Weak Interaction in Nuclear Astrophysics
-Main actor: Gamow-Teller transitions-

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Euro. SS on Exp. Nucl. Astrophysics
Santa Tecla, Italy, Sep. 18 – Sep.27 , 2011

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

- ✧Representing "Spin Isospin" response of nuclei,
  that 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

Crucial Weak Processes during the Core Collapse

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

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

$$(A,Z) + e^- \rightleftarrows (A,Z-1) + \nu_e ,$$

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

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

$$N + \ldots$$

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

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

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

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

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

(***A***,***Z***)=nuclei in the Fe, Ni region

β-decay, e-capture,
ν-induced reactions

mainly by τ & στ

↓

Gamow-Teller (GT) transitions

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

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

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 !

***Nucleus = Bell

Operators = Hammers ??

*$B(Op)$ *ex.* B(E1), B(M1), B(GT)…

Reduced Transition Strength

$\propto |\langle f \,|\mathbf{Op}|\, i\rangle|^2$

*various kinds of Operators (*Op*)

Various Operators / Various Hammers!

wooden hammers

metal hammers

hammers
=operators

The sound from the bell is different depending on hammas!

The mode of nuclear excitation is decided by an operator!

Various Reaction Mechanism / How and Where you hit the bell!

how and where you hit
=reaction mechanism

The sound from the bell is different how and where you hit!

The strength of nuclear excitation is dependent on them!

Vibration Modes in Nuclei (Operators)

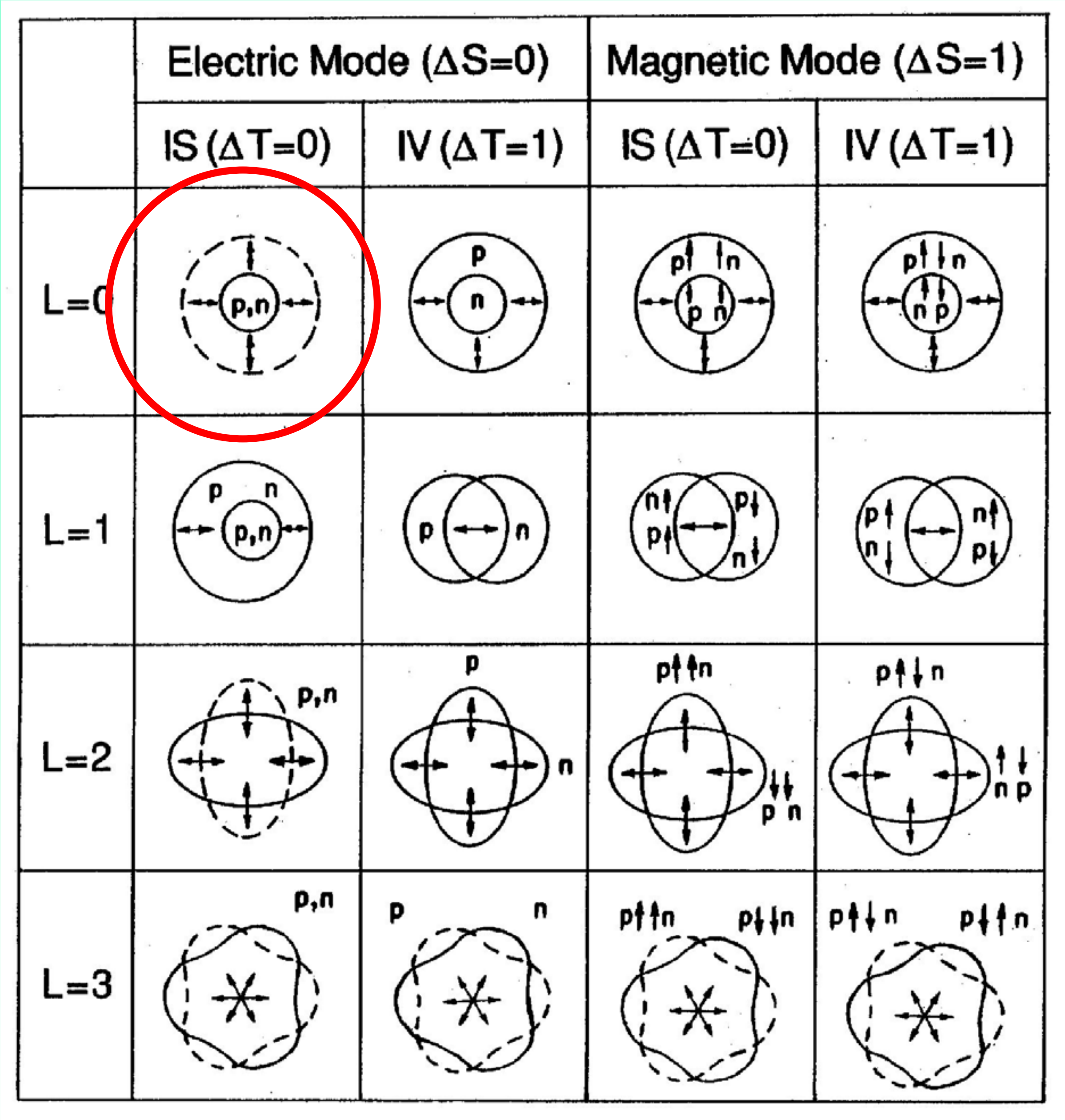
Microscopic classification of giant resonances

	ΔS = 0, ΔT = 0	ΔS = 0, ΔT = 1	ΔS = 1, ΔT = 0	ΔS = 1, ΔT = 1
L = 0		$\sum \tau_i$ IAS		$\sum \vec{\sigma}_i \tau_i$ GTR
2nd order	$\sum r_i^2$ ISGMR	$\sum r_i^2 \tau_i$ IVGMR	$\sum r_i^2 \vec{\sigma}_i$ ISSMR	$\sum r_i^2 \vec{\sigma}_i \tau_i$ IVSMR
L = 1		$\sum r_i Y_m^1 \tau_i$ IVGDR	$\sum r_i Y_m^1 \vec{\sigma}_i$ ISSDR	$\sum r_i Y_m^1 \vec{\sigma}_i \tau_i$ IVSDR
2nd order	$\sum r_i^3 Y_m^1$ ISGDR			
L = 2	$\sum r_i^2 Y_m^2$ ISGQR	$\sum r_i^2 Y_m^2 \tau_i$ IVGQR	$\sum r_i^2 Y_m^2 \vec{\sigma}_i$ ISSQR	$\sum r_i^2 Y_m^2 \vec{\sigma}_i \tau_i$ IVSQR
L = 3	$\sum r_i^3 Y_m^3$ ISGOR	$\sum r_i^3 Y_m^3 \tau_i$ IVGOR	$\sum r_i^3 Y_m^3 \vec{\sigma}_i$ ISSOR	$\sum r_i^3 Y_m^3 \vec{\sigma}_i \tau_i$ IVSOR

ΔS=1:
spin excitation

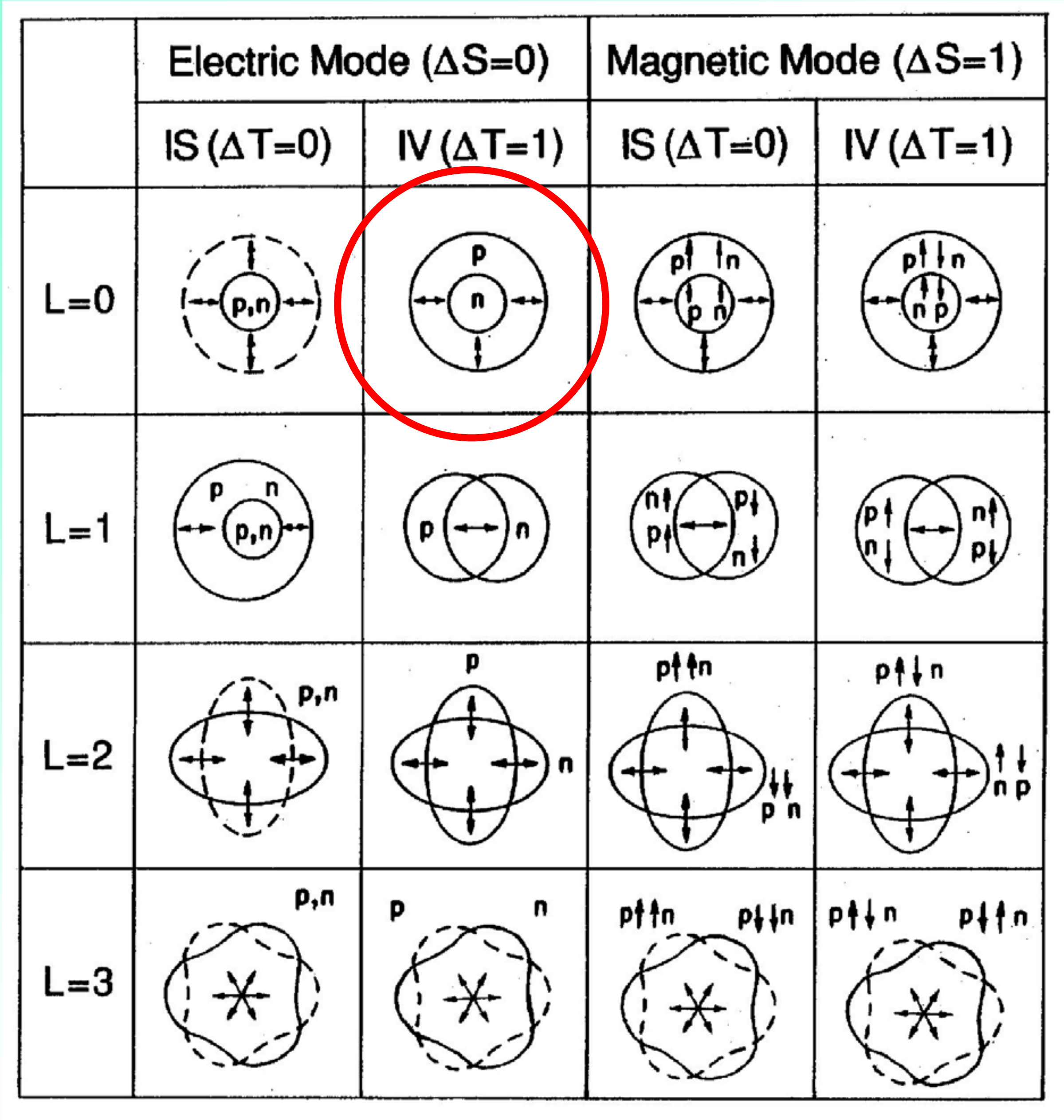
ΔT=1:
IV excitation
(isospin related!)

