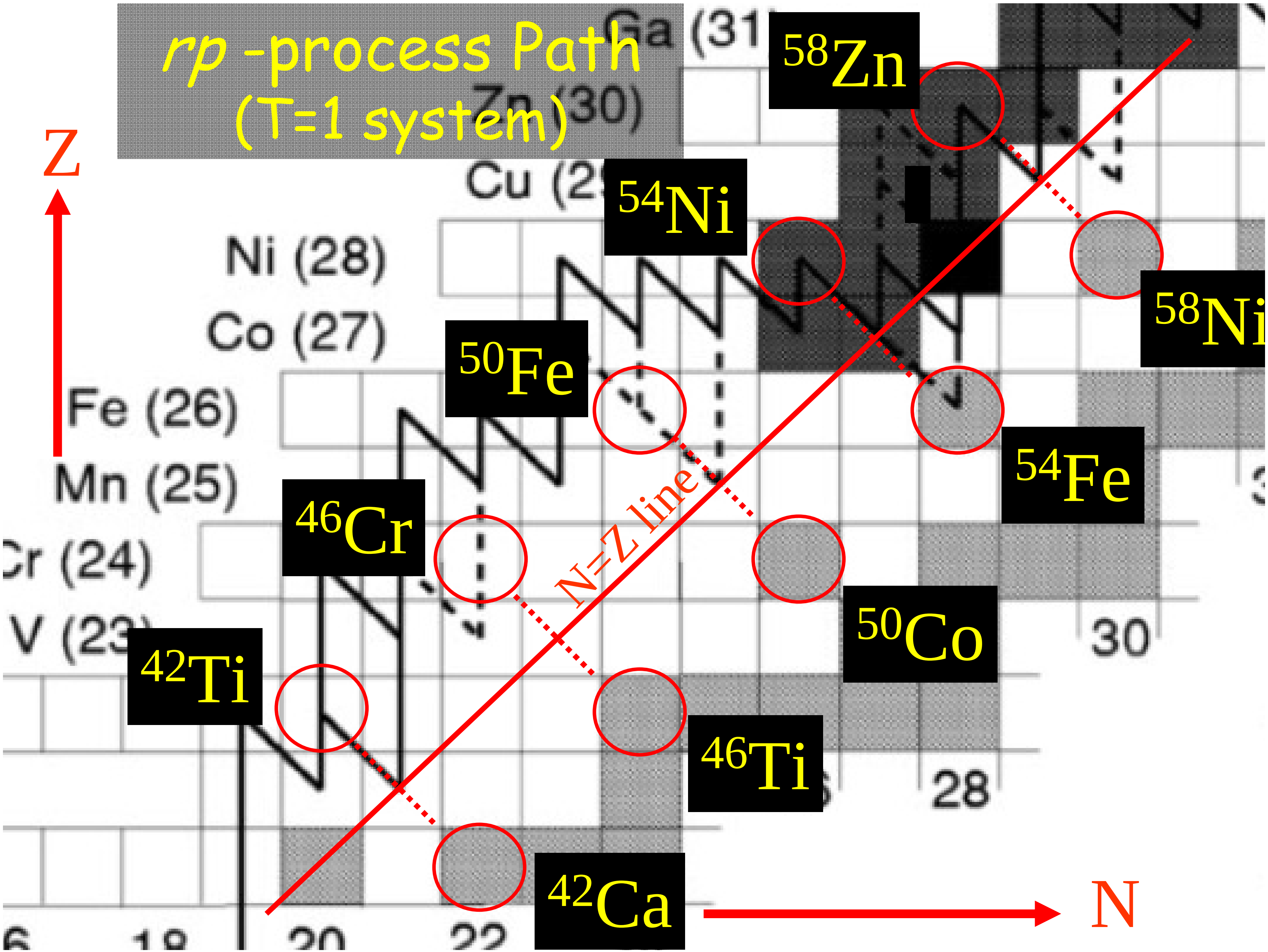
H. Fujita et al., PRC 75 (2007)

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



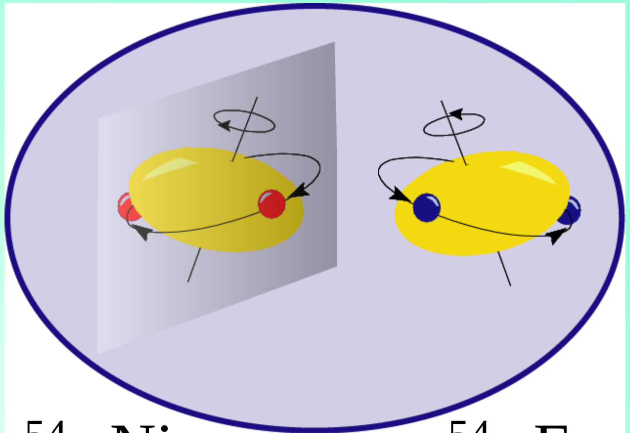
***Exotic GT transitions from Unstable Nuclei

- Combined (^{3}He,t) and β-decay Study -

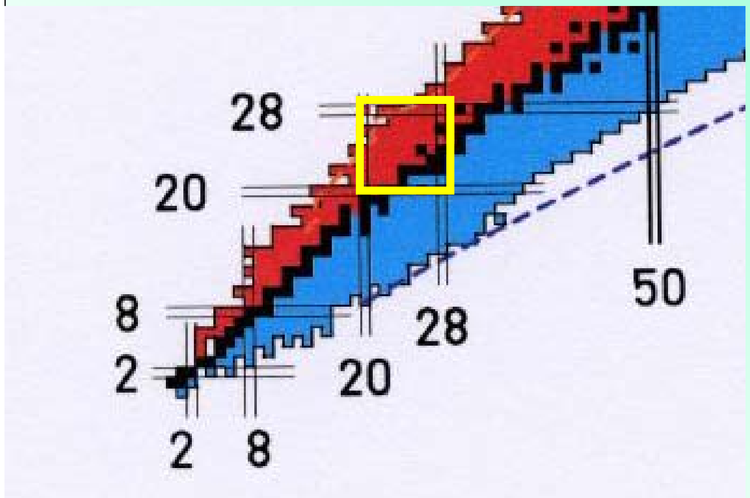

rp -process Path
(T=1 system)
Z
N
Ni (28)
Co (27)
Fe (26)
Mn (25)
Cr (24)
^{58}Zn
^{54}Ni
^{58}Ni
^{50}Fe
^{54}Fe
^{46}Cr
^{50}Co
^{42}Ti
^{46}Ti
^{42}Ca
N=Z line
30
28
20
22

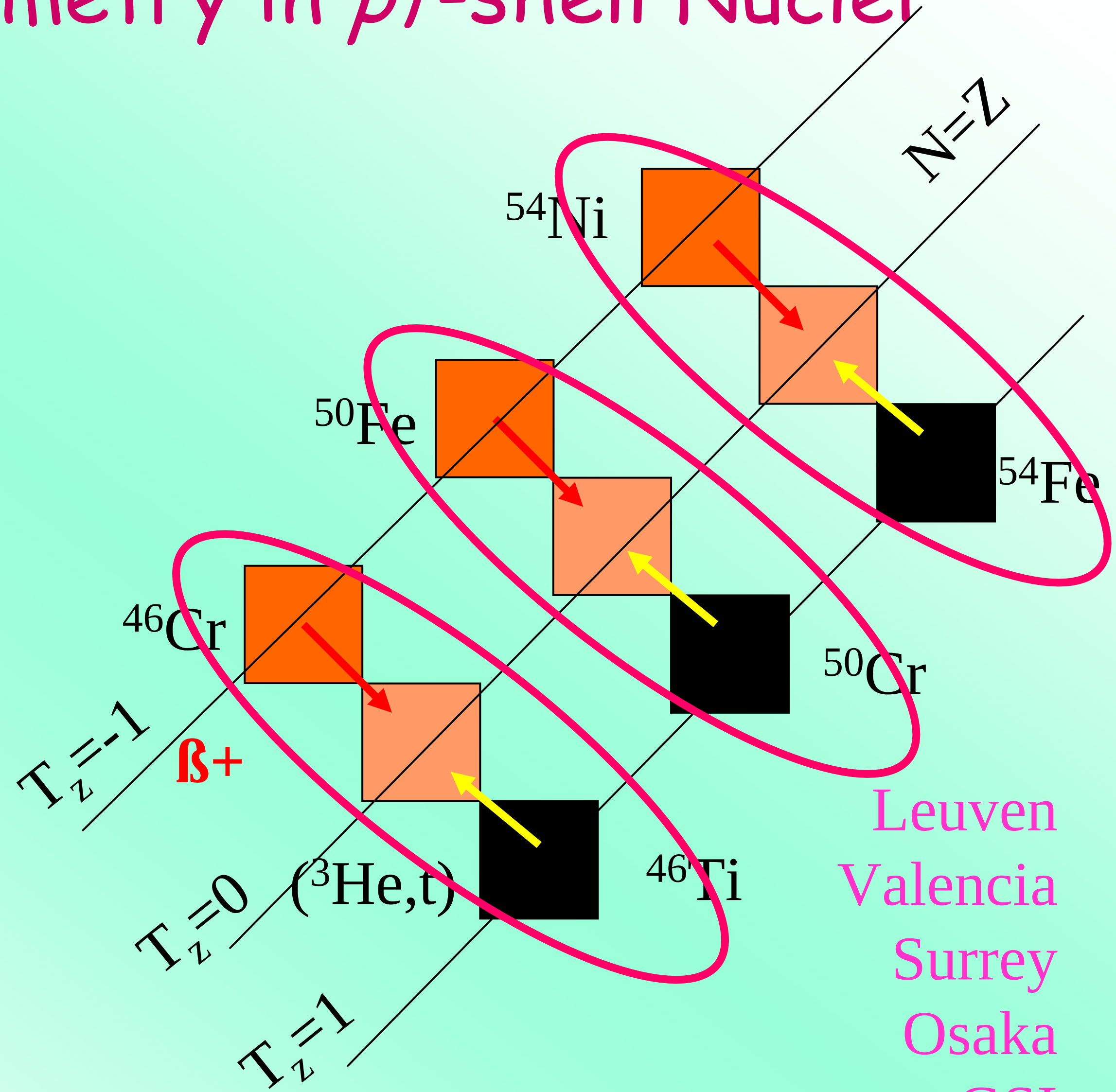
T=1 Isospin Symmetry in *pf*-shell Nuclei