Vibration Modes in Nuclei (Schematic)



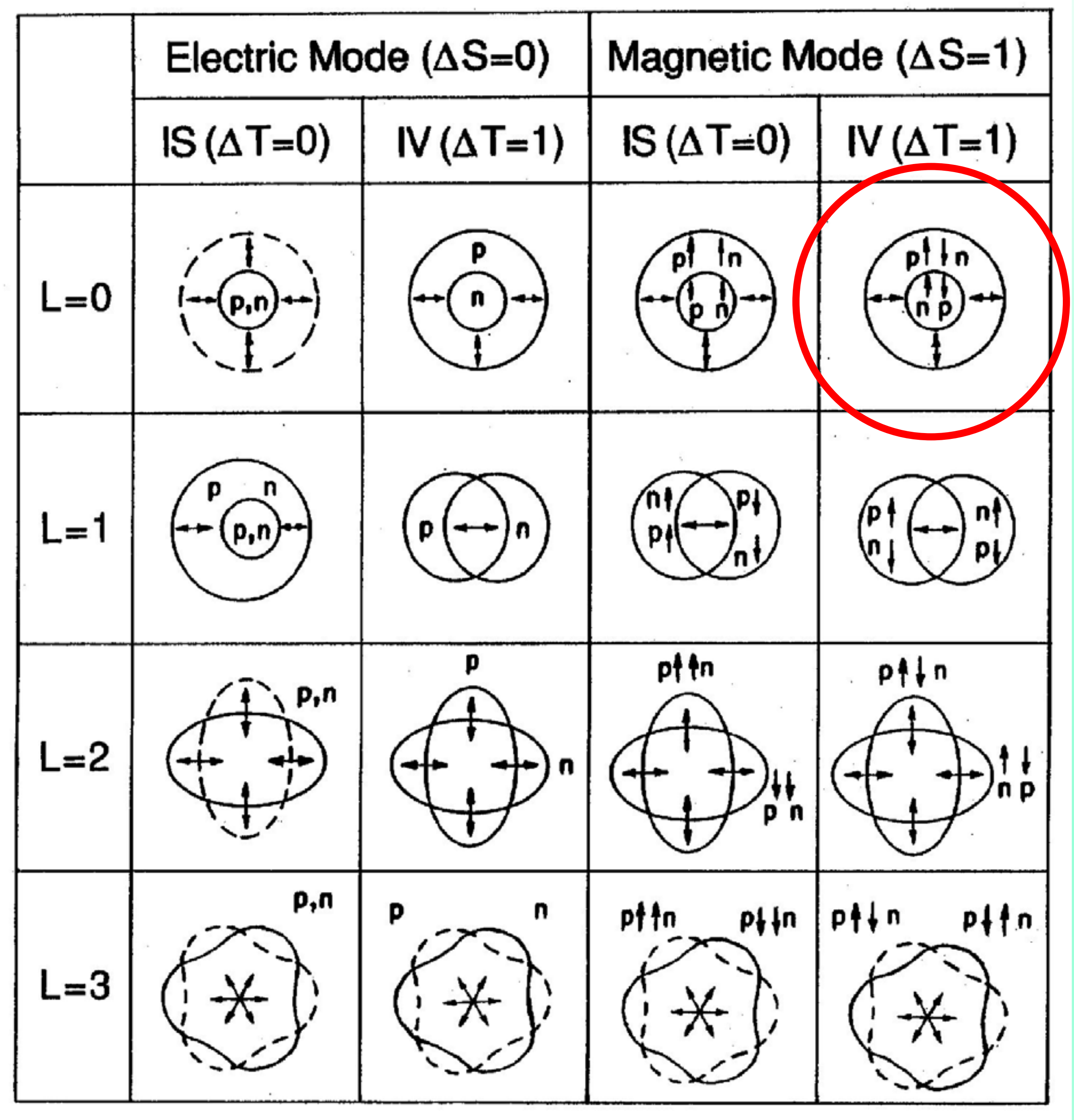
IS-Giant Monopole Resonance (GMR)

Vibration Modes in Nuclei (Schematic)



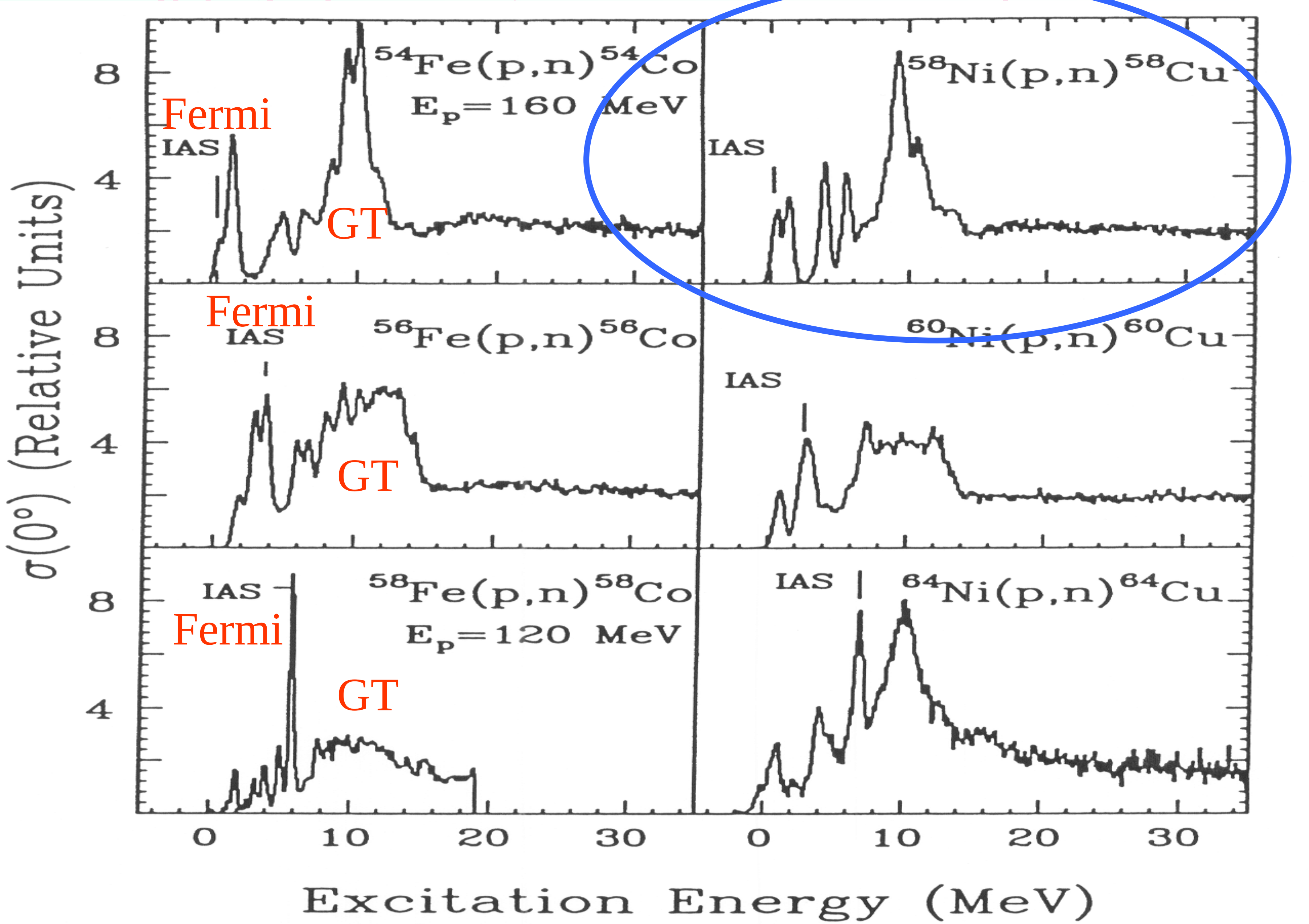
IV-Giant Monopole Resonance (IVGMR)

Vibration Modes in Nuclei (Schematic)

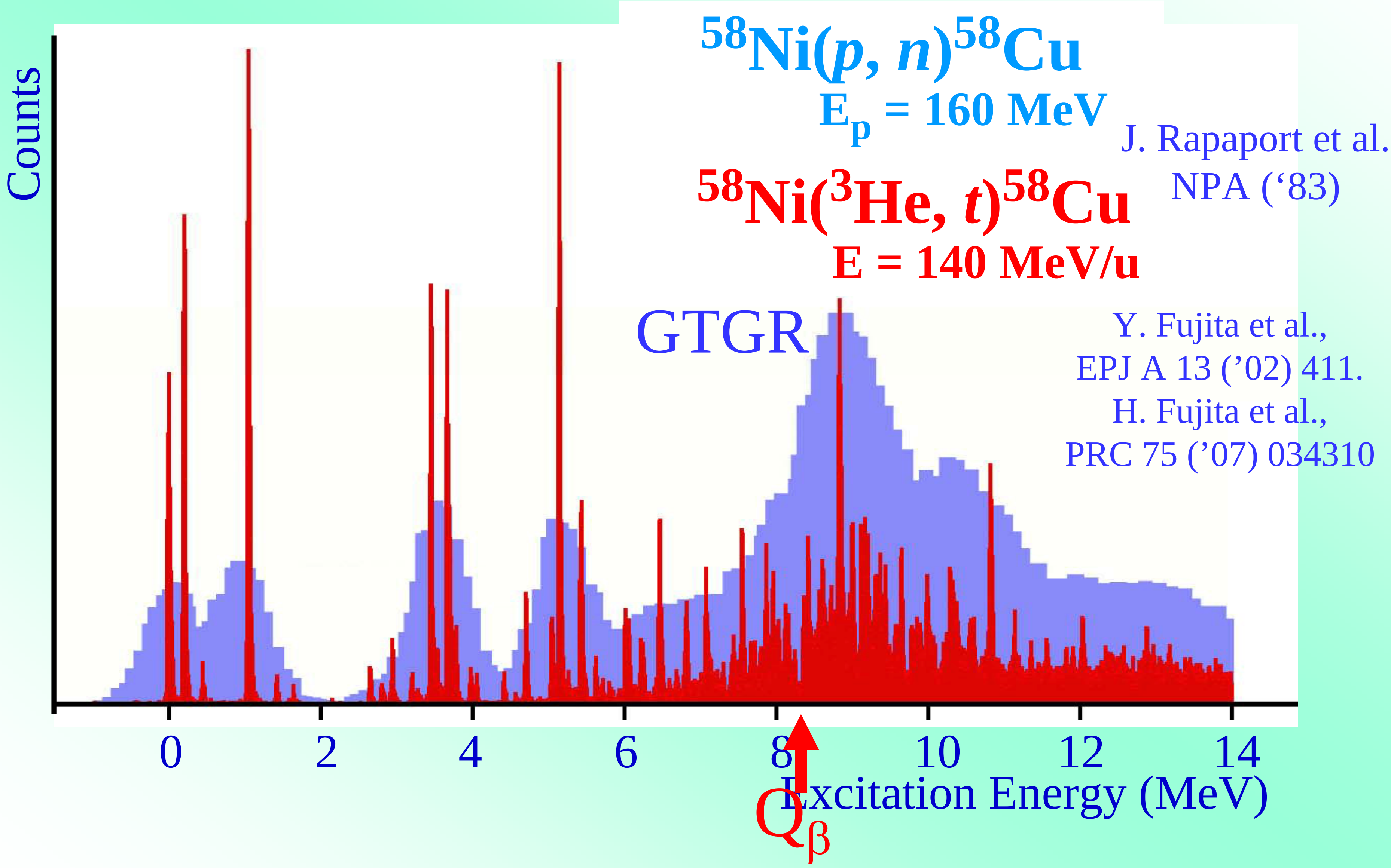


Gamow-Teller mode
($\sigma\tau$)

(p, n) spectra for Fe and Ni Isotopes



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



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

β decays :