Mirror nuclei



$^{54}_{28}Ni_{26}$ $^{54}_{26}Fe_{28}$



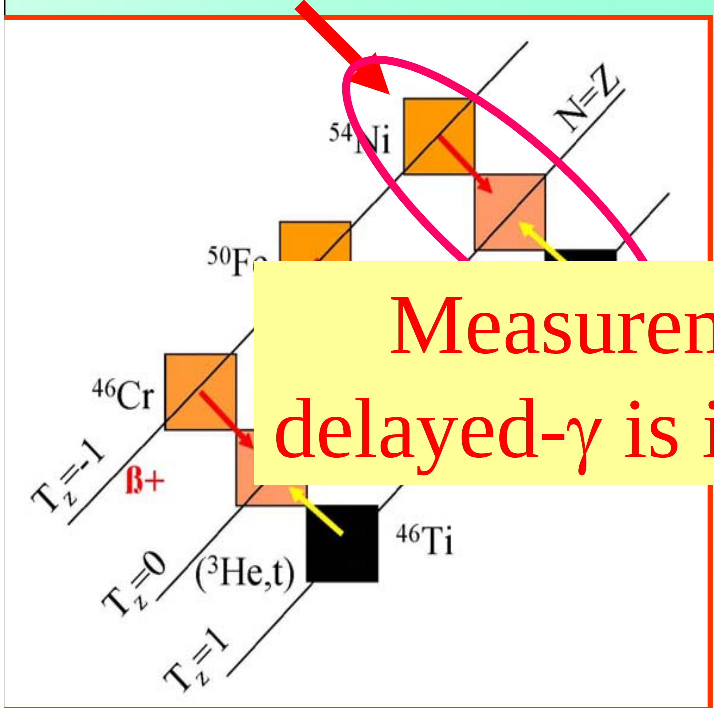


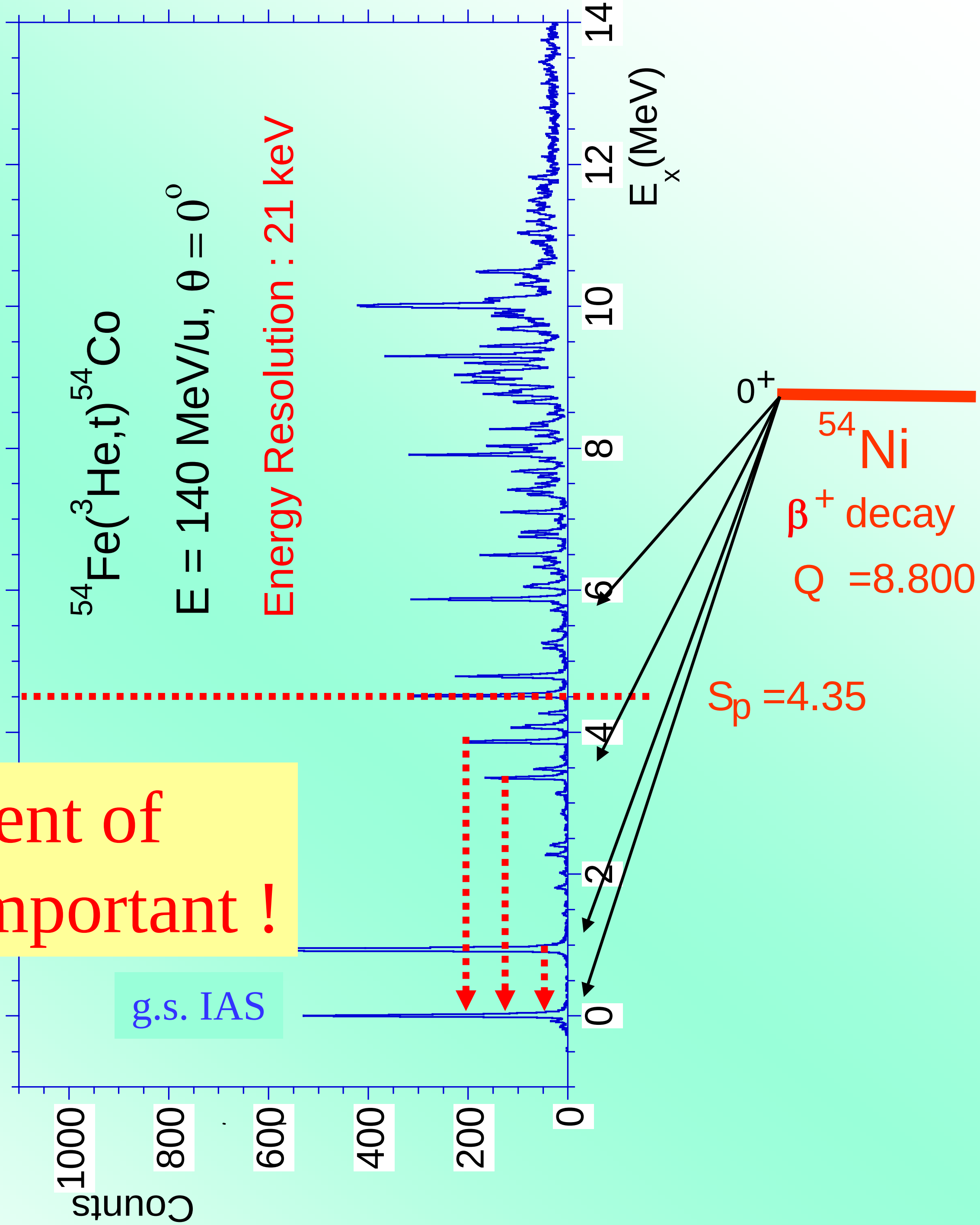
Leuven
Valencia
Surrey
Osaka
GSI
CNS

by B. Rubio

^{54}Ni β-decay measurement

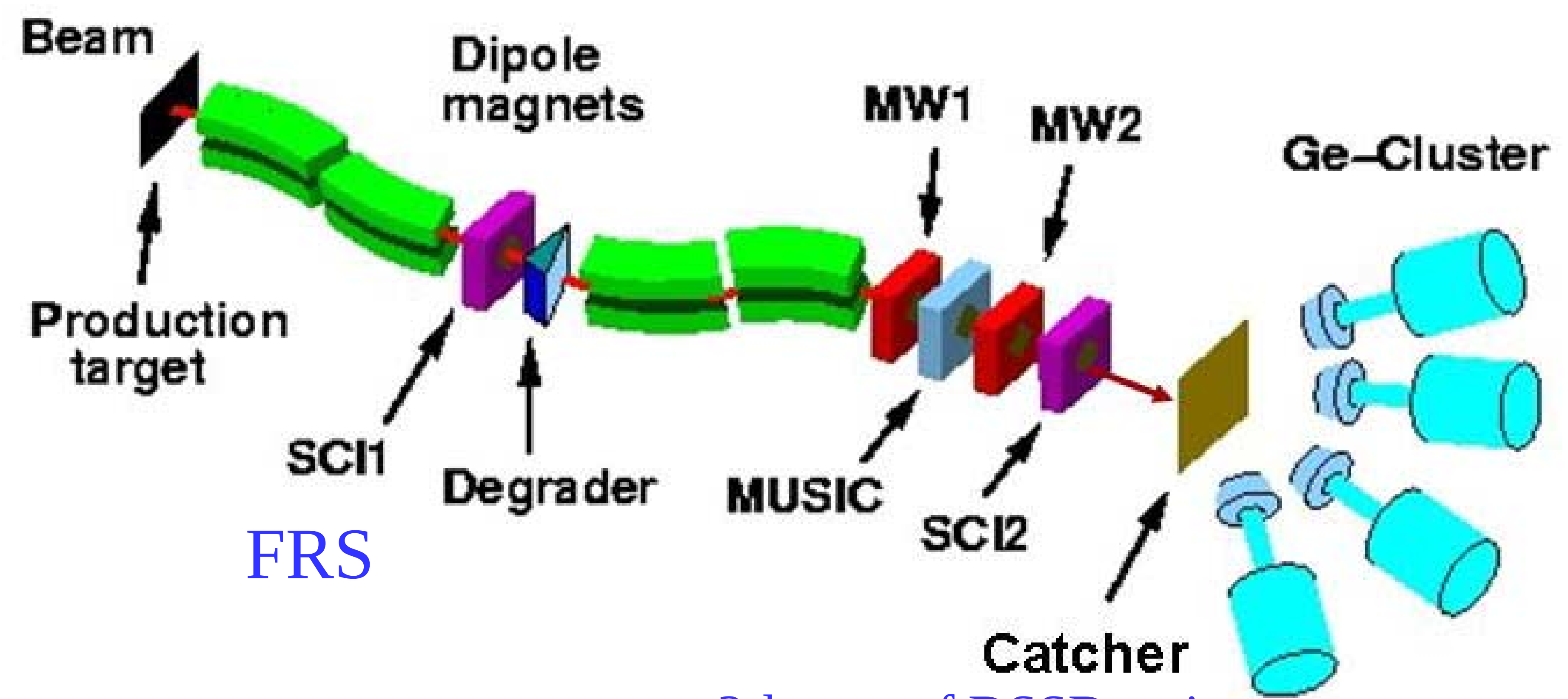
- at GSI
  (FRS facility)
- RISING
  (stopped beam campaign)





Measurement of delayed-γ is important !

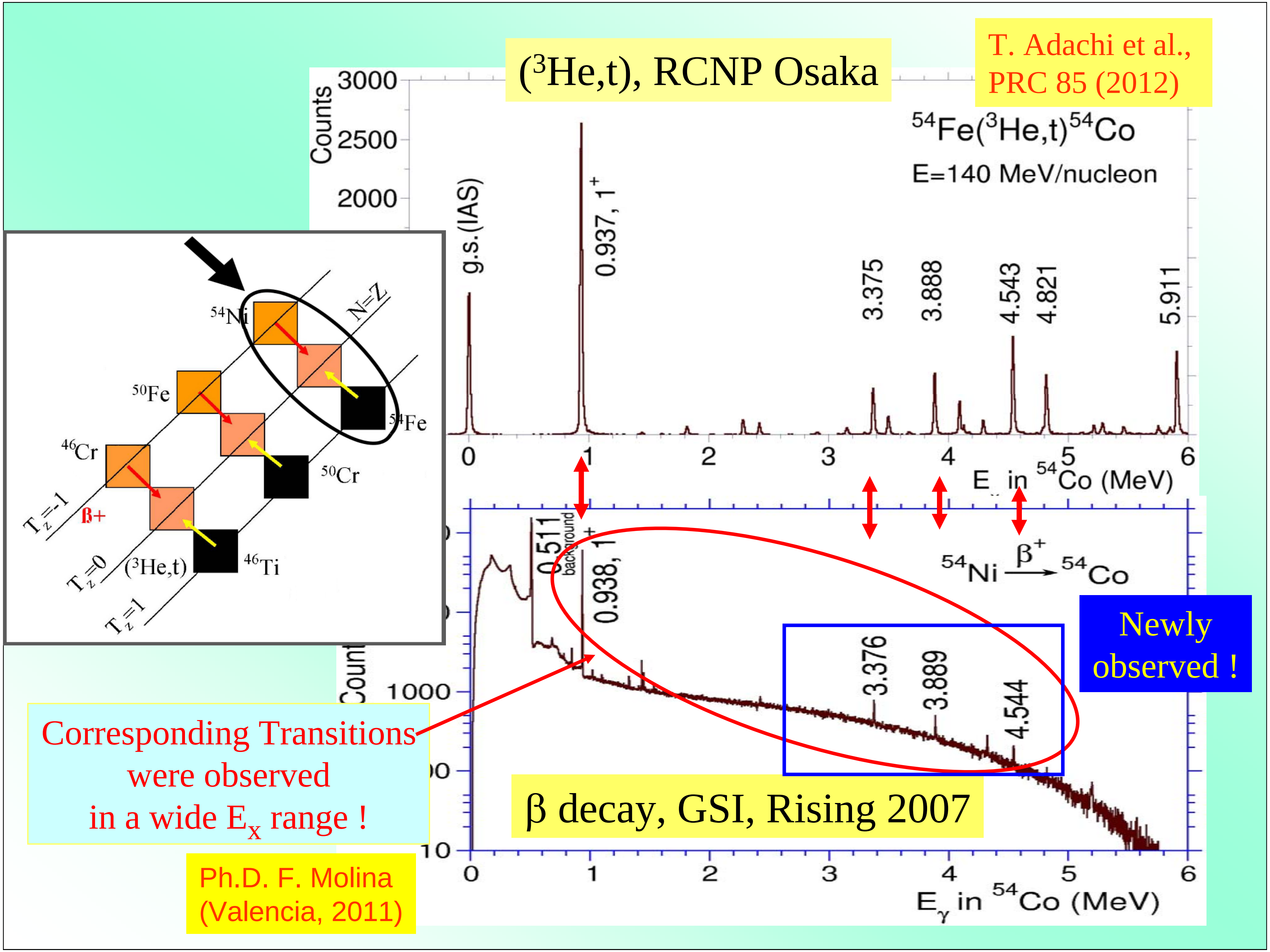
GSI: RISING set up
- active stopper campaign -



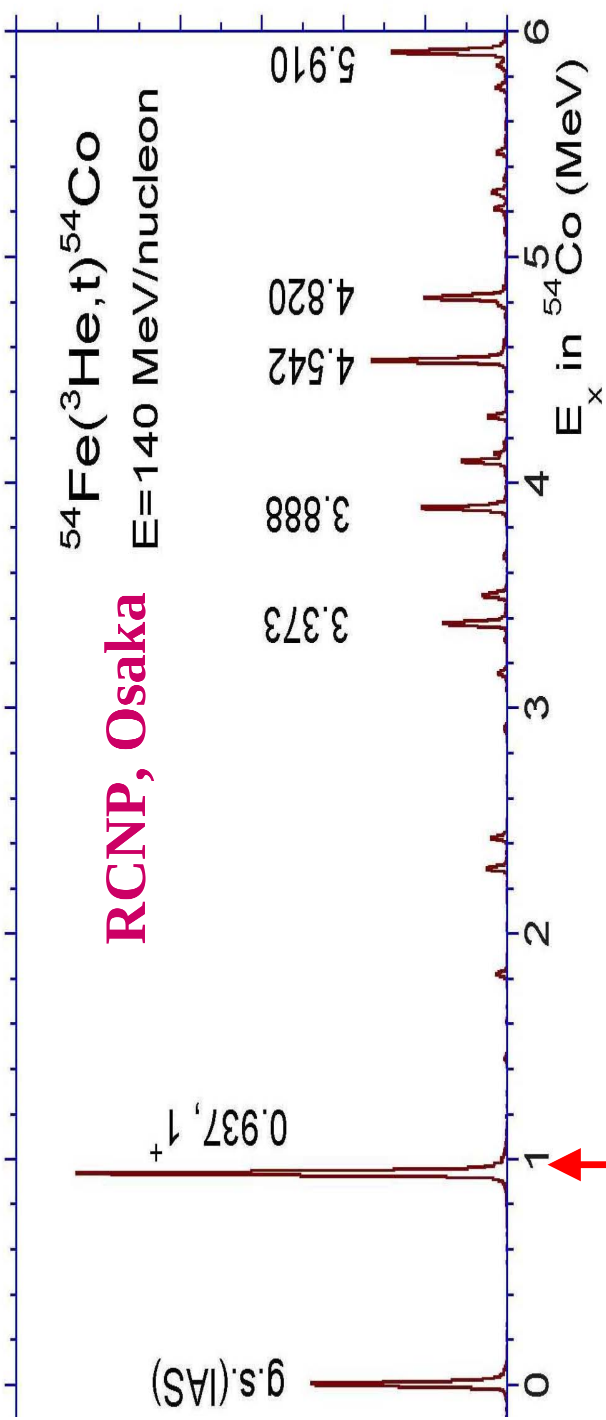
FRS

3-layors of DSSD active stopper

GSI RISING set up

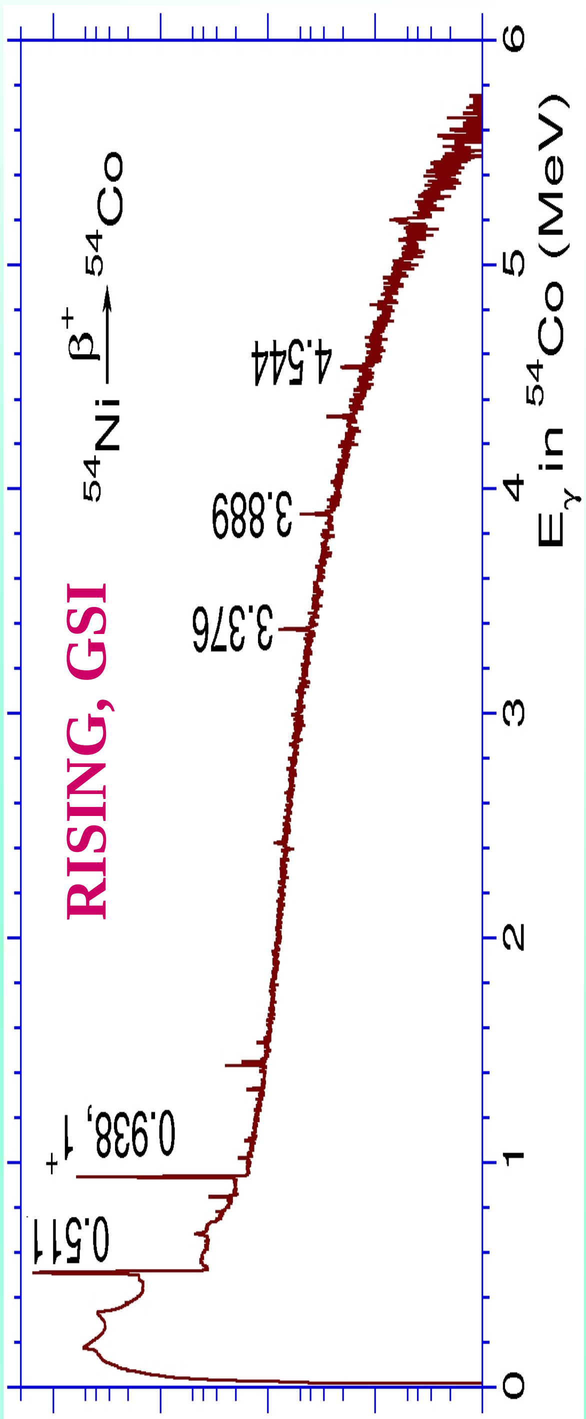


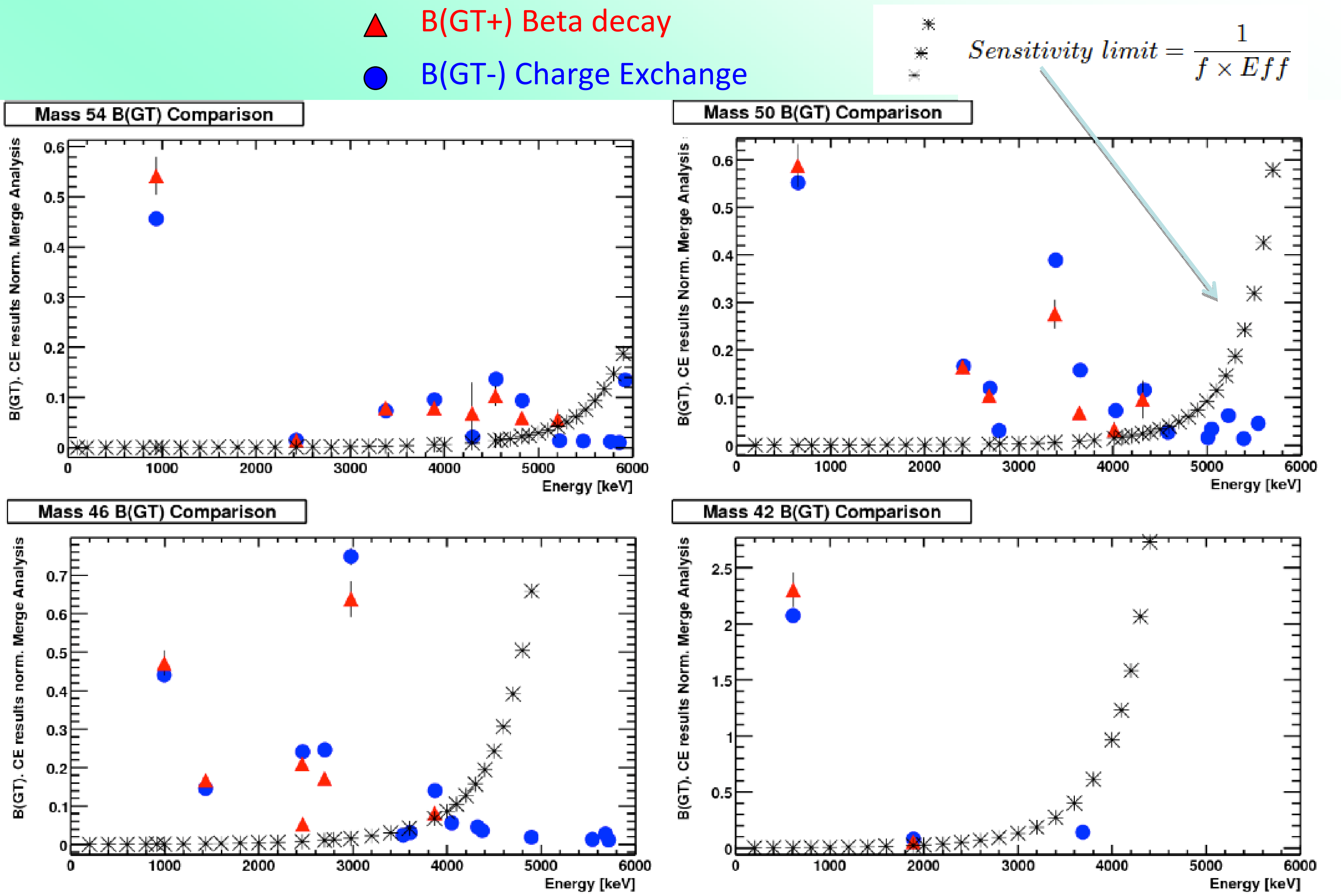
(3He,t), RCNP Osaka
T. Adachi et al.,
PRC 85 (2012)
54Fe(3He,t)54Co
E=140 MeV/nucleon
Counts
3000
2500
2000
g.s.(IAS)
0.937, 1+
3.375
3.888
4.543
4.821
5.911
0
1
2
3
4
5
6
Ex in 54Co (MeV)
54Ni
50Fe
46Cr
54Fe
50Cr
46Ti
N=Z
Tz=-1
Tz=0
Tz=1
ß+
(3He,t)
0.511 background
0.938, 1+
54Ni β+ → 54Co
Newly observed !
3.376
3.889
4.544
Counts
1000
100
10
Corresponding Transitions were observed in a wide Ex range !
β decay, GSI, Rising 2007
Ph.D. F. Molina (Valencia, 2011)
Eγ in 54Co (MeV)



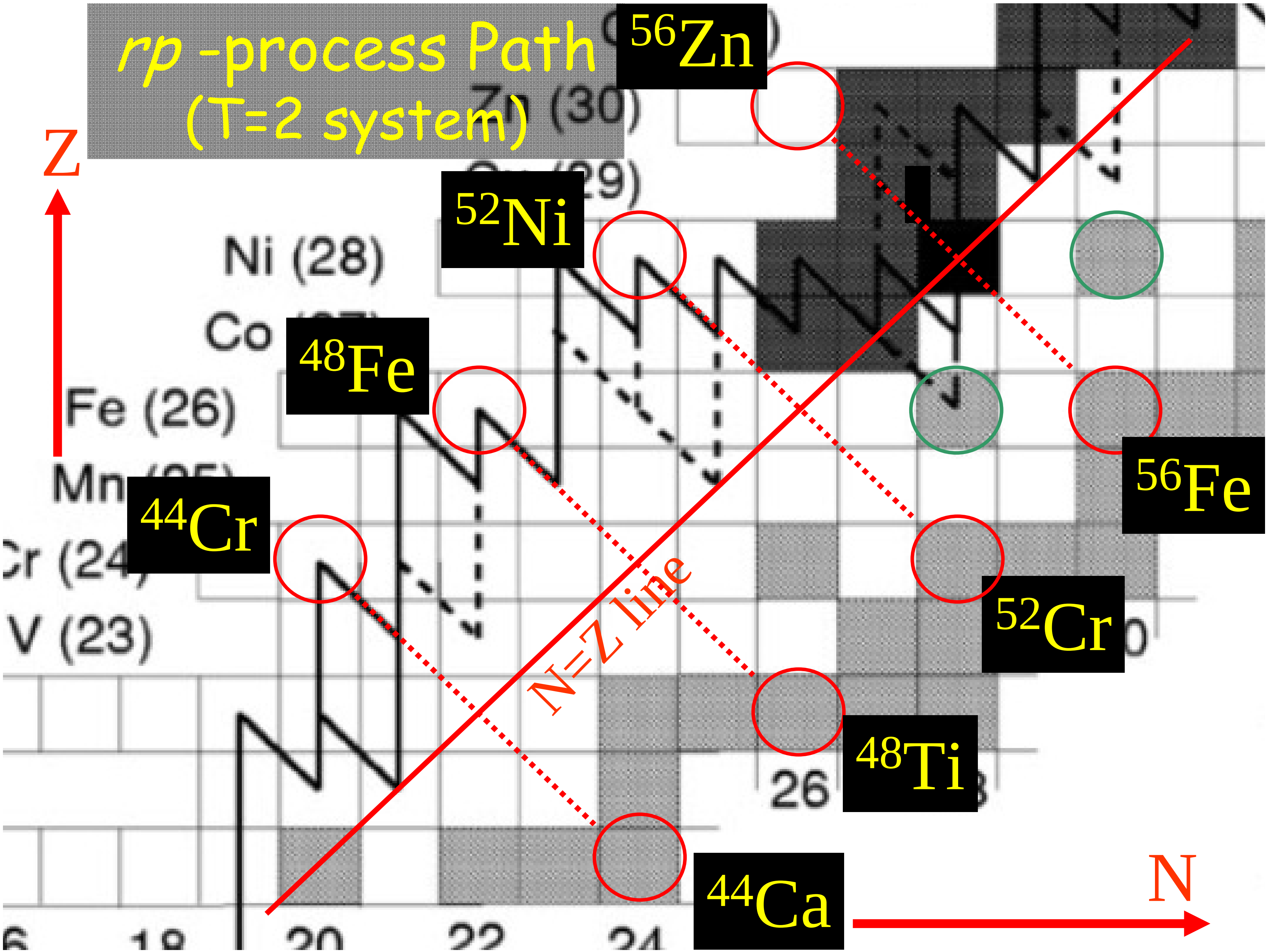
Comparison

B(GT) (^{3}He,t)	B(GT) β-decay
0.09	0.07
0.07	0.07
0.46	0.53



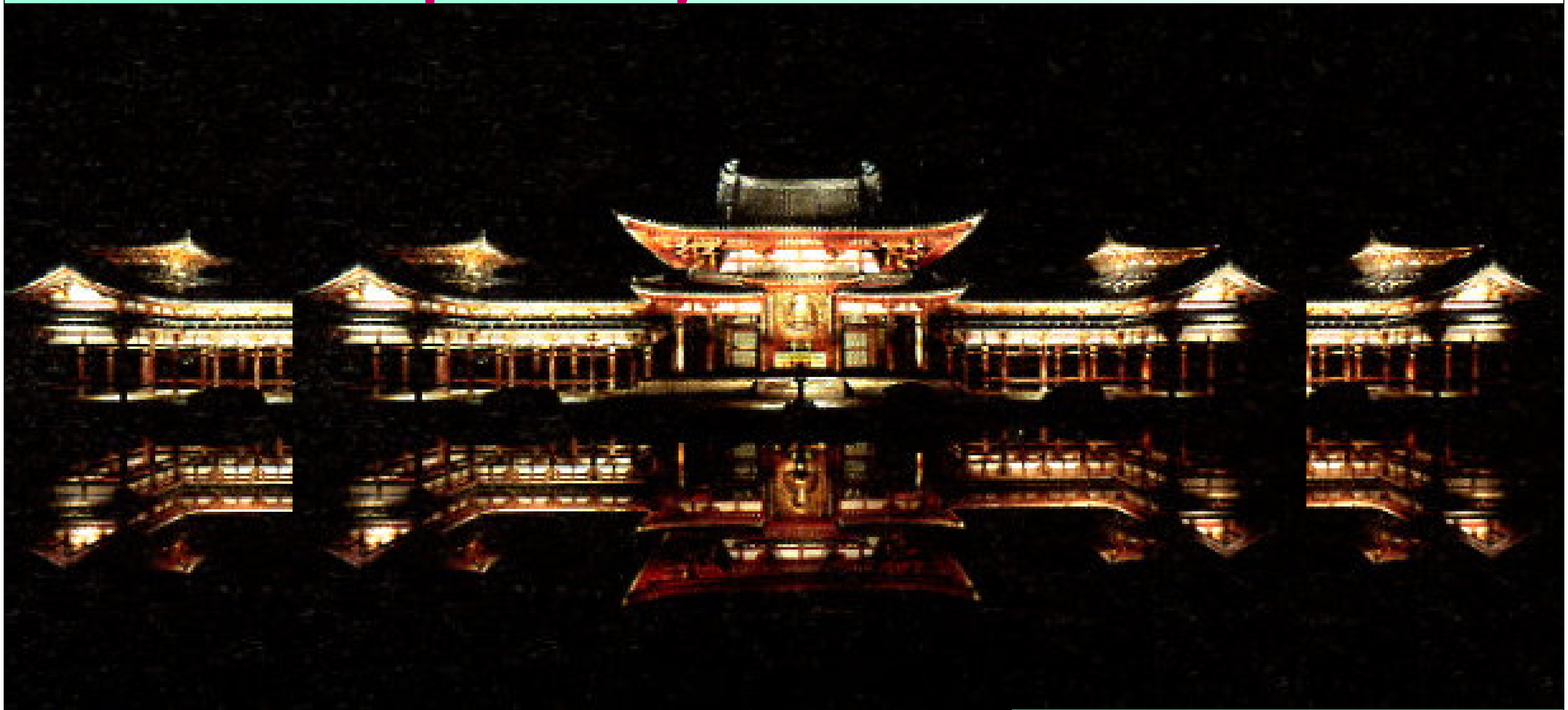


B. Rubio, F. Molina, Y. Fujita et al.

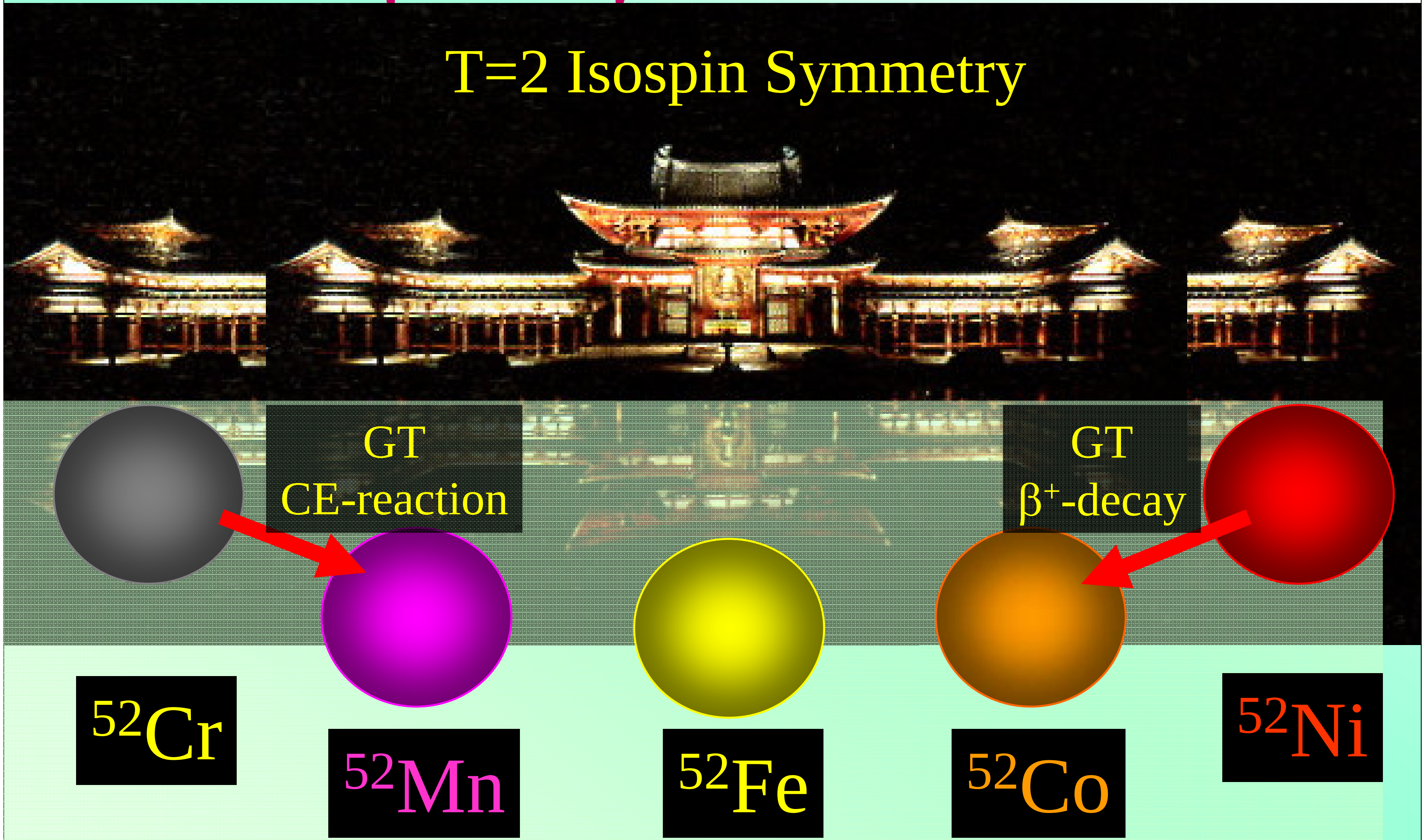


rp -process Path
(T=2 system)
56Zn
52Ni
48Fe
44Cr
56Fe
52Cr
48Ti
44Ca
N=Z line
Z
N
Zn (30)
Ni (28)
Co
Fe (26)
Mn
Cr (24
V (23)
20
22
24
26