Absolute *B*(GT) values,

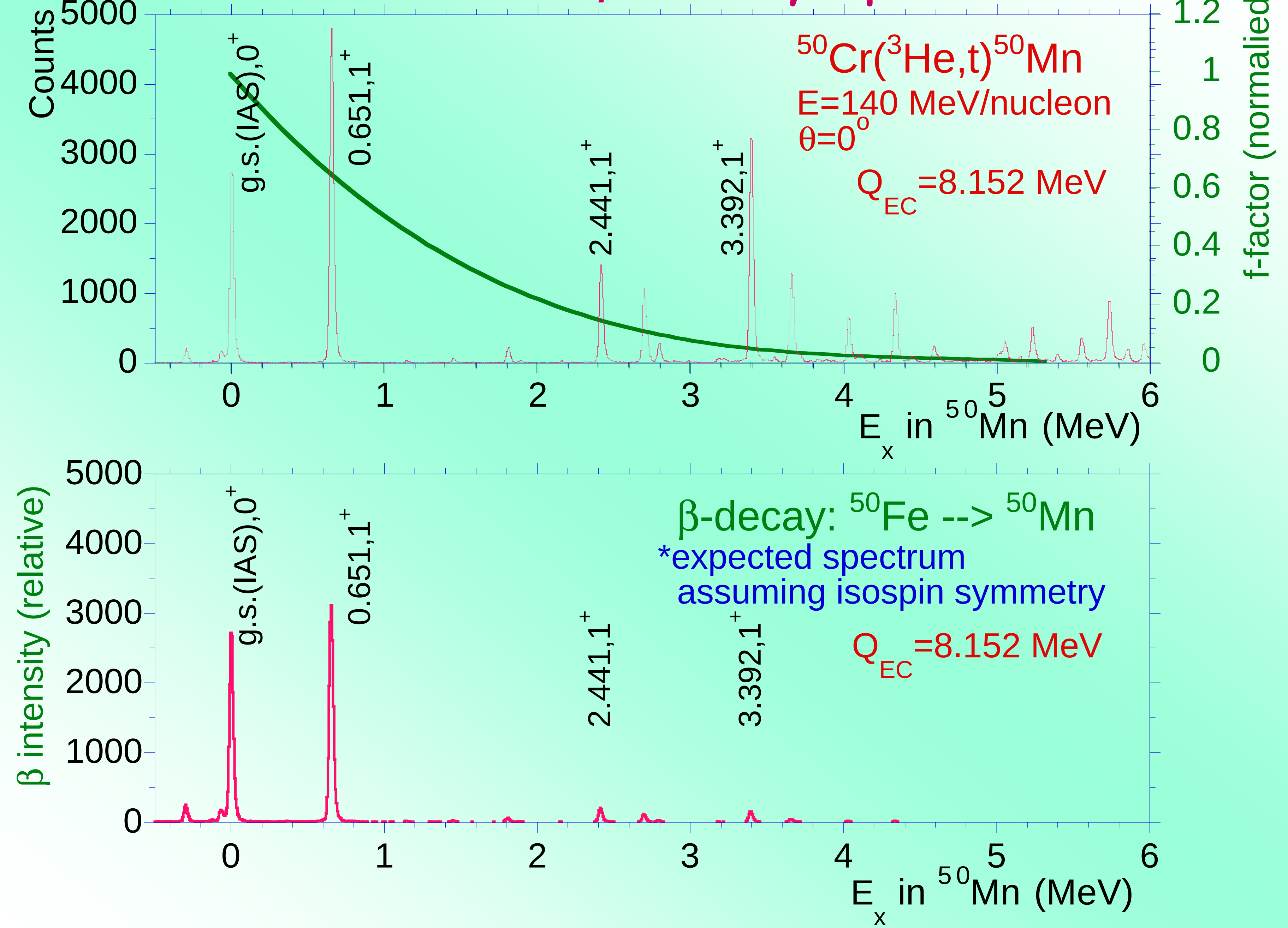
but usually the study is limited to low-lying state

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

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

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

Simulation of β-decay spectrum



β-decay transition strength

* β-decay transition strength

$$\frac{K}{ft_{1/2}} = B(\mathrm{GT})\lambda^2 + B(\mathrm{F}) \quad \text{where} \quad \lambda = \frac{g_A}{g_V}$$

then

$$\frac{1}{t_{1/2}} = \frac{f}{Kg_V^2}[g_A^2 B(\mathrm{GT}) + g_V^2 B(\mathrm{F})]$$

transition strength

coupling constants

where

$$B(\mathrm{GT}) \propto |< f \,|\, \sigma\tau \,|\, i >|^2$$

$$B(\mathrm{F}) \propto |< f \,|\, \tau \,|\, i >|^2$$

β-decay & Nuclear Reaction

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

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

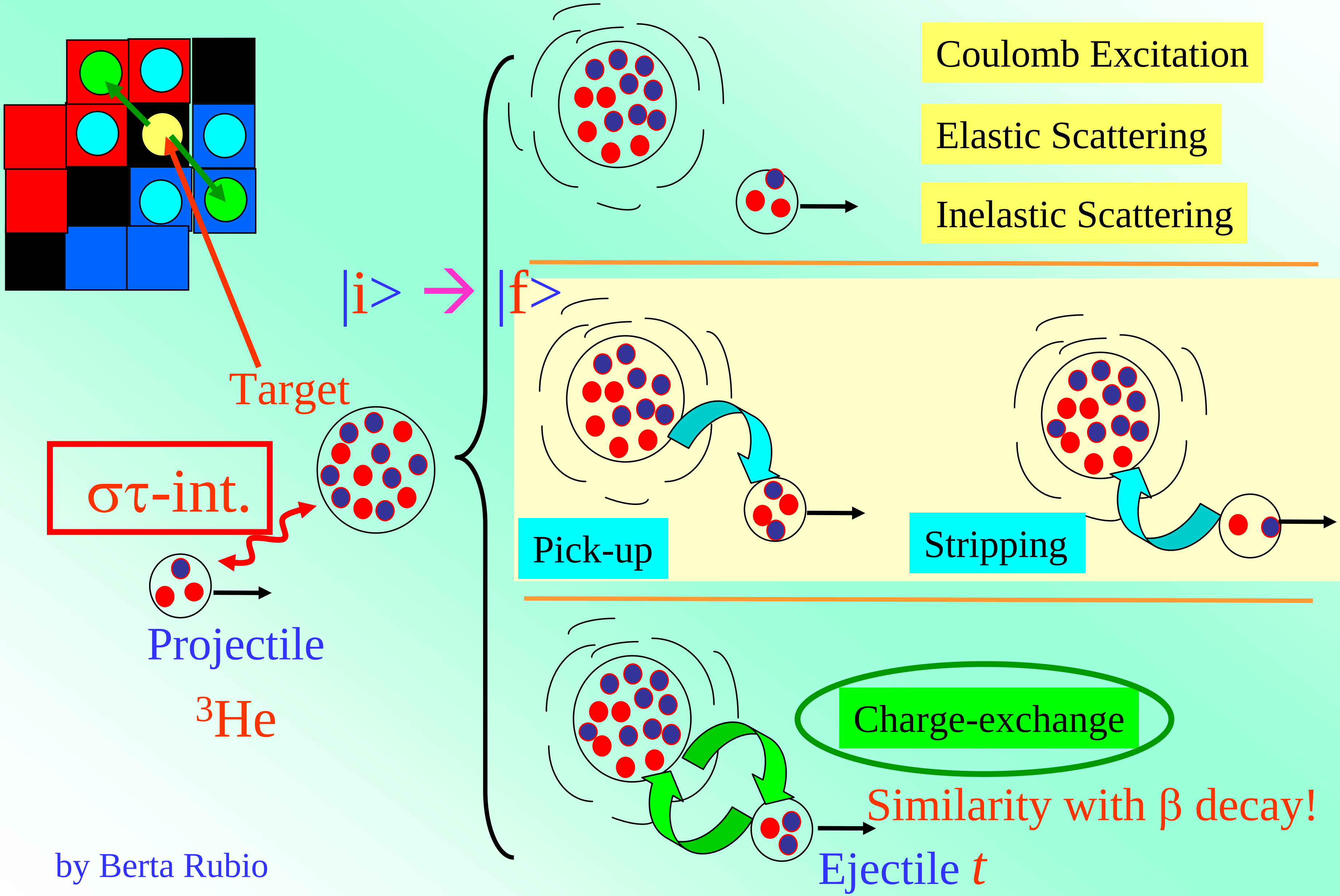
*At intermediate energies (100 < E_{in} < 500 MeV)

➡ dσ/dω(q=0) : proportional to B(GT)

Nuclear Excitations
by
Charge Exchange Reaction
and β-Decay

Study of Weak Response of Nuclei
by means of
Strong Interaction !?

Direct Reactions with Light Projectiles



by Berta Rubio

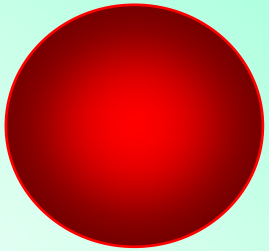
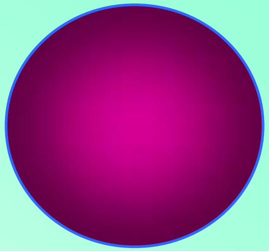
Connection between β-decay and (^{3}He,t) reaction