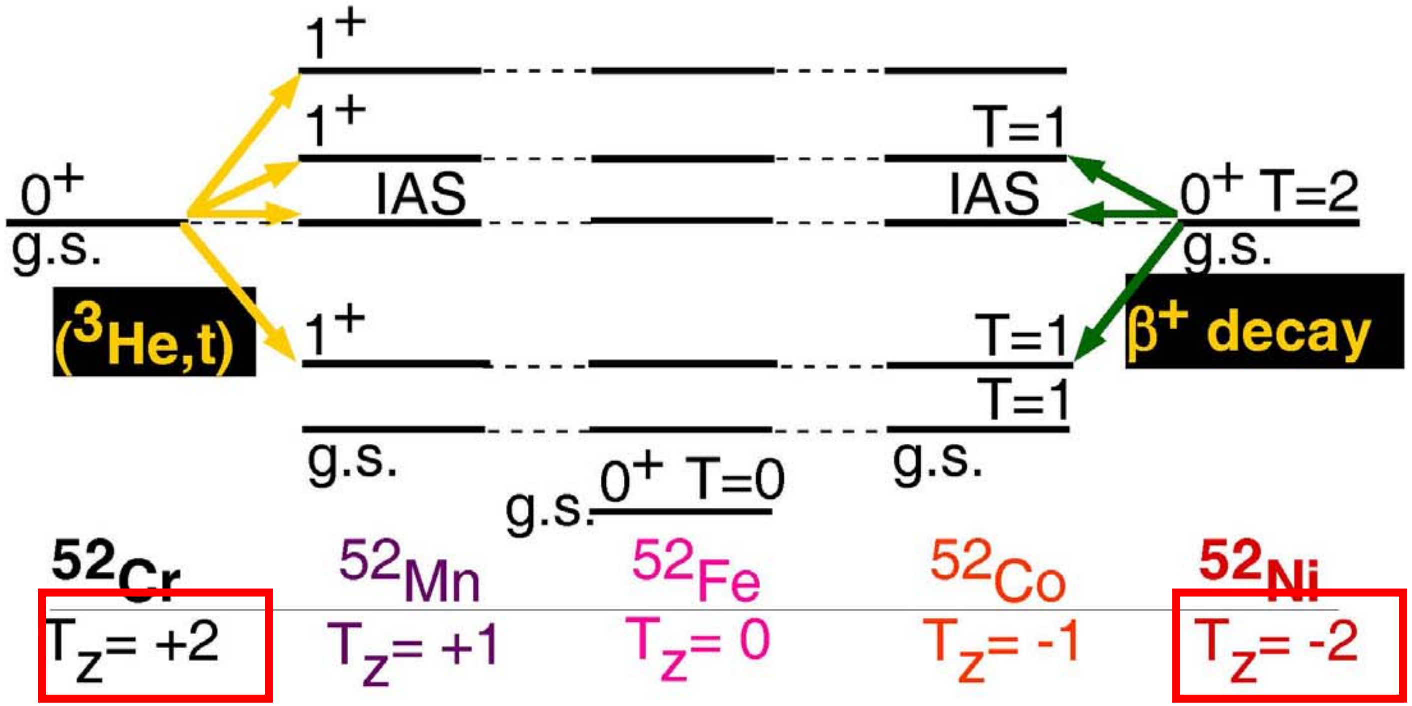
Super-Byodoin 平等院



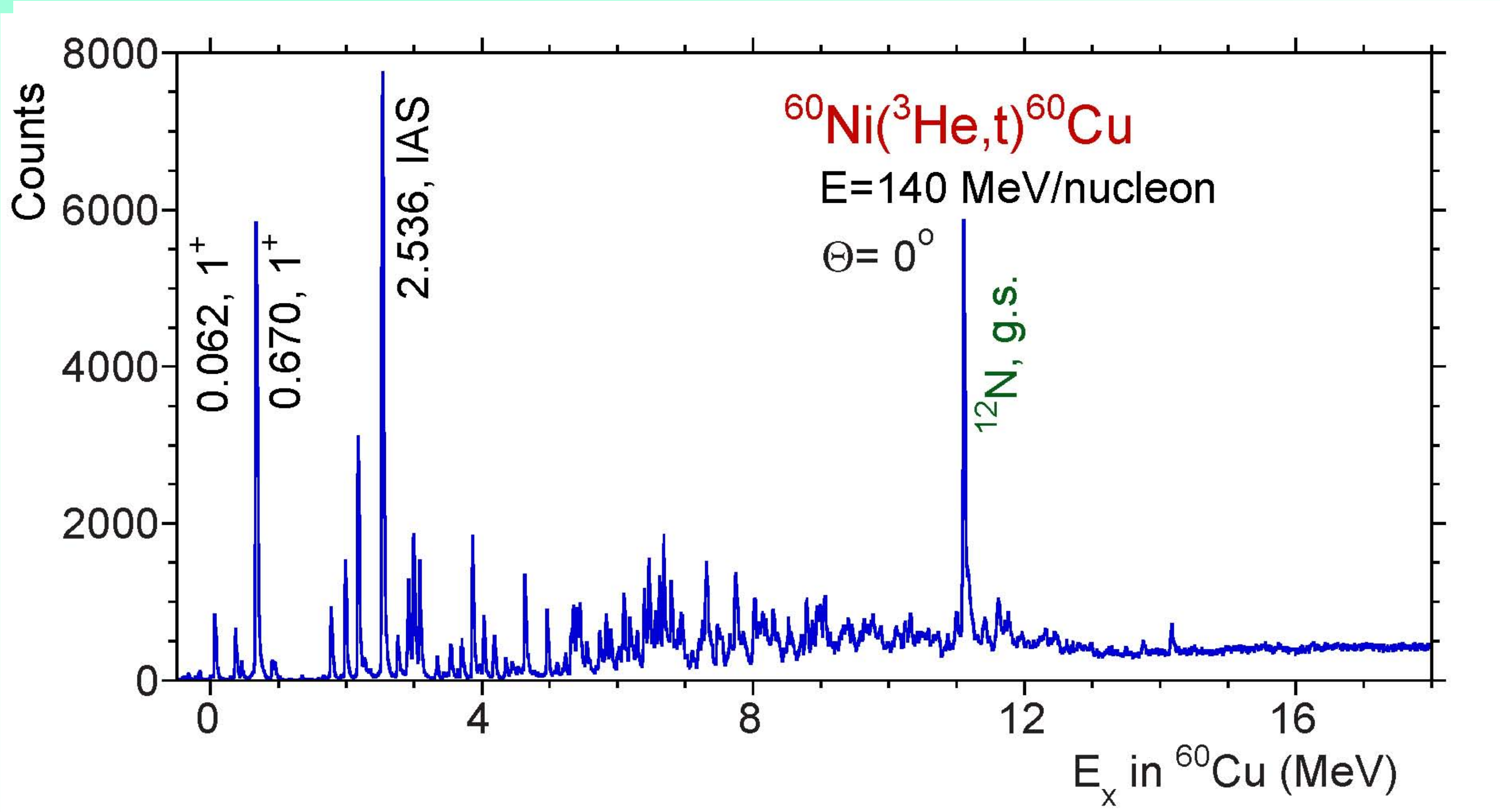
Super-Byodoin 平等院



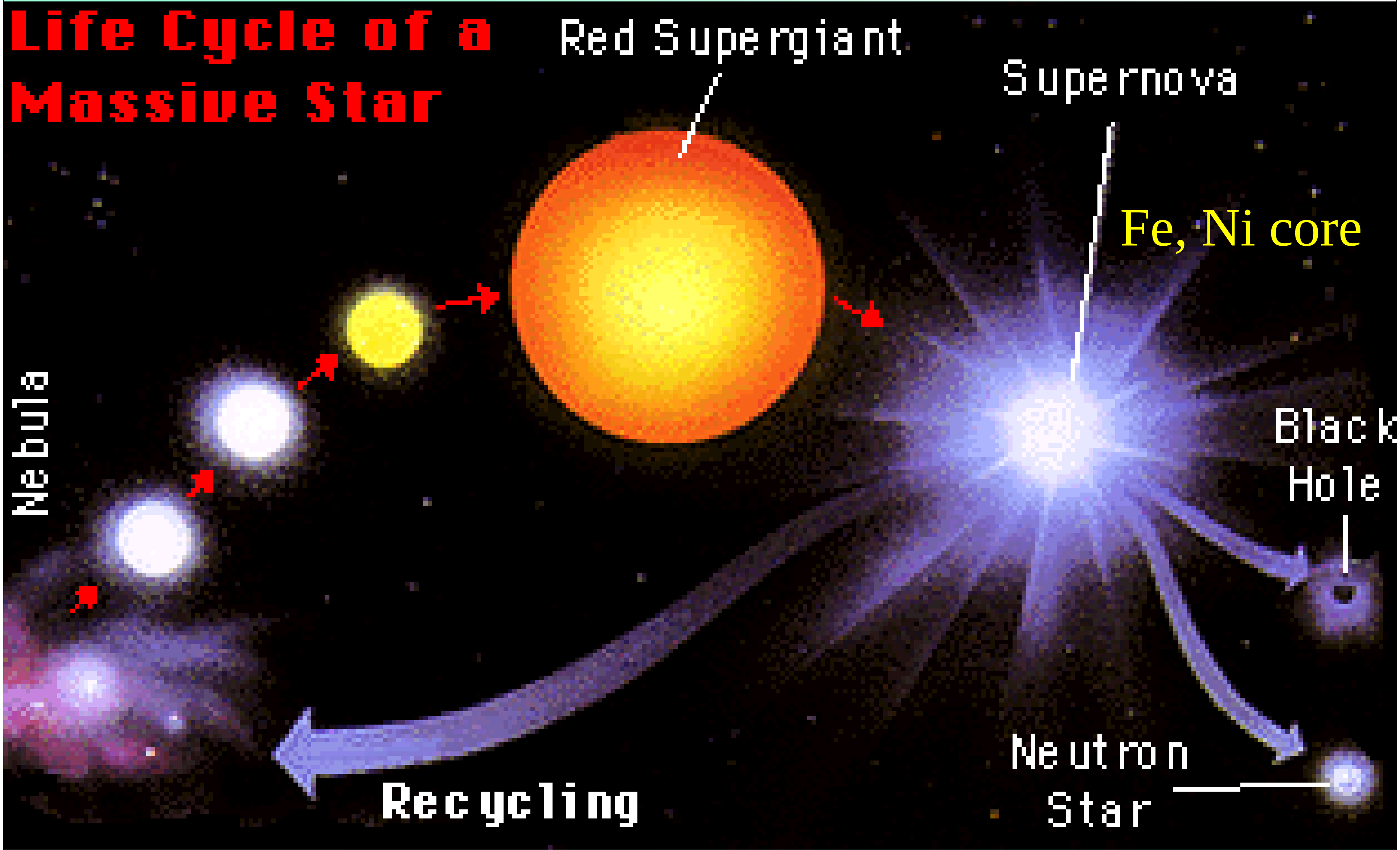
Isospin Structure of T=2 system (low-lying states)



Tz= +2→ +1 GT strengths in A=44-60



Supernova Cycle



Crucial Weak Processes during the Core Collapse

$$p + e^- \rightleftarrows n + \nu_e ,$$

$$n + e^+ \rightleftarrows p + \bar{\nu}_e ,$$

στ: important → $$(A,Z) + e^- \rightleftarrows (A,Z-1) + \nu_e ,$$

→ $$(A,Z) + e^+ \rightleftarrows (A,Z+1) + \bar{\nu}_e ,$$

$$\nu + N \rightleftarrows \nu + N,$$

$$N + N \rightleftarrows N + N + \nu + \bar{\nu},$$

$$\nu + (A,Z) \rightleftarrows \nu + (A,Z),$$

$$\nu + e^{\pm} \rightleftarrows \nu + e^{\pm},$$

$$\nu + (A,Z) \rightleftarrows \nu + (A,Z)^*,$$

$$e^+ + e^- \rightleftarrows \nu + \bar{\nu},$$

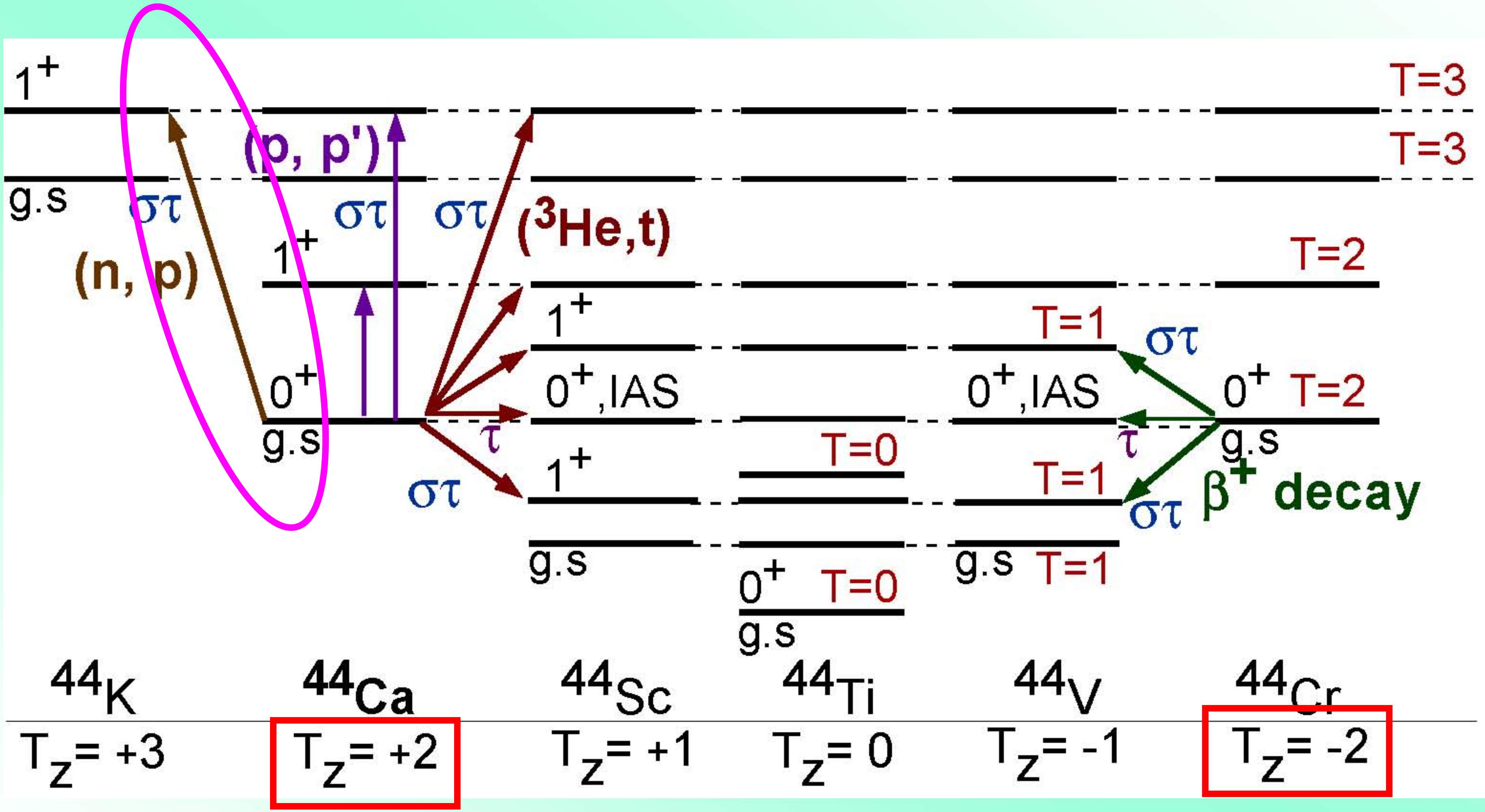
$$(A,Z)^* \rightleftarrows (A,Z) + \nu + \bar{\nu}.$$

(***A***,***Z***)=nuclei in the
Cr, Mn, Fe, Co, Ni region
pf -shell Nuclei !

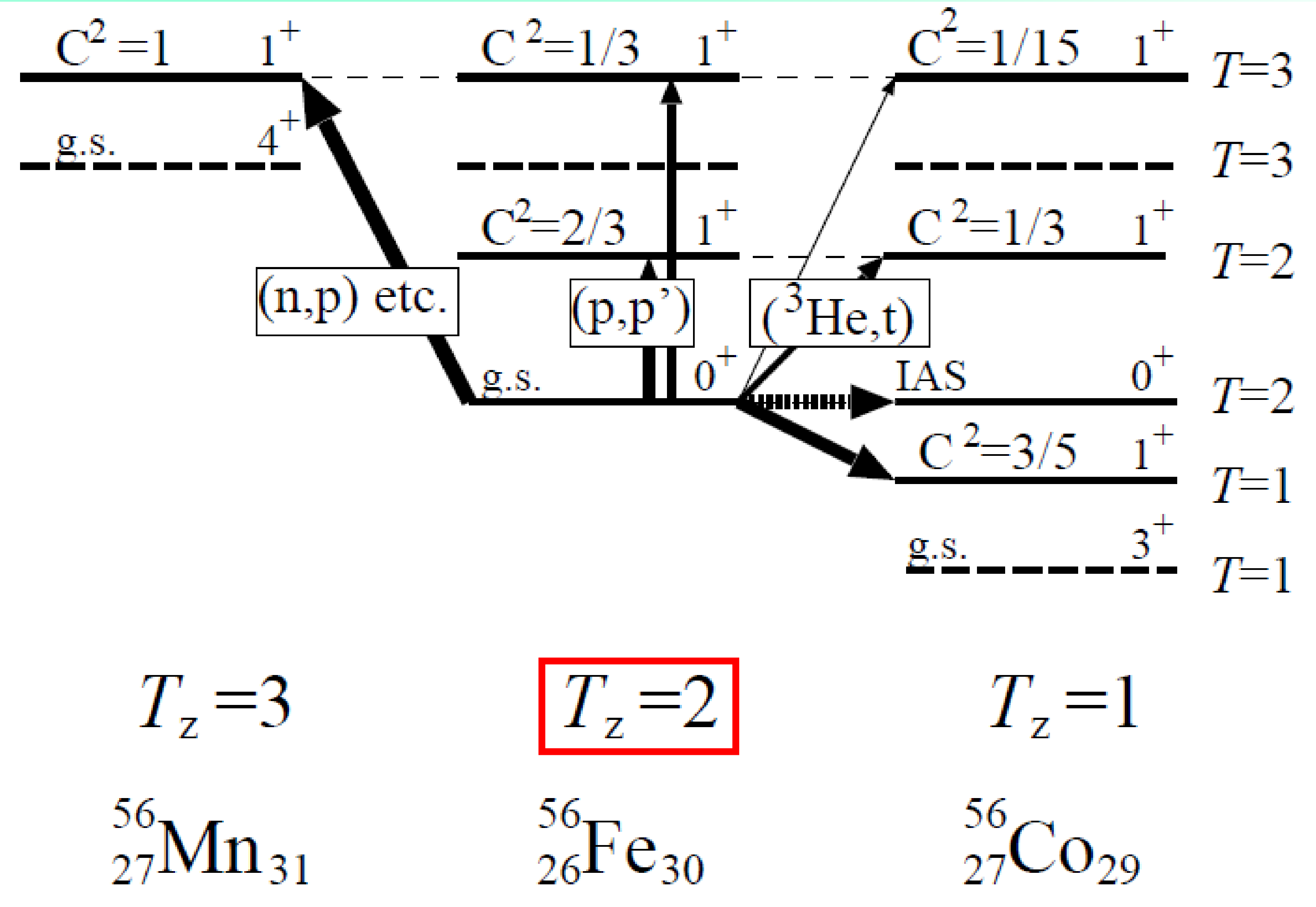
Langanke & Martinez-Pinedo
Rev.Mod.Phys.75('04)819

Balantekin & Fuller
J.Phys.G 29('03)2513

Isospin Structure of T=2 system

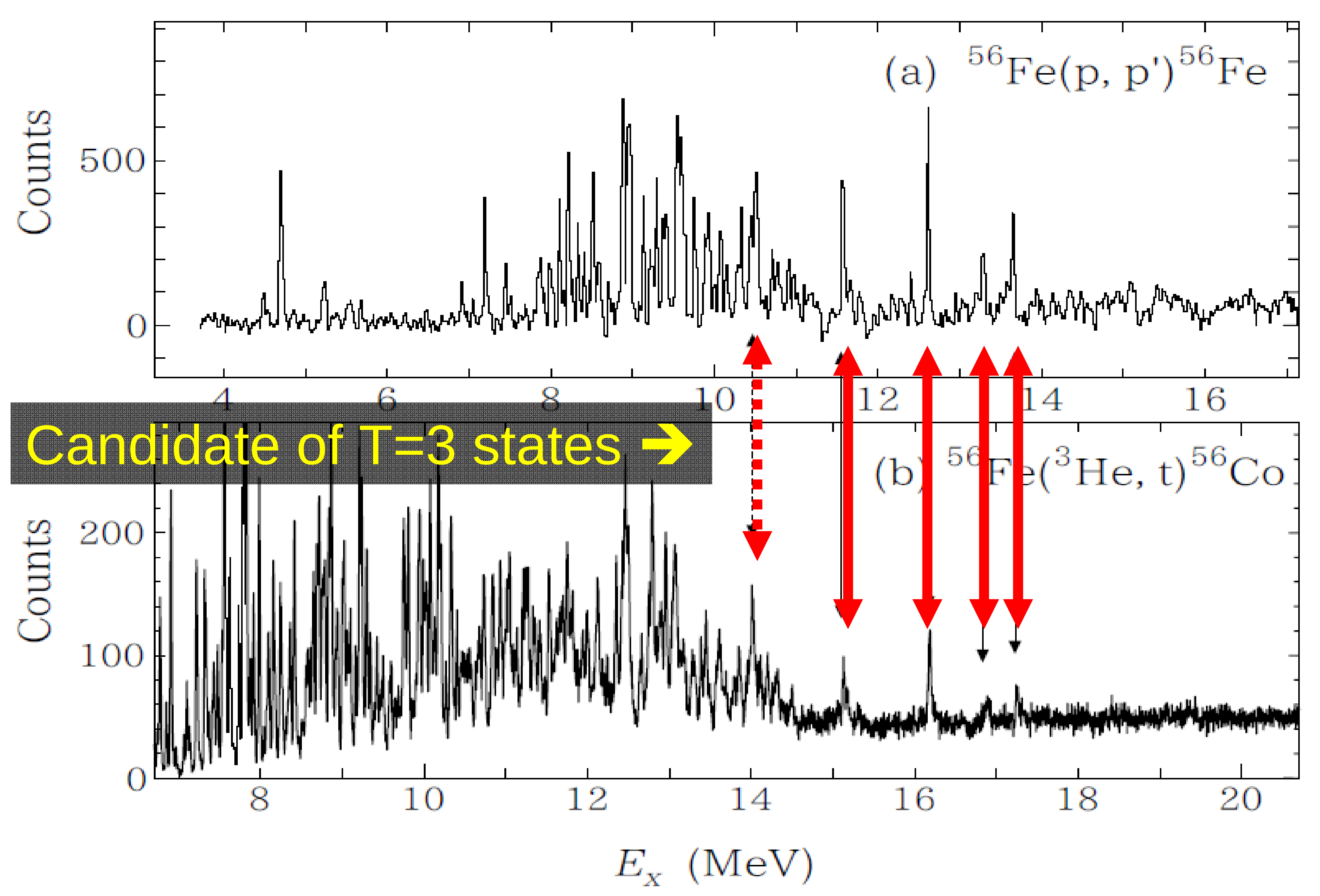


Isospin Structure of T=2 system (CG-coefficients)