by means of
Isospin Symmetry

Nuclei & Coin

back front

= Coin

= Isomer

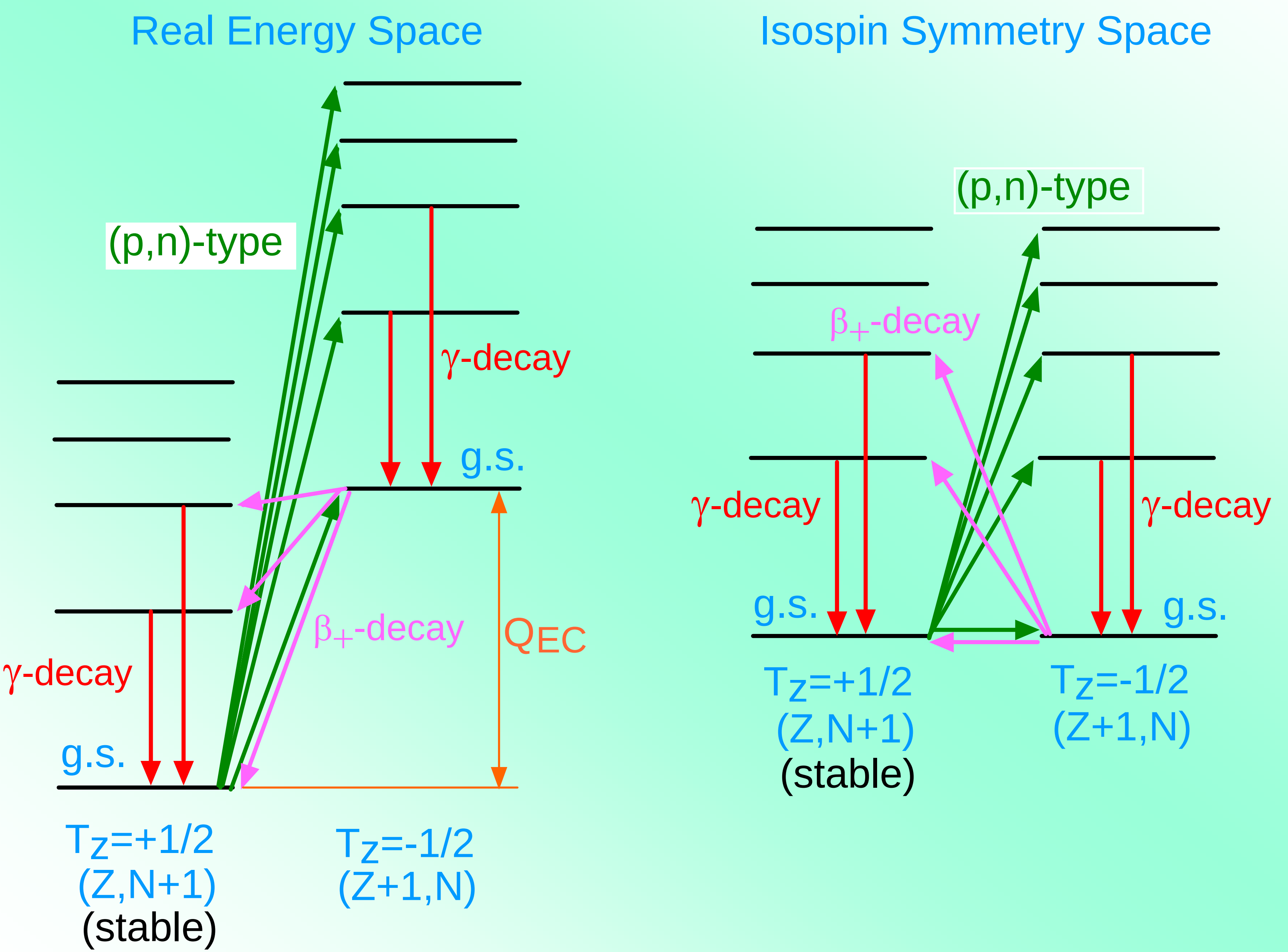
$^{27}_{13}Al_{14}$ $^{27}_{14}Si_{13}$

$T_z = (1/2)N + (-1/2)Z$

*z-component: conserved

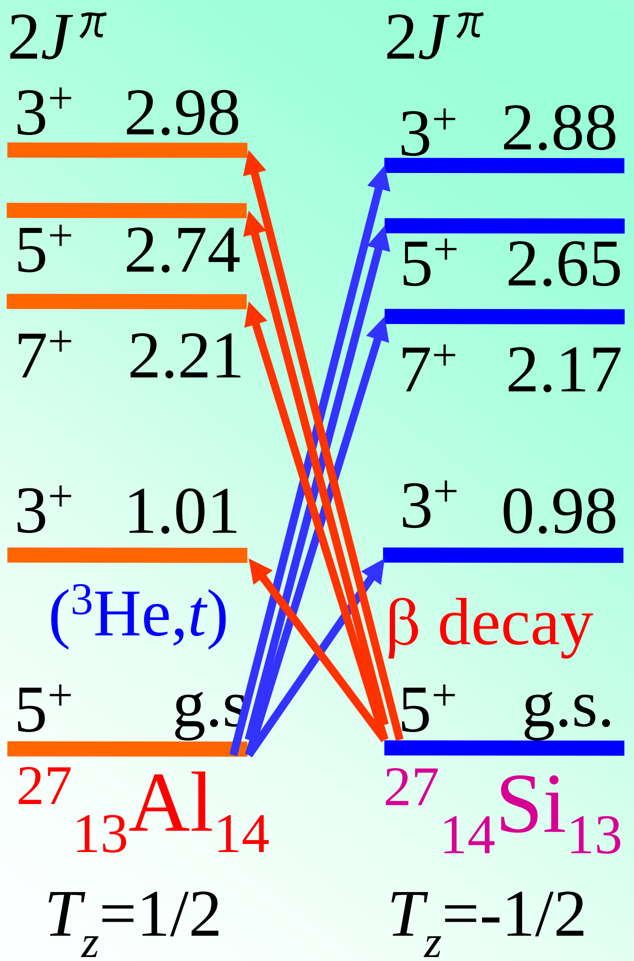
$T_z=1/2$ $T_z= -1/2$ isospin T=1/2, 3/2, …

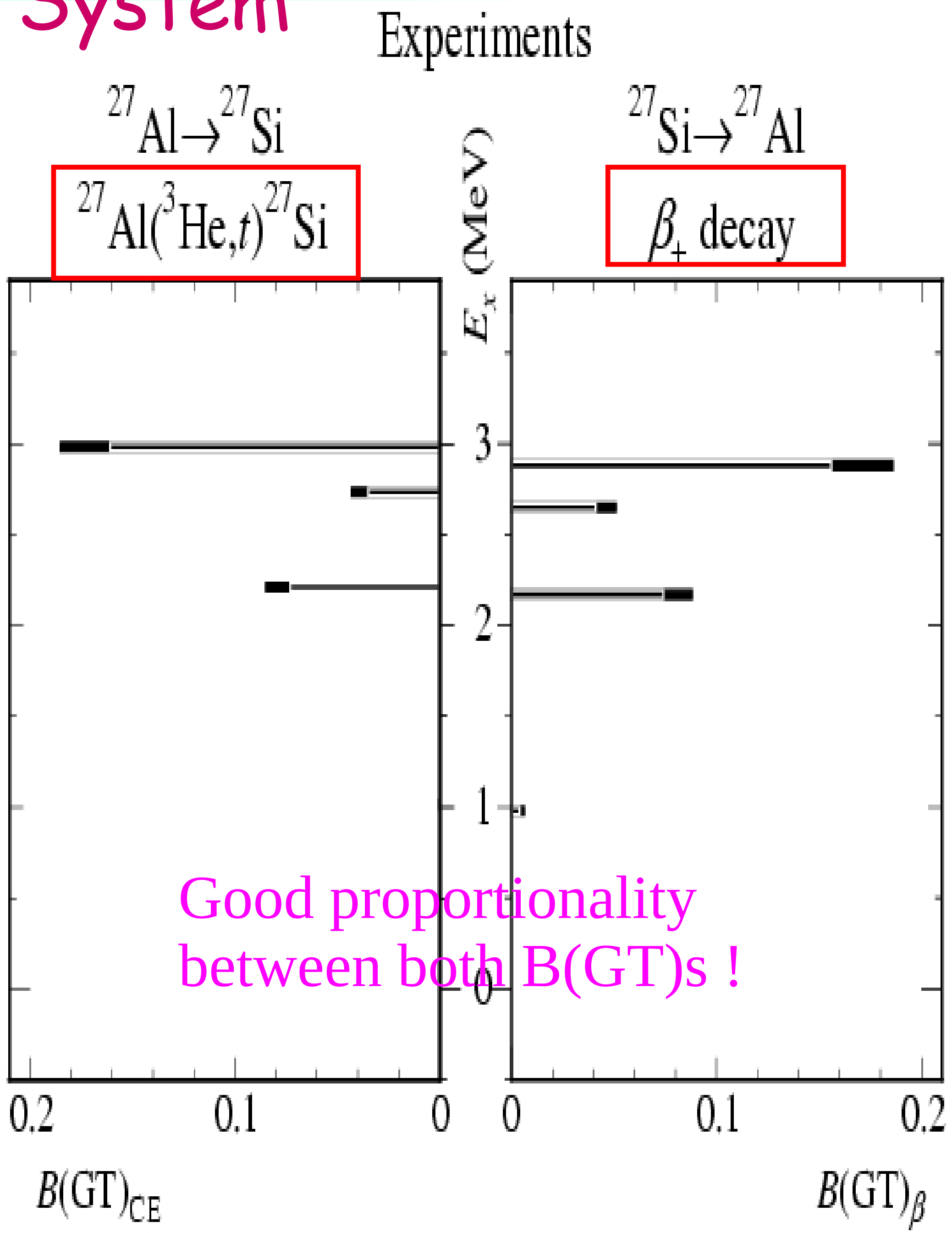
Analogous Structures and Transitions in T=1/2 System