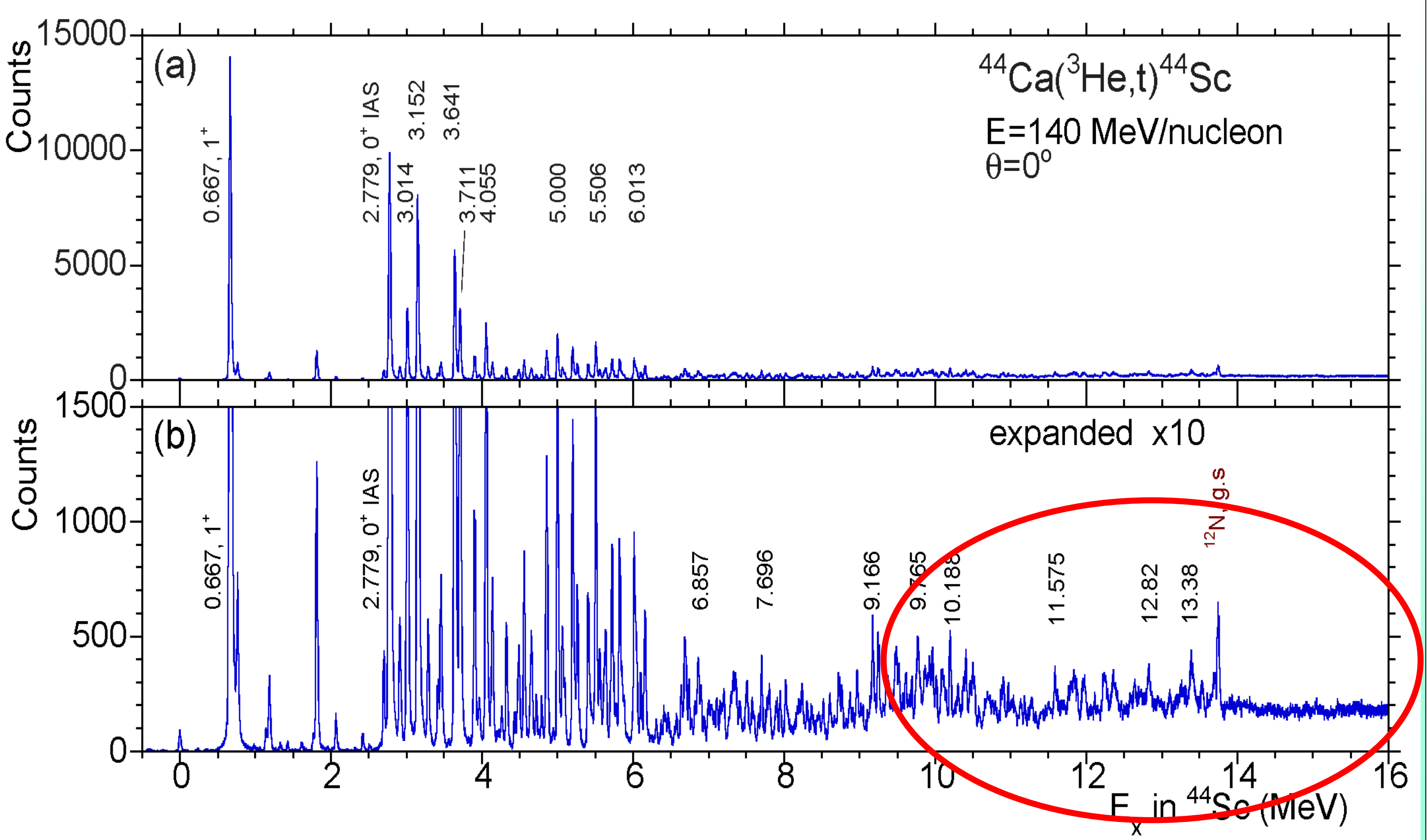


T identification of GT states in A=56

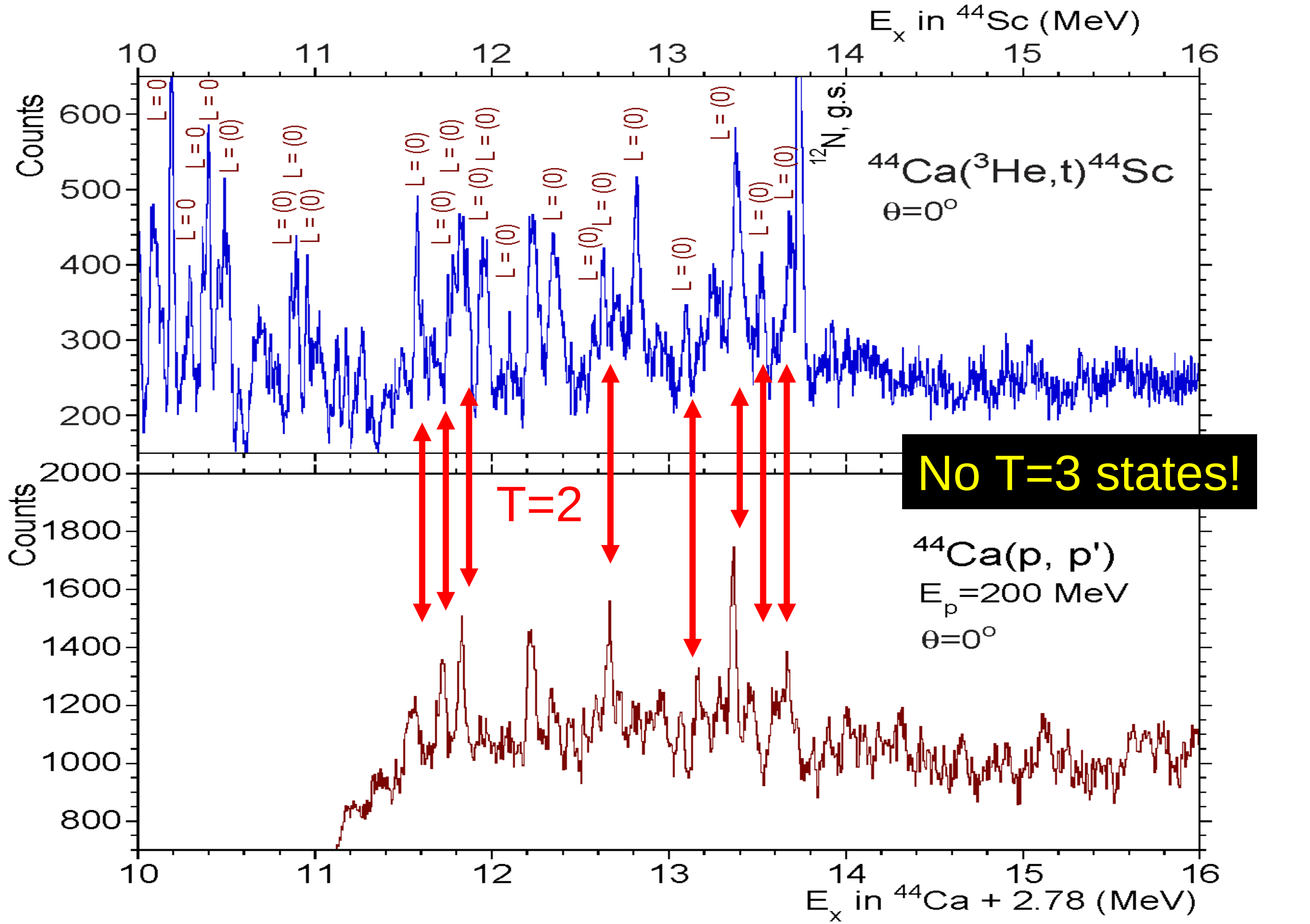
Y.Shimbara & H.Fujita



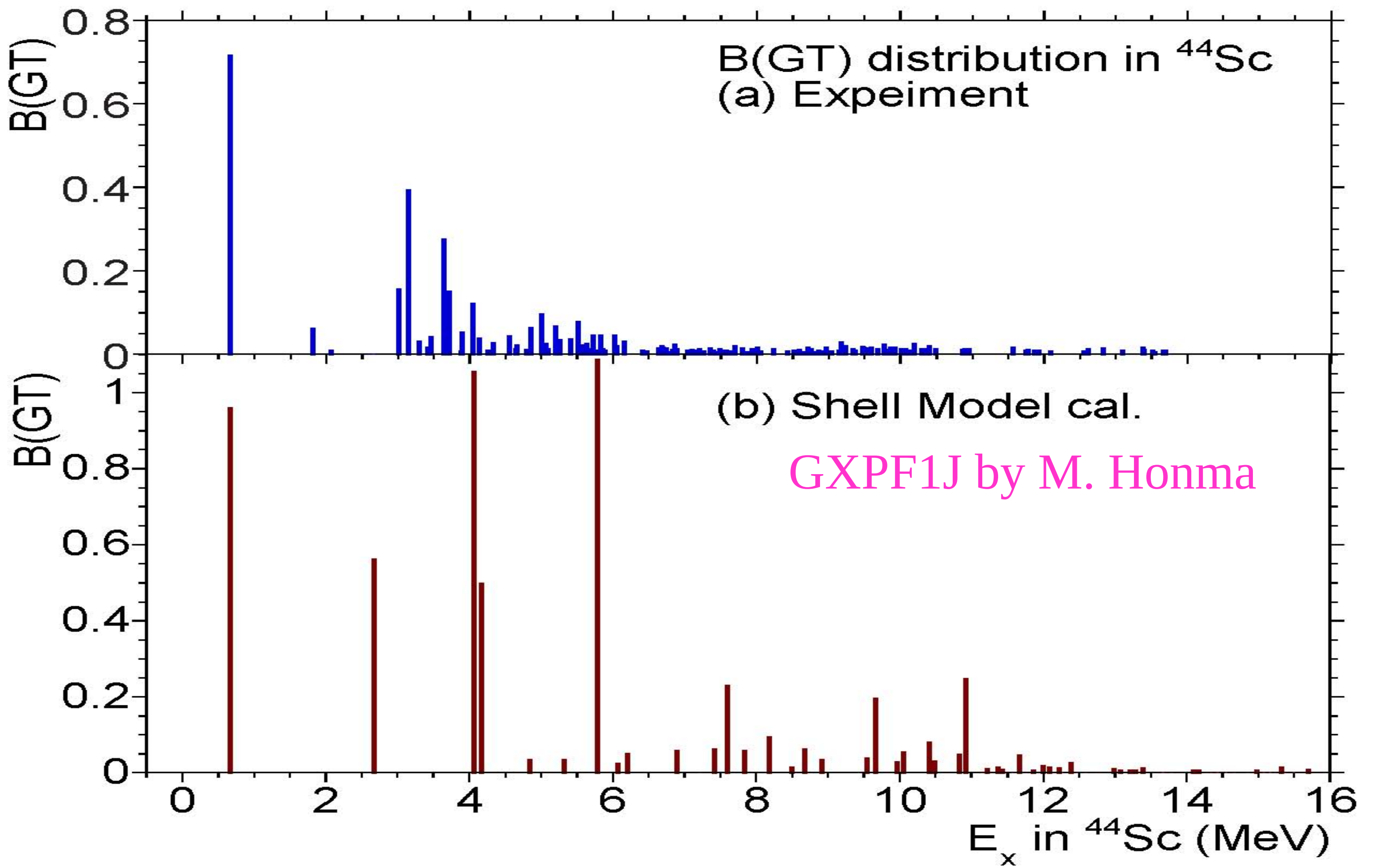
$^{44}Ca(^{3}He,t)^{44}Sc$ spectrum



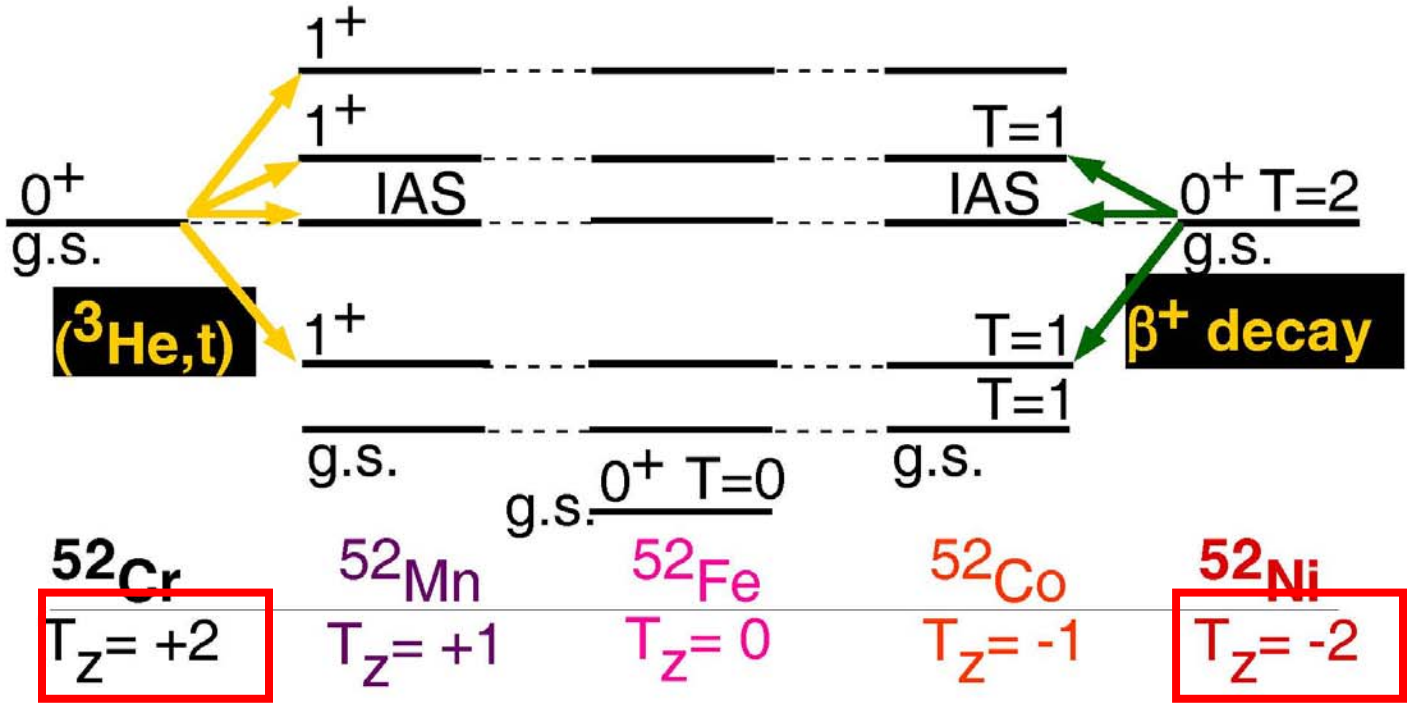
T identification of GT states in A=44



Comparison B(GT): (3He,t) exp vs. SM cal.

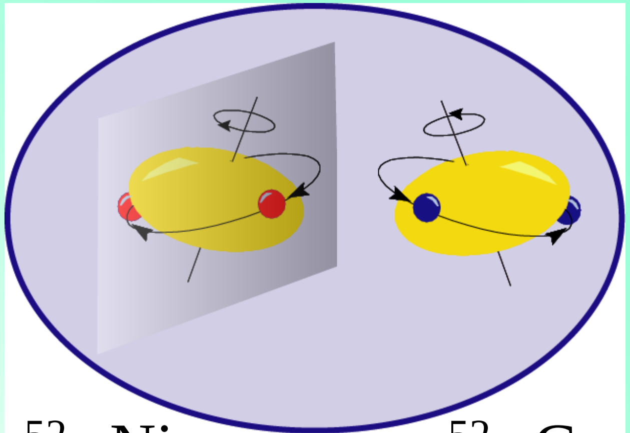


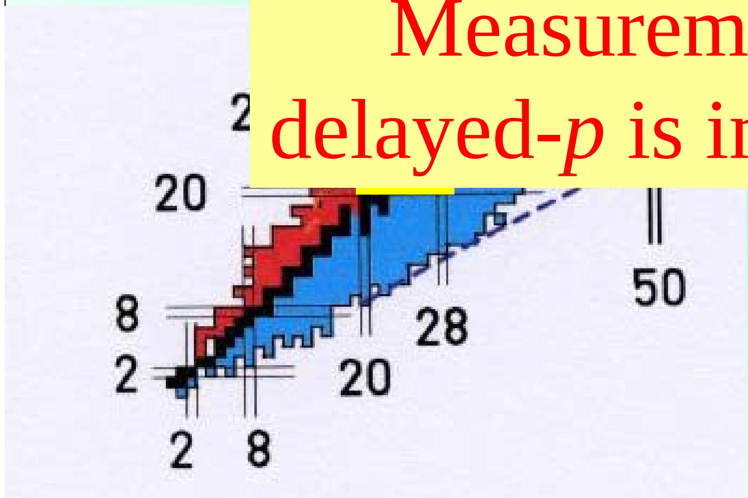
Isospin Structure of T=2 system (low-lying states)



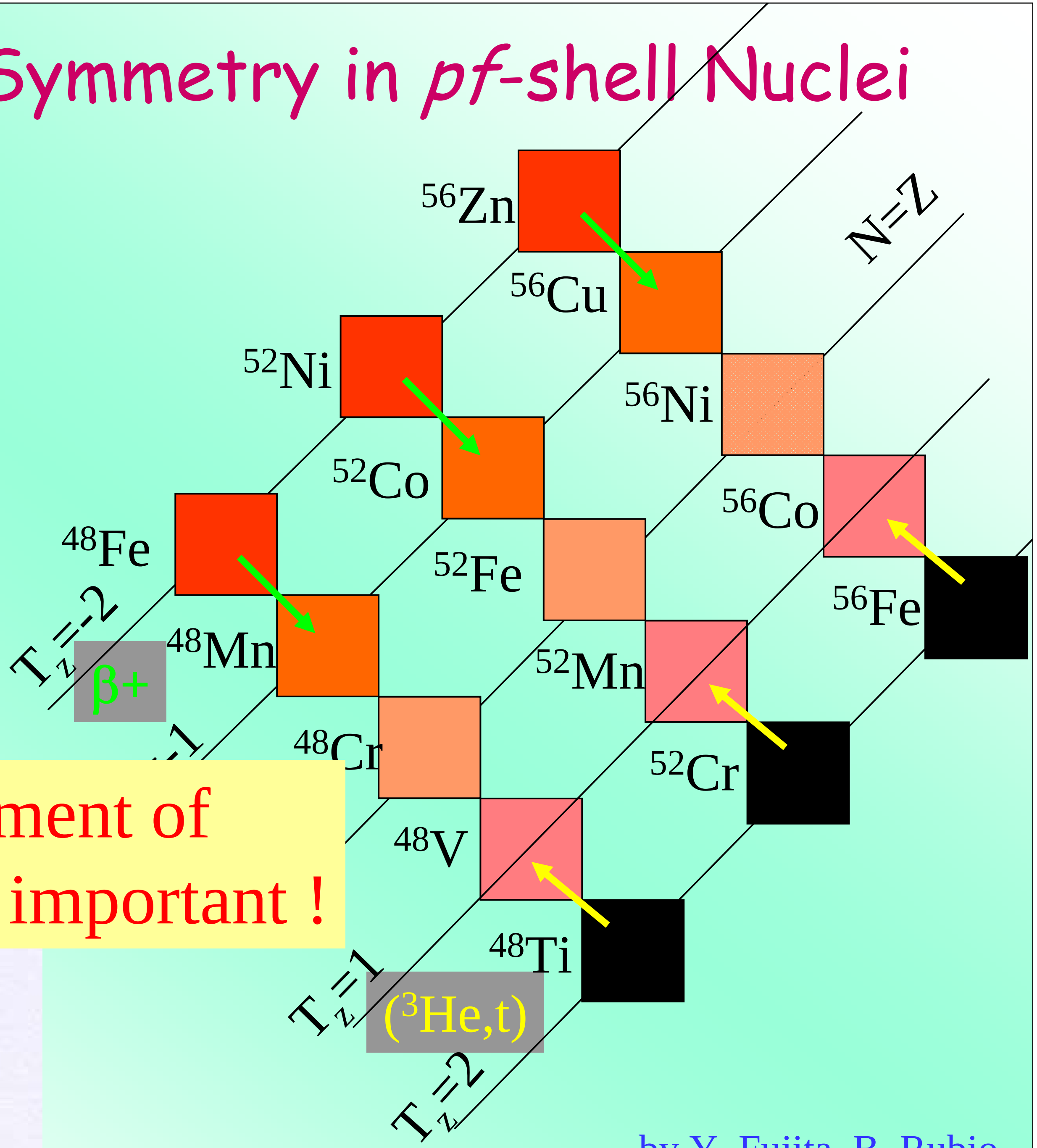
T = 2 Isospin Symmetry in *pf*-shell Nuclei

Mirror nuclei



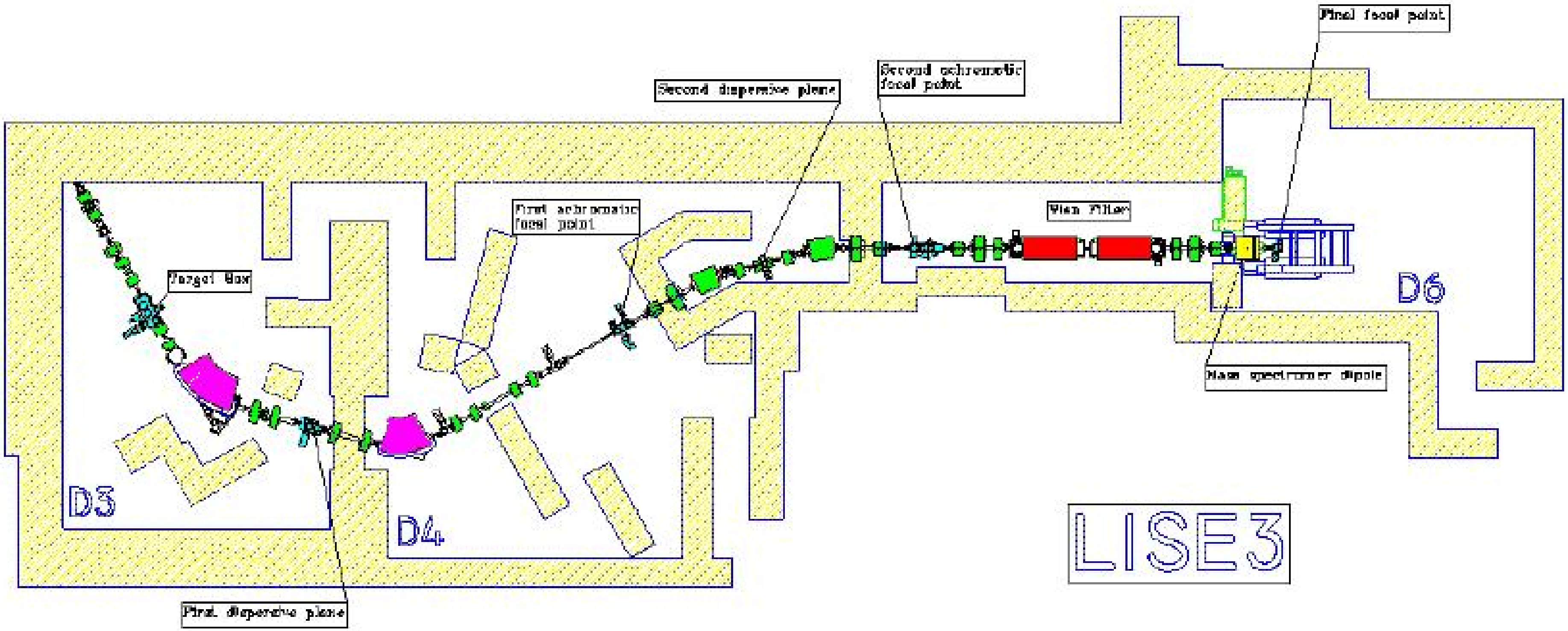


Measurement of delayed-*p* is important !



by Y. Fujita, B. Rubio

GANIL LISE3 fragment separator

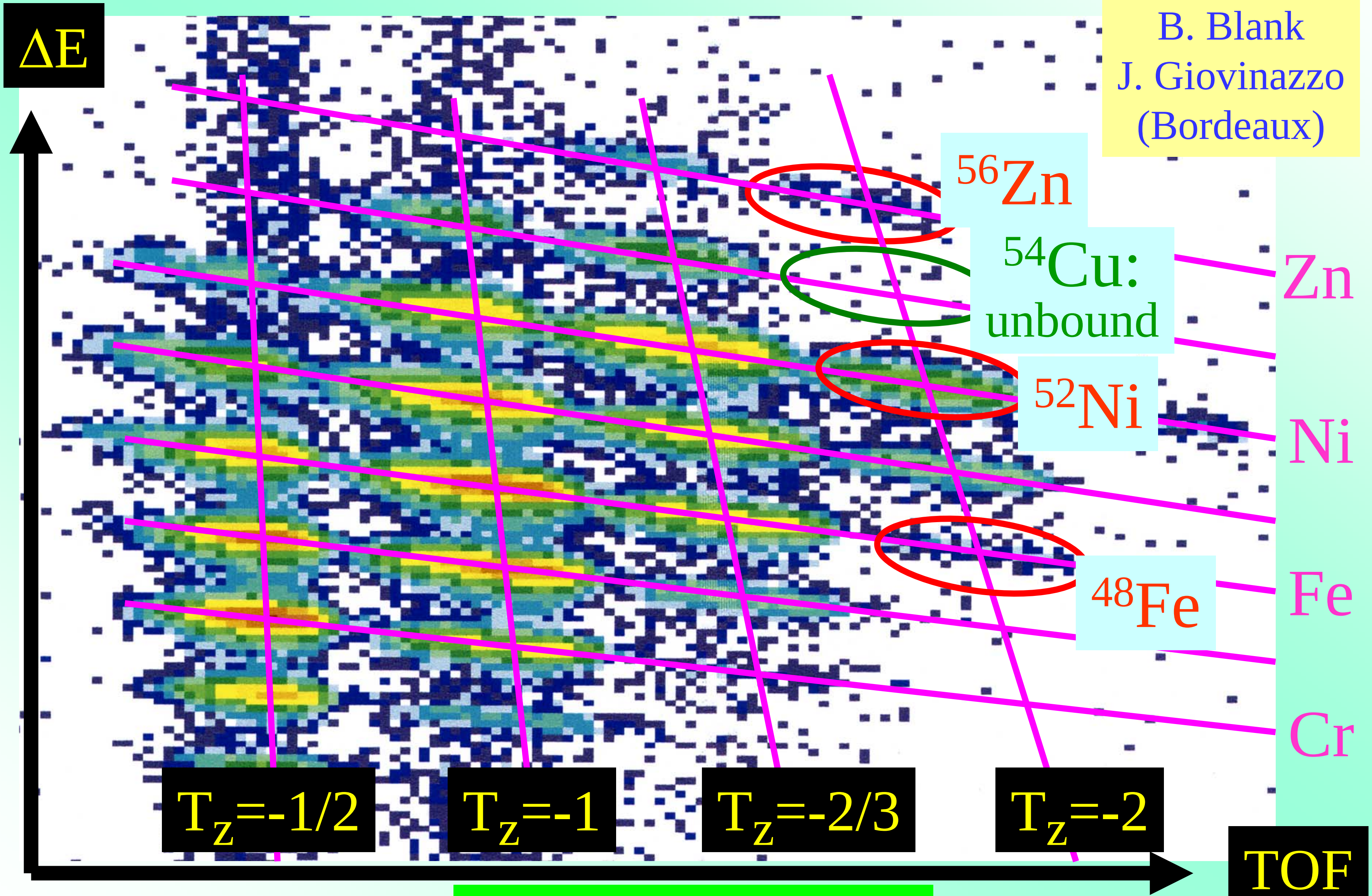


^{58}Ni beam: ~ 79MeV/u, 3.5 eμA,   production target: Ni

p-decay: by DSSD,   γ-decay: by Ge detectors

TOF-ΔE Particle Id. LISE3 GANIL

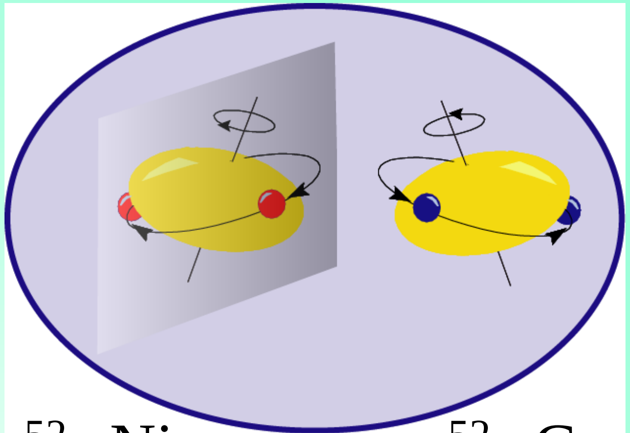
B. Blank
J. Giovinazzo
(Bordeaux)



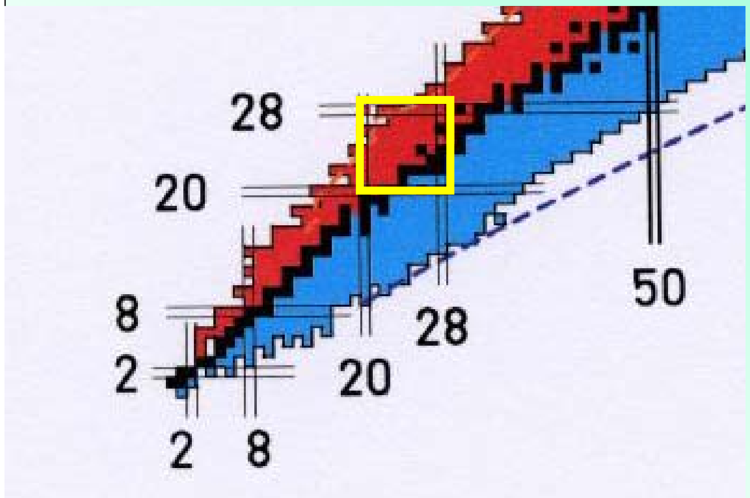
October, 2010

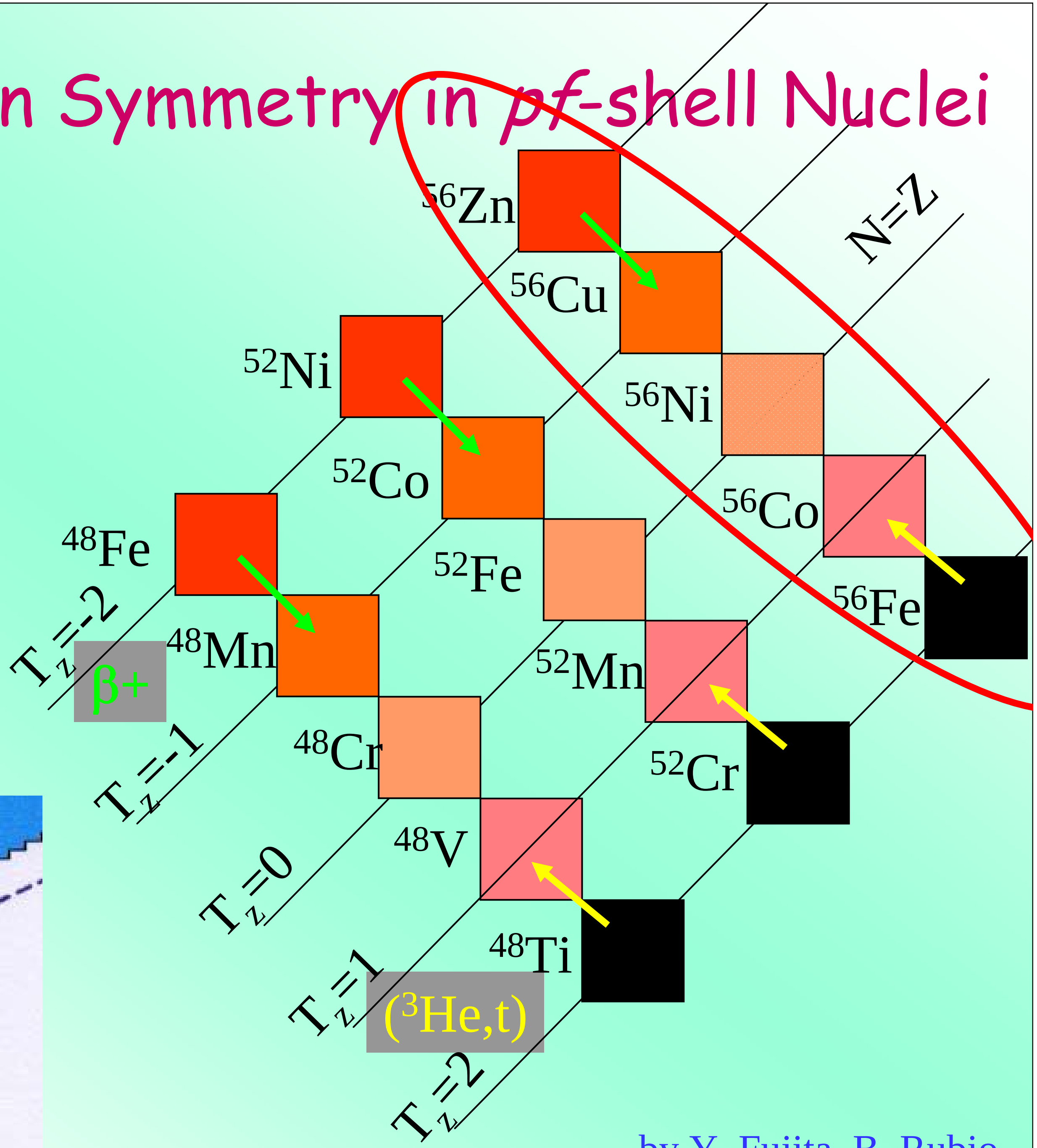
T = 2 Isospin Symmetry in *pf*-shell Nuclei