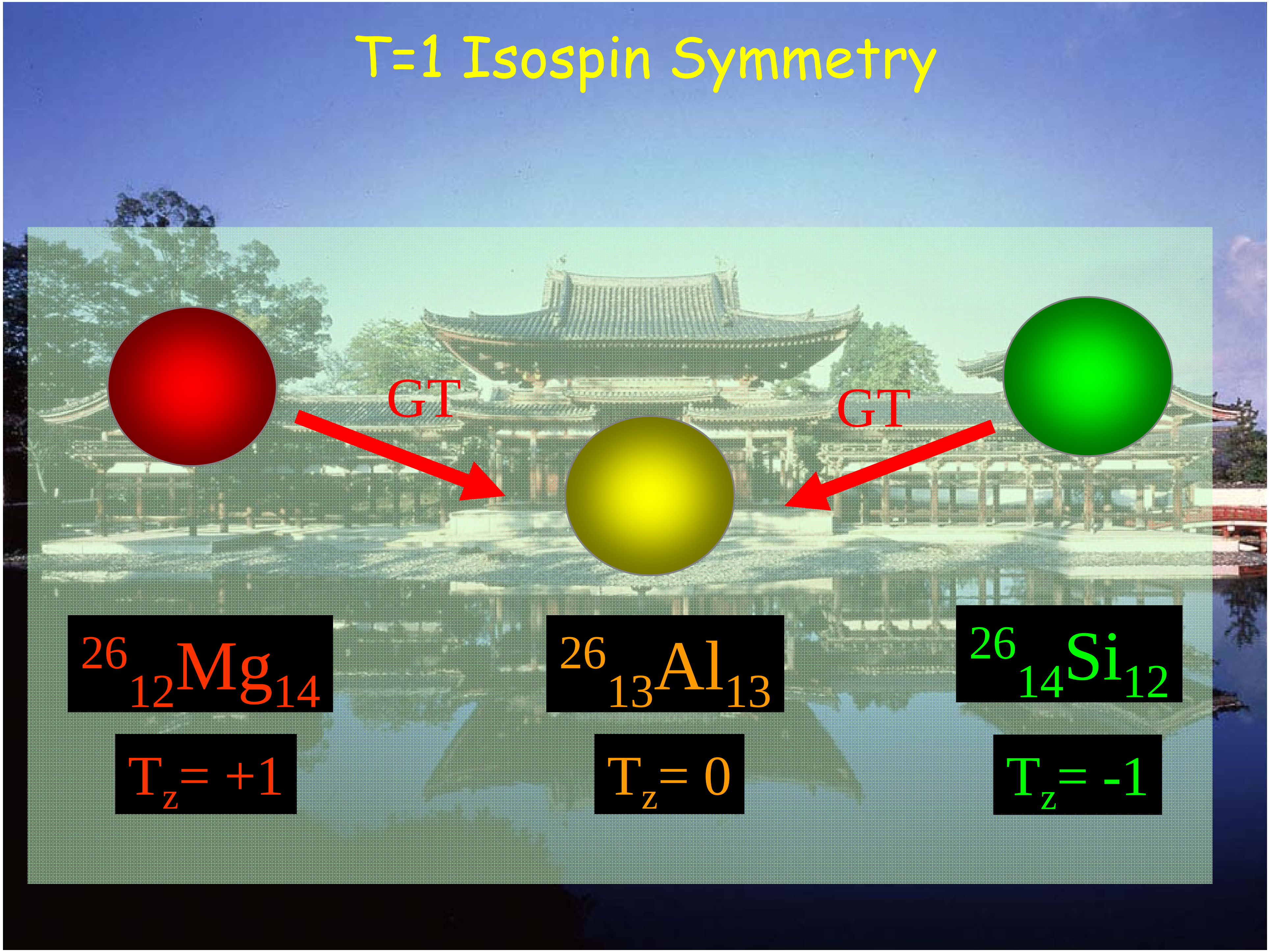
Symmetry in A=27 System

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





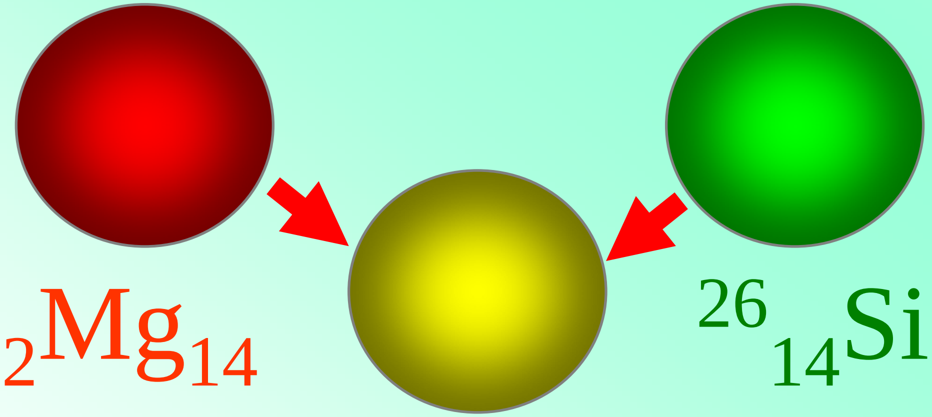
Good proportionality between both B(GT)s !


T=1 Isospin Symmetry
GT
GT
26 12Mg14
26 13Al13
26 14Si12
Tz= +1
Tz= 0
Tz= -1

Nuclei & Coin

= Coin

back front



= Nuclei

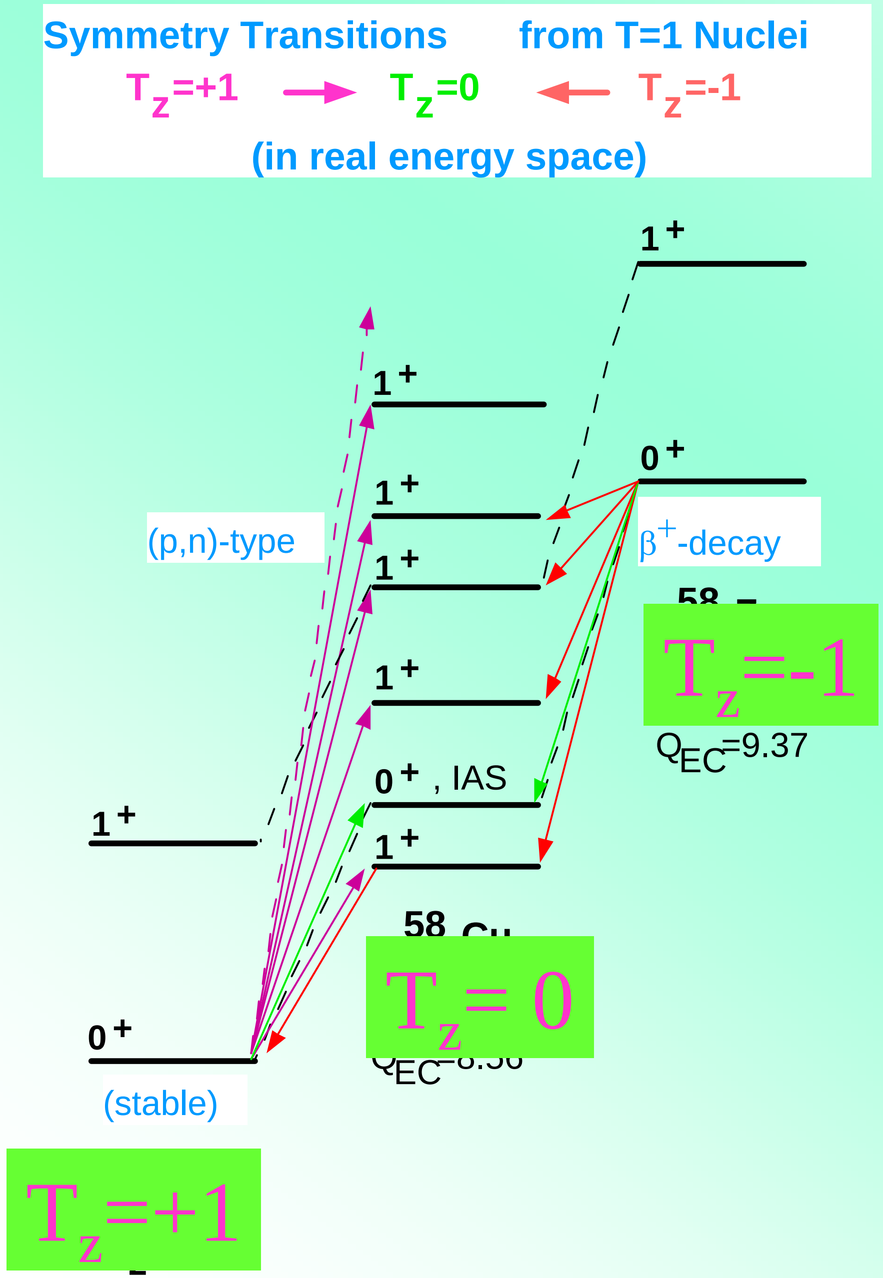
$^{26}_{12}Mg_{14}$ $^{26}_{13}Al_{13}$ $^{26}_{14}Si_{12}$

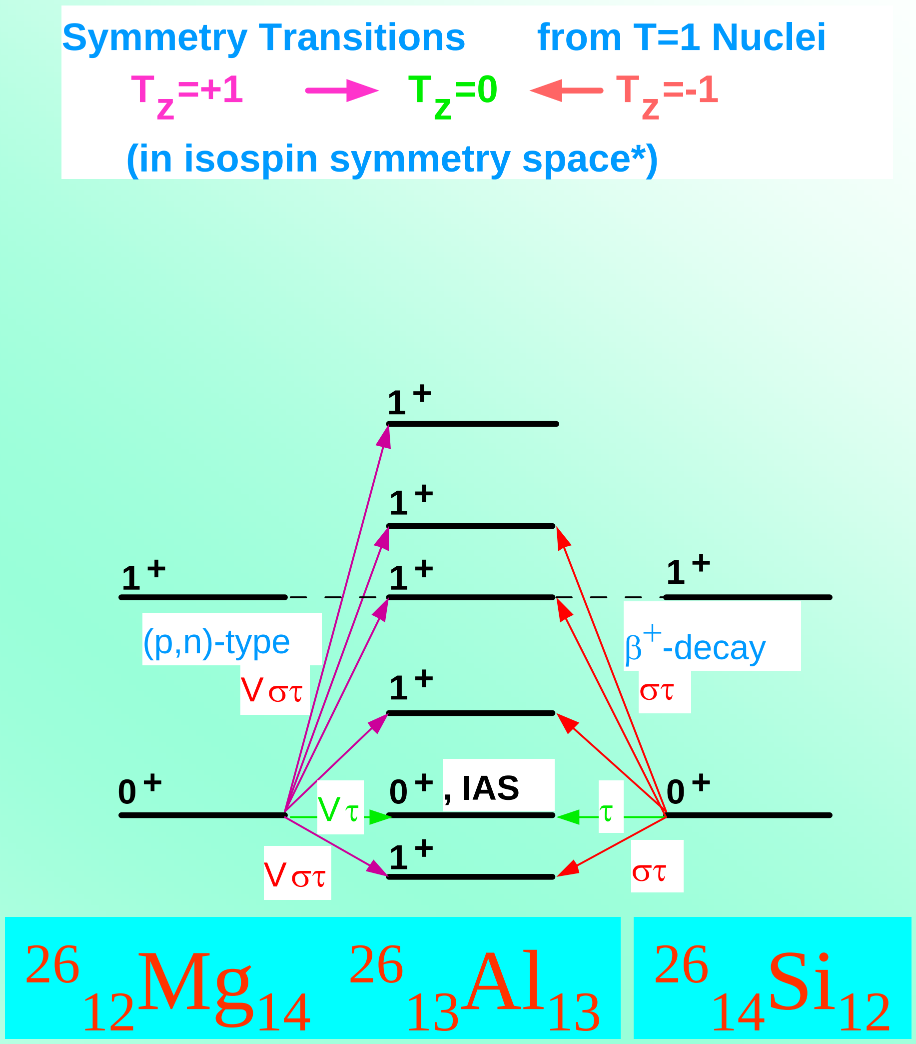
Symmetry in

1) structure
2) transitions

$T_z = +1$ $T_z = 0$ $T_z = -1$ isospin T=1 triplet

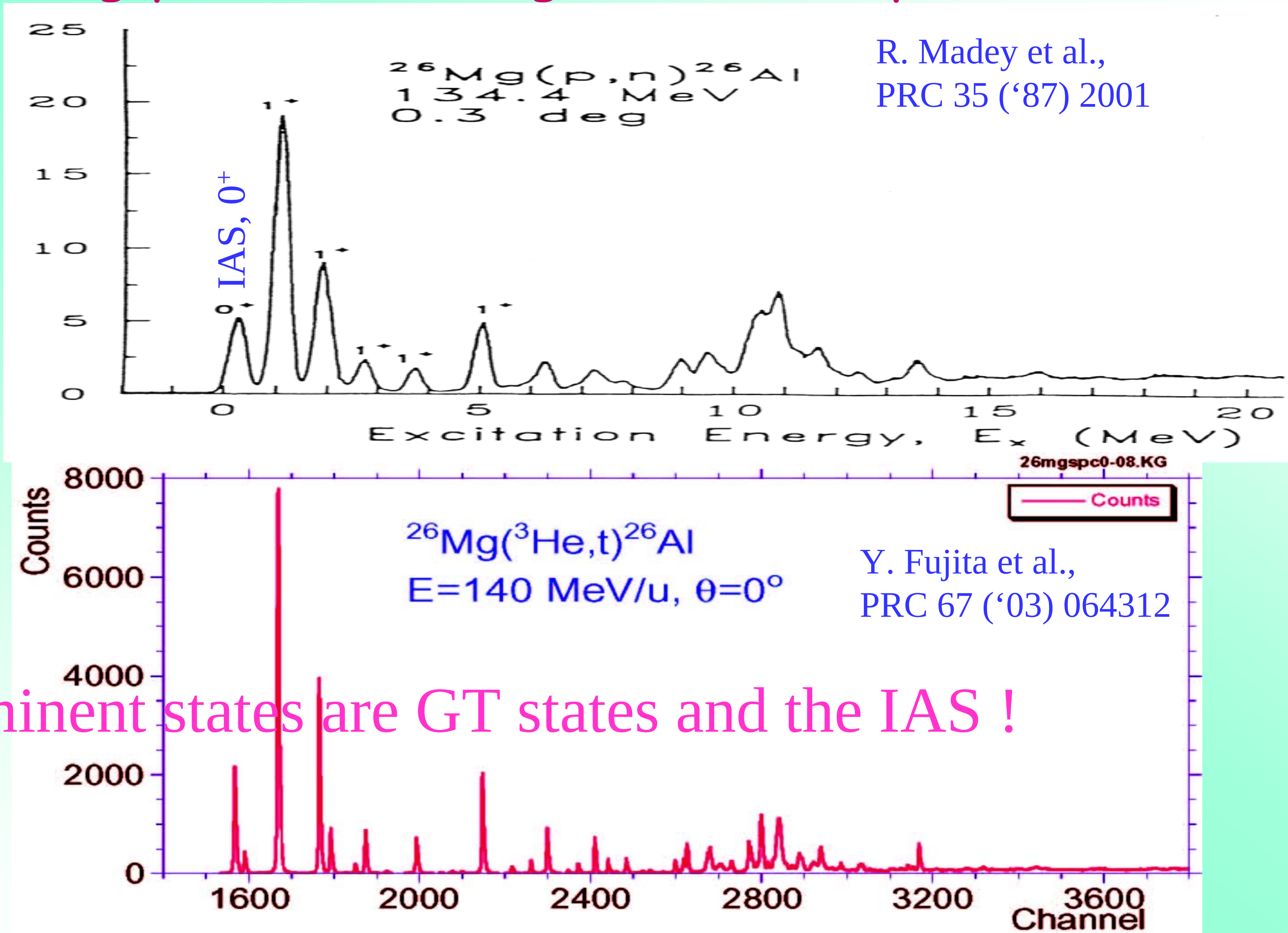
Transitions in real & isospin space (T=1)