Mirror nuclei



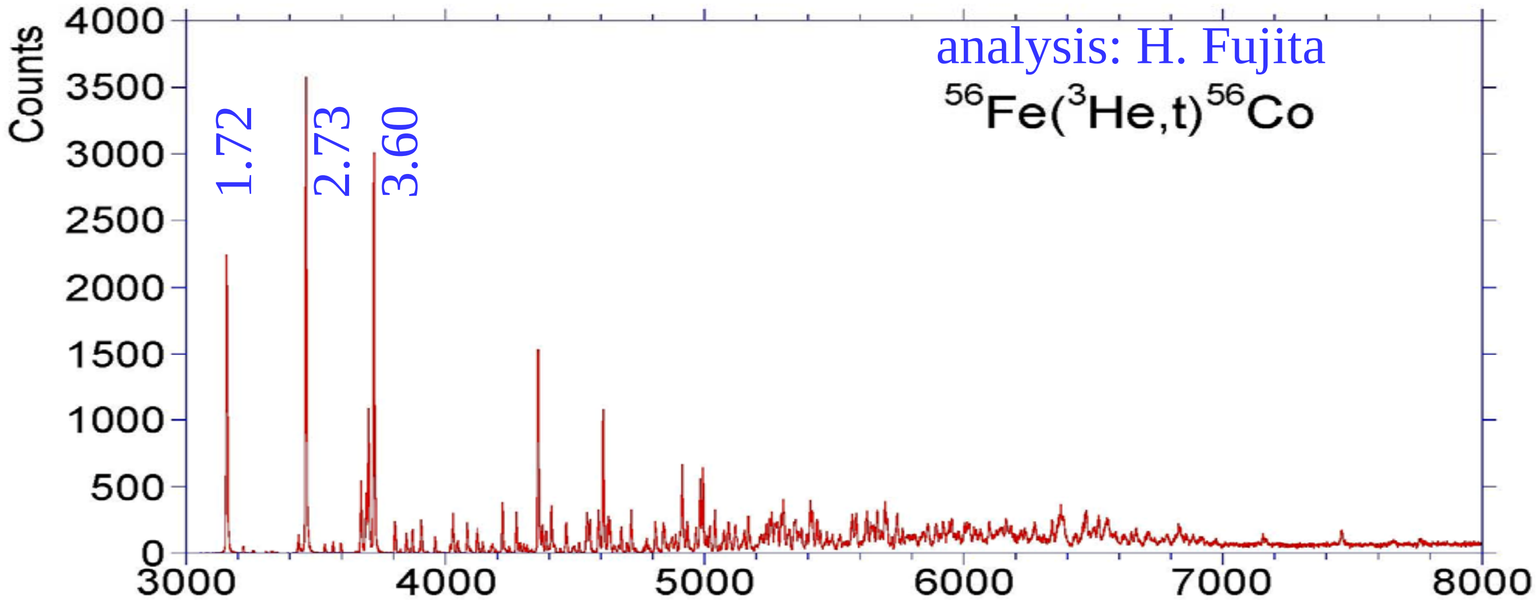
$^{52}_{28}Ni_{24}$ $^{52}_{24}Cr_{28}$

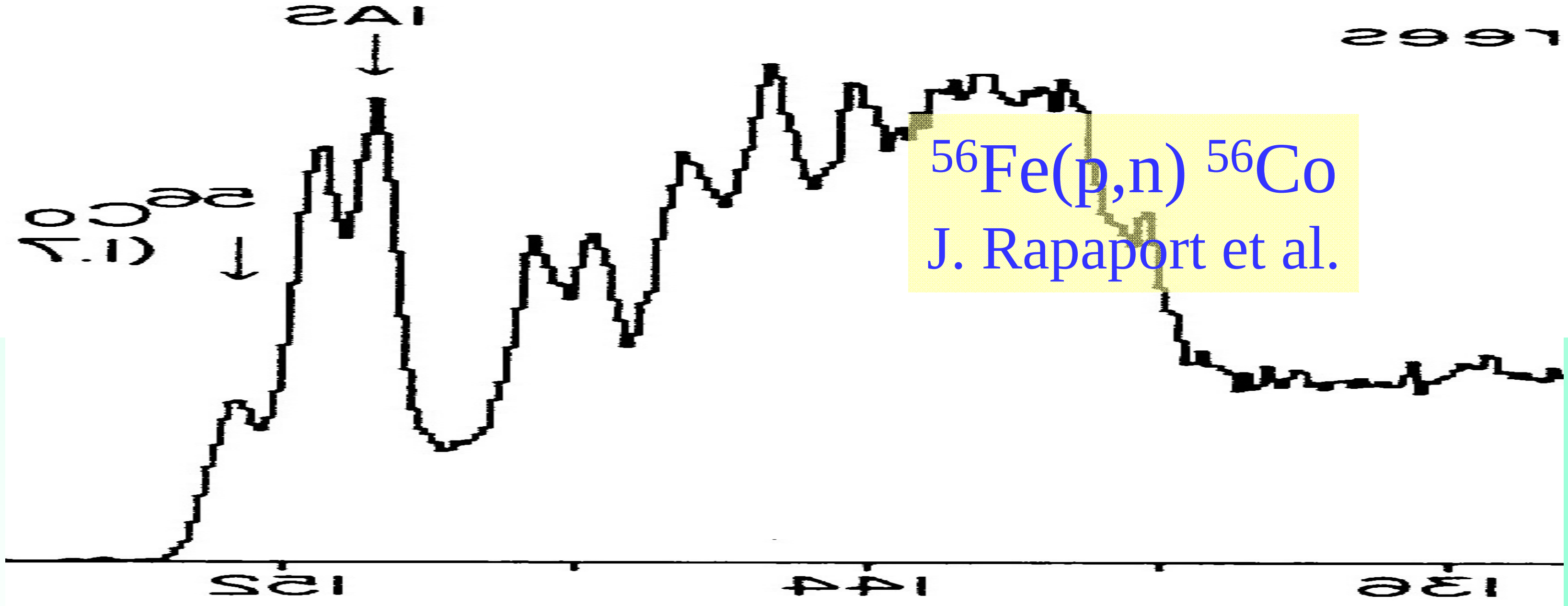




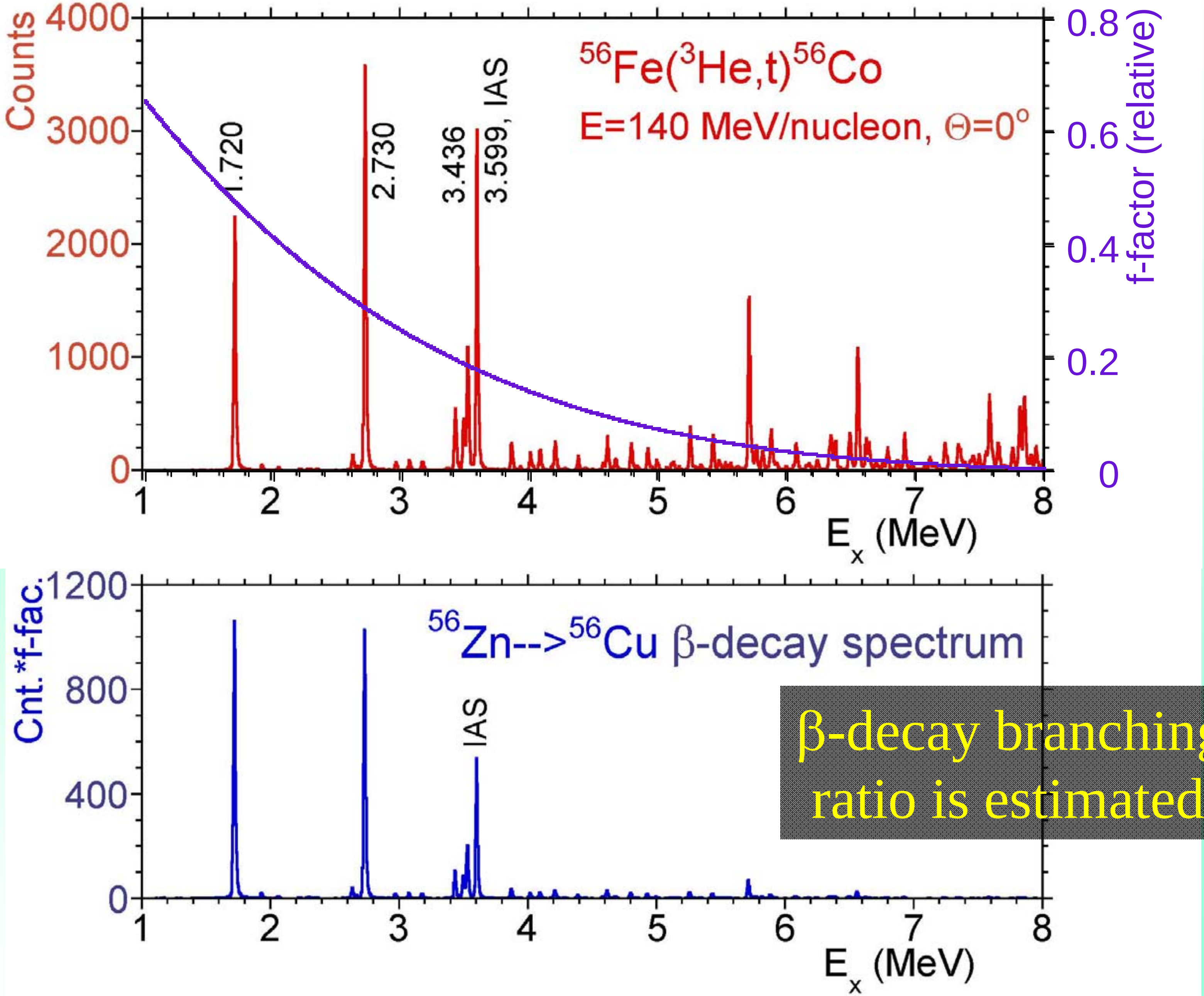
by Y. Fujita, B. Rubio

$^{56}Fe(p,n)^{56}Co$ & $^{56}Fe(^{3}He,t)^{56}Co$



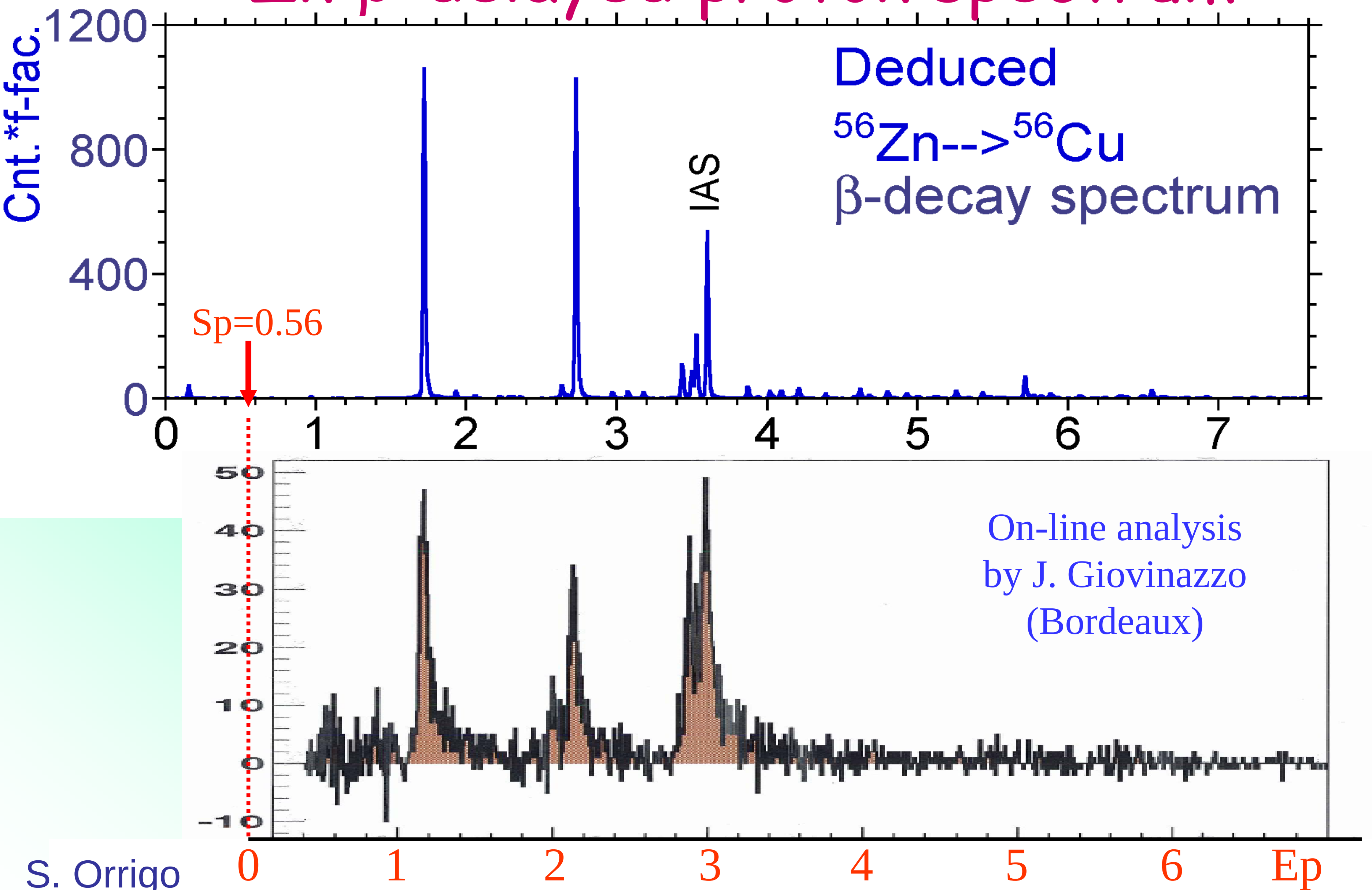


$^{56}Fe(^{3}He,t)$ and ^{56}Zn β-decay



β-decay branching ratio is estimated!

^{56}Zn β-delayed proton spectrum



S. Orrigo
(Valencia)

GANIL, October, 2010

Summary

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

* GT transitions: sensitive to the structure of |i> and |f>
* Isospin quantum number *T* plays an important role

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

* Width & fine structures of GT transitions
* Precise comparison with mirror β-decay results

➔ GT transitions in each nucleus are UNIQUE !
➔ Assuming T-symmetry → GT in unstable nuceli !

GT transitions:
- transitions with full of personality -

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

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

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

Y. Fujita [a,*], B. Rubio [b], W. Gelletly [c]

[a] *Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[b] *IFIC, CSIC-University of Valencia, E-46071 Valencia, Spain*
[c] *Department of Physics, University of Surrey, Guildford GU2 7XH, Surrey, UK*

PPNP
66 (2011) 549