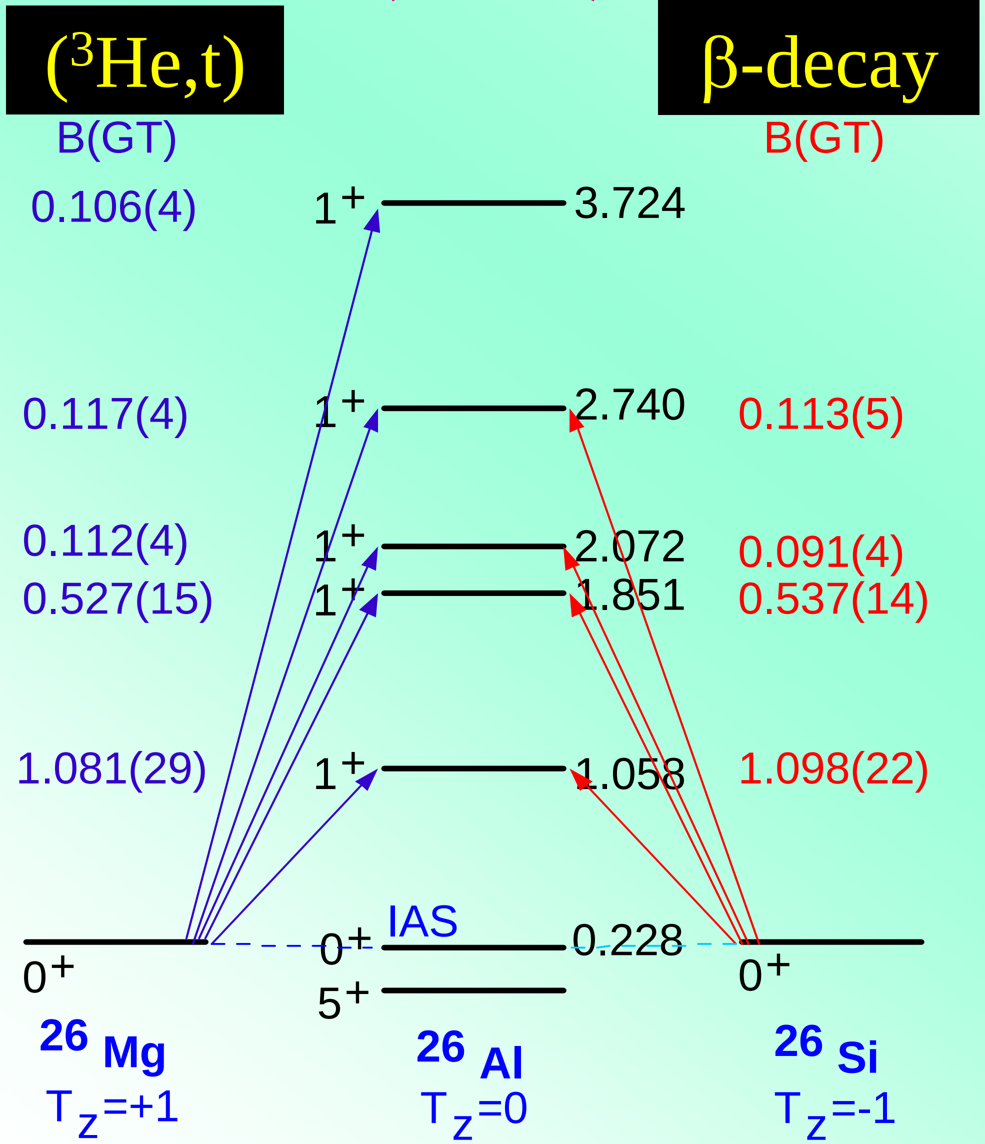
*after the correction of Coulomb displacement energy

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

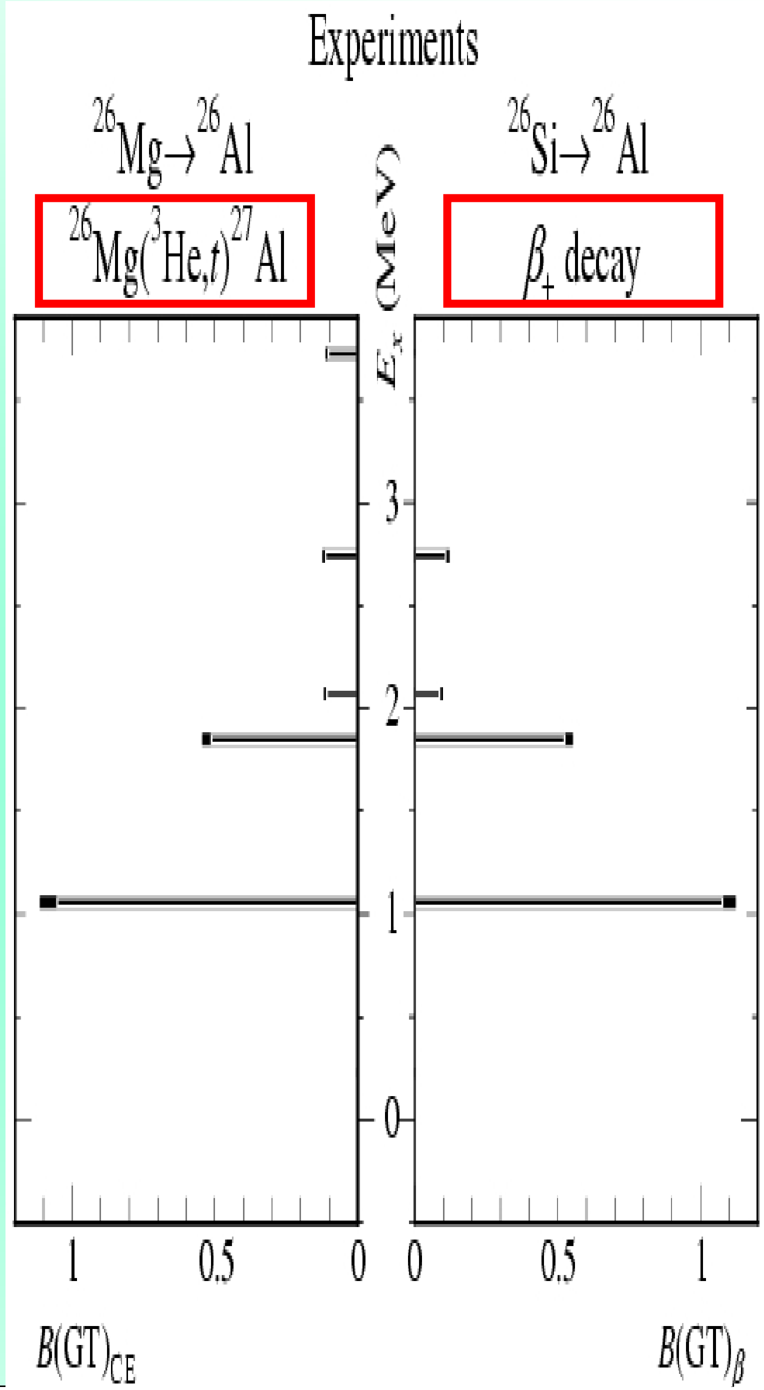


Prominent states are GT states and the IAS !

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

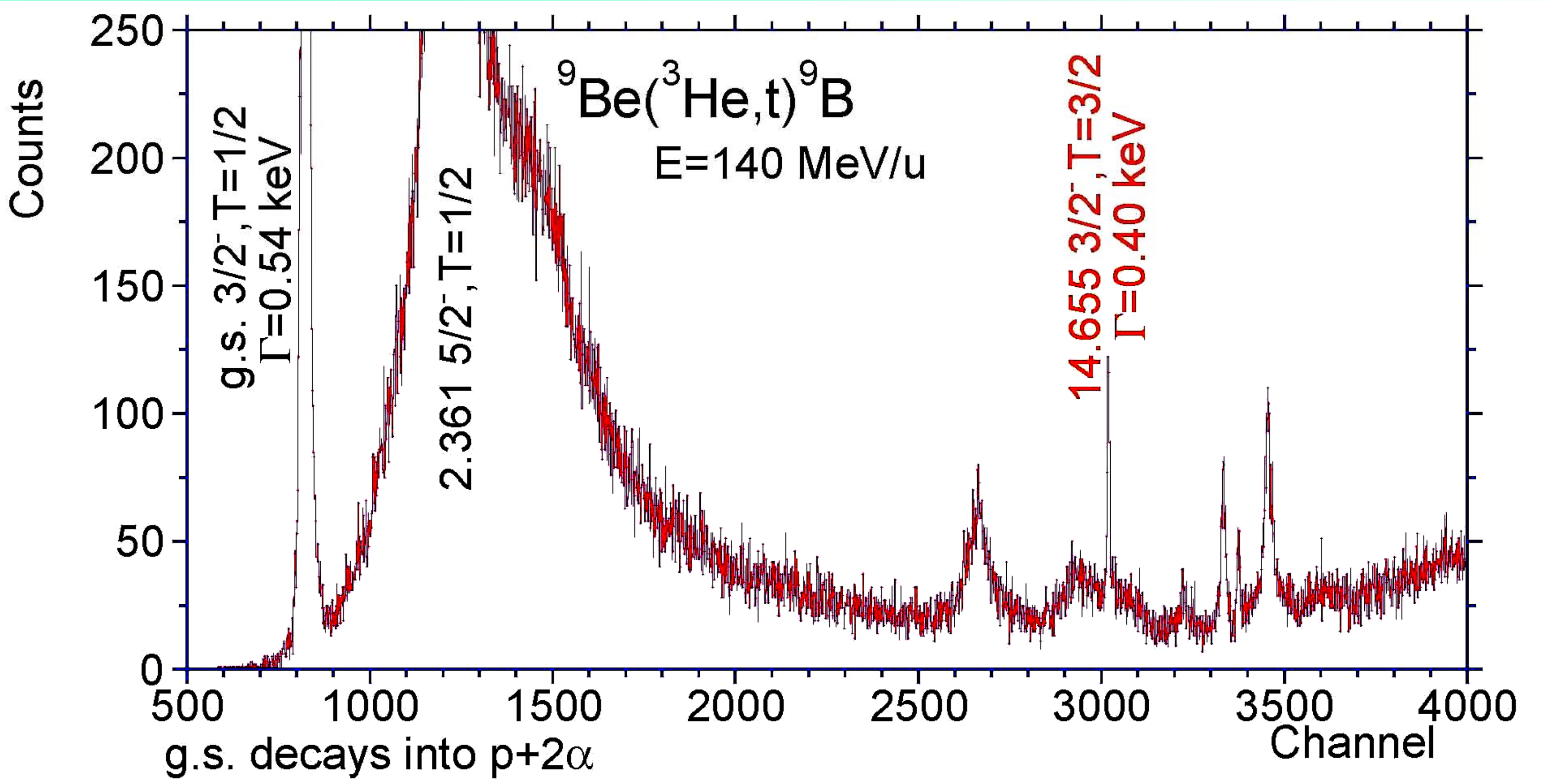


Y. Fujita et al., PRC 67 ('03) 064312



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

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



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

C. Scholl, Koeln

Relationship: Decay and Width

Heisenberg's Uncertainty Priciple

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

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

Width $\Gamma = \Delta E$

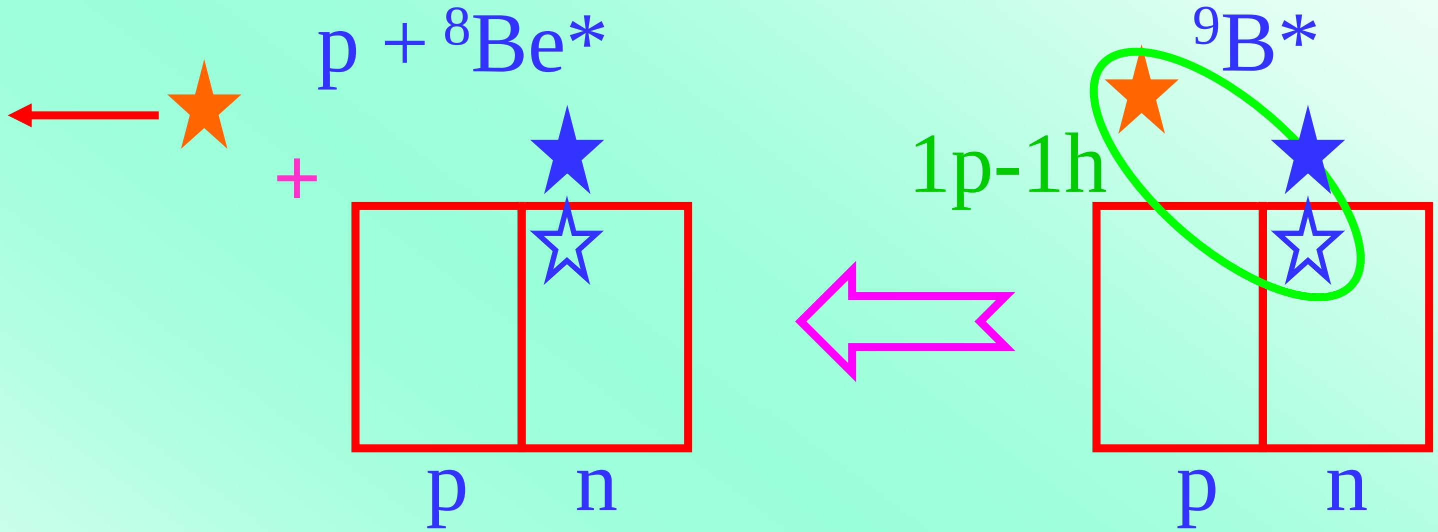
*if: Decay is Fast,

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)

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



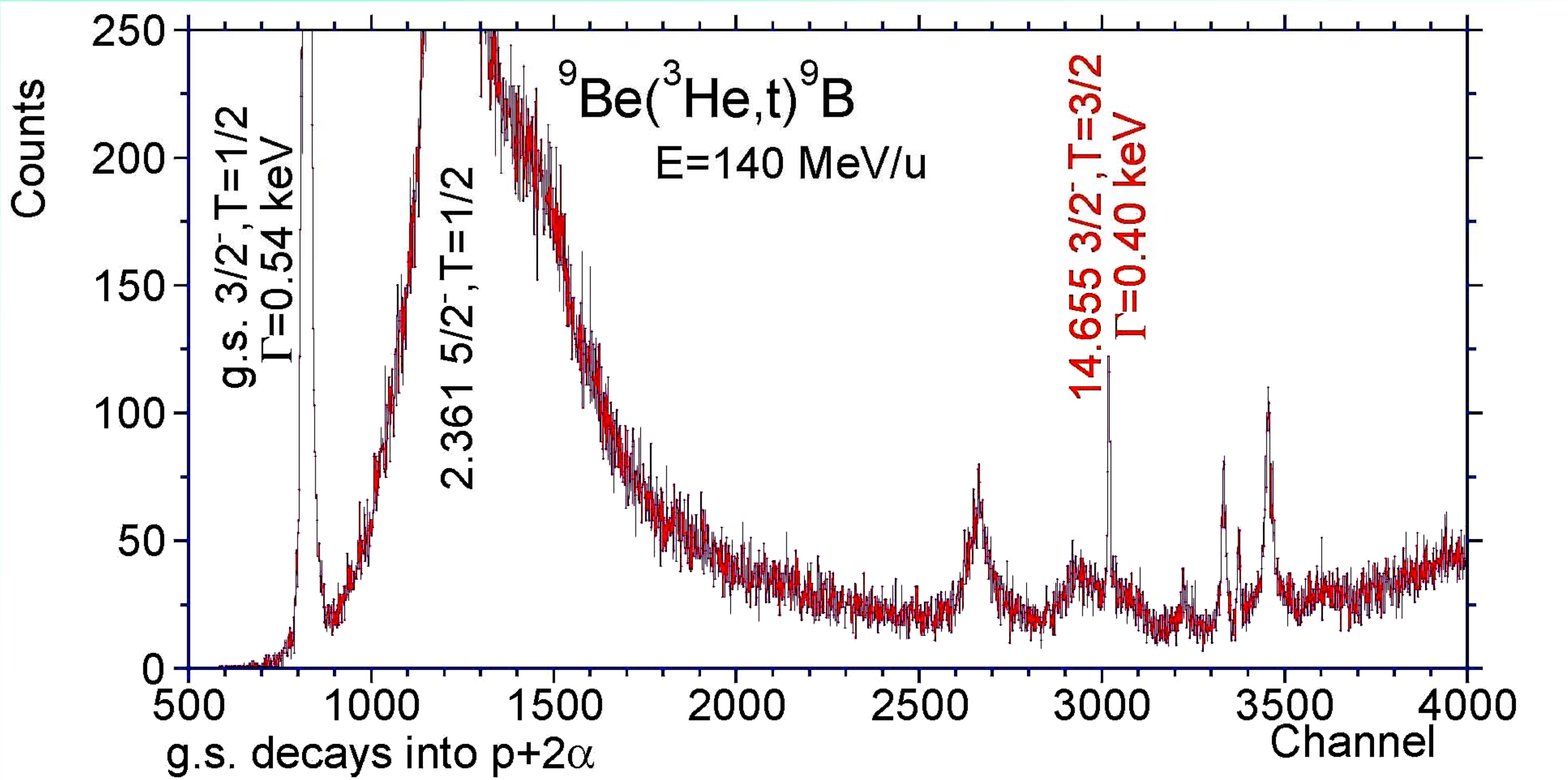
T_z : -1/2 + 0 = -1/2

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

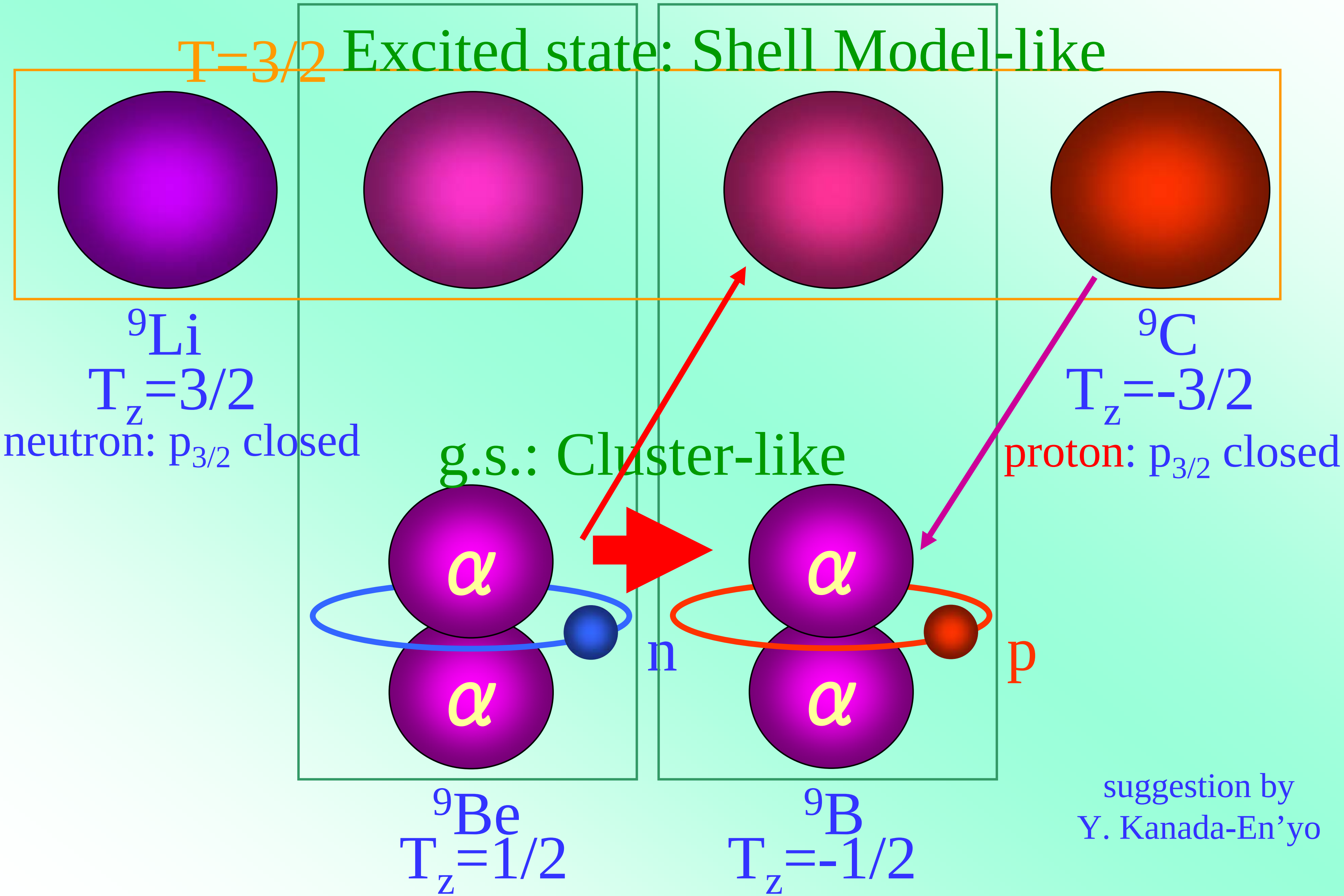
$^{9}Be(^{3}He,t)^{9}B$ spectrum (III)



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

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

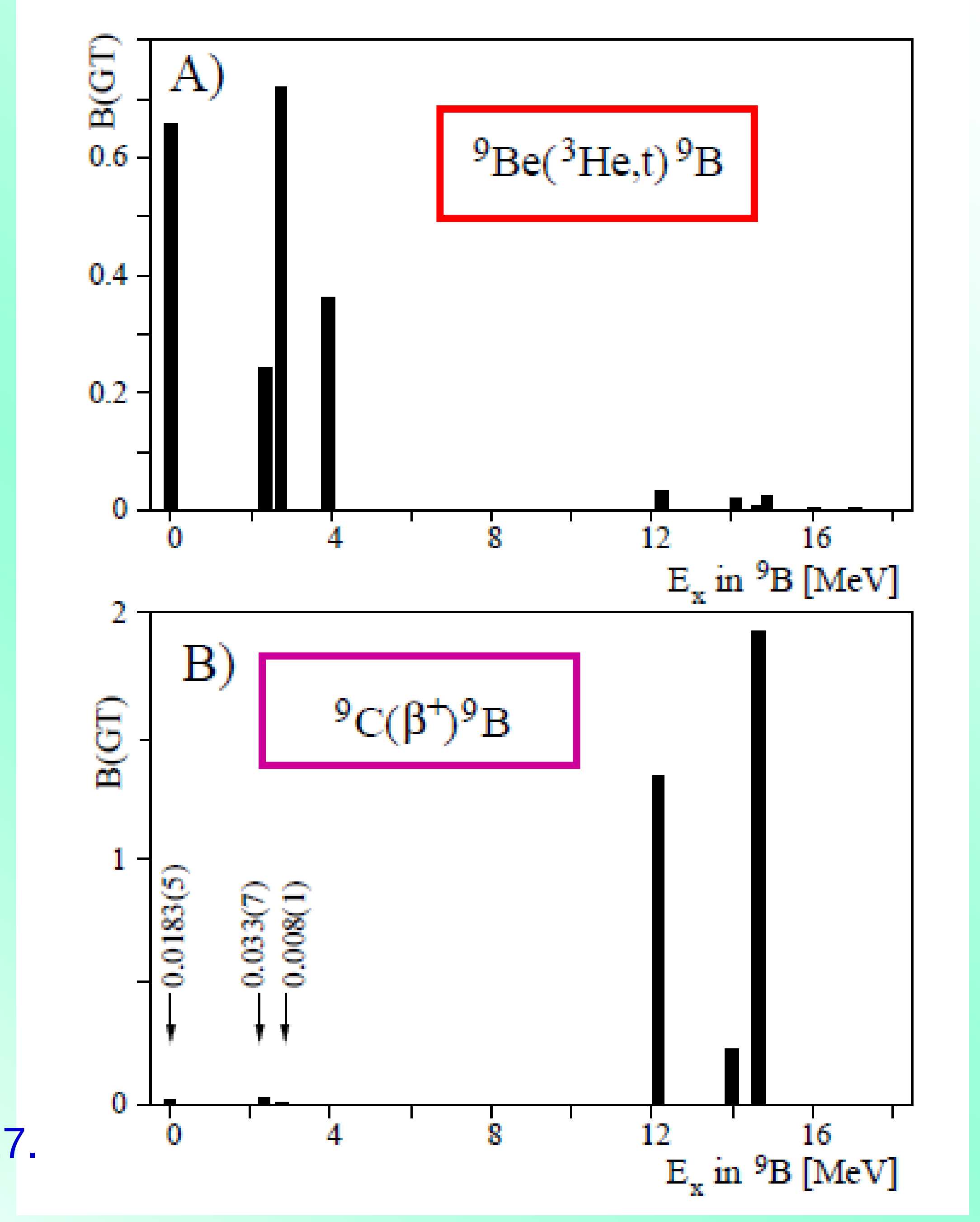
Shell Structure and Cluster Structure



suggestion by
Y. Kanada-En'yo

β-decay and (^{3}He,t) results

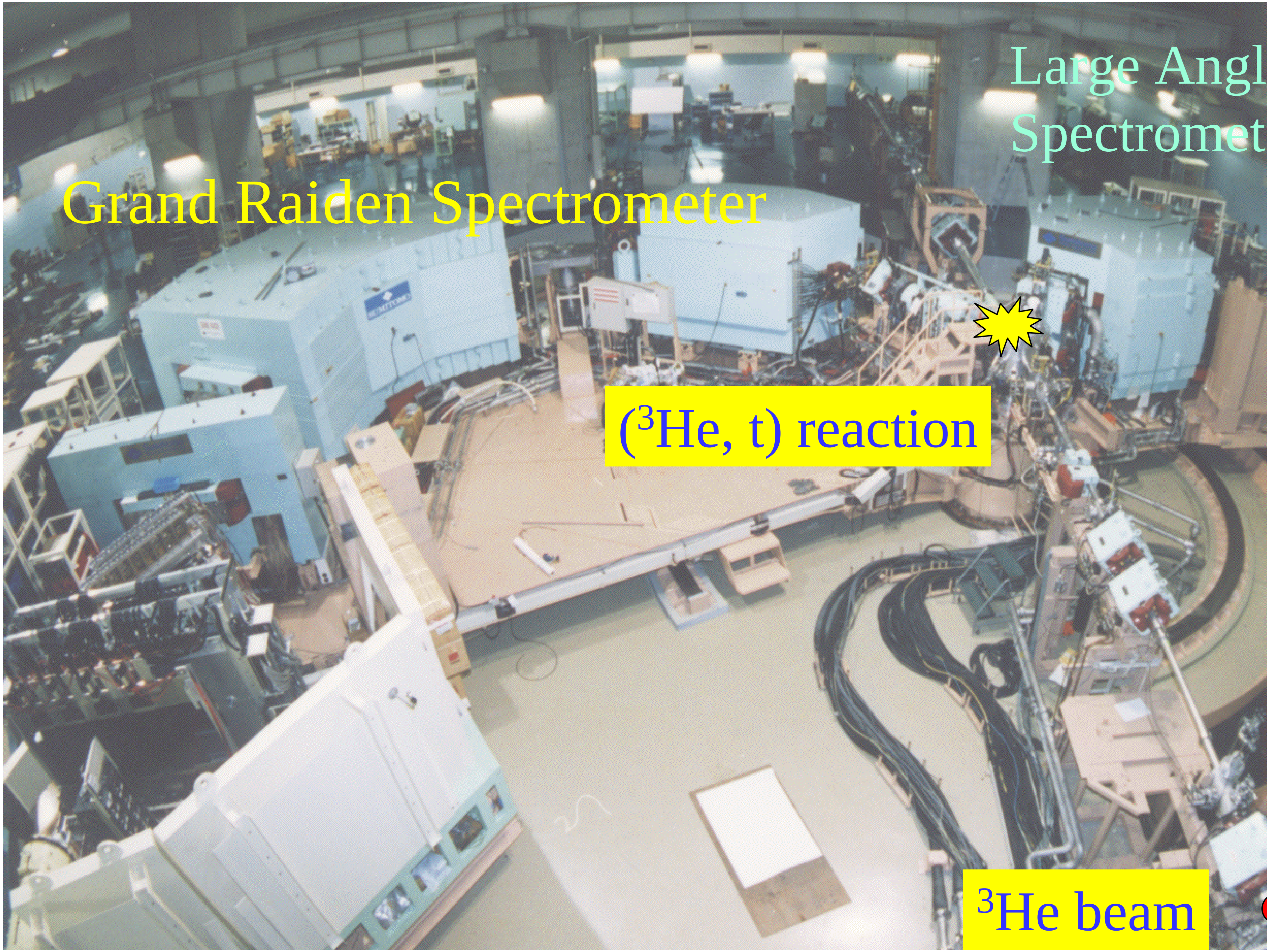
C. Scholl et al,
PRC 84, 014308 (2011)



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

High-resolution Experiment

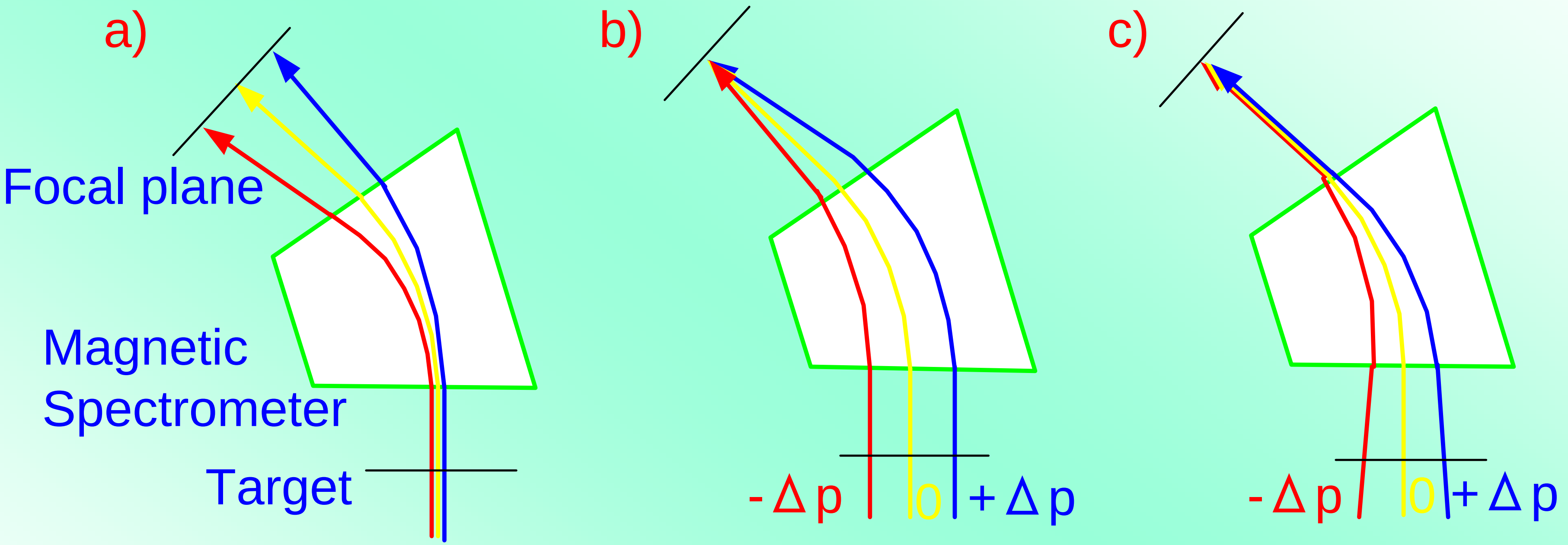
-beam matching techniques-
(dispersion matching techniques)


Large Angl
Spectromet
Grand Raiden Spectrometer
(3He, t) reaction
3He beam

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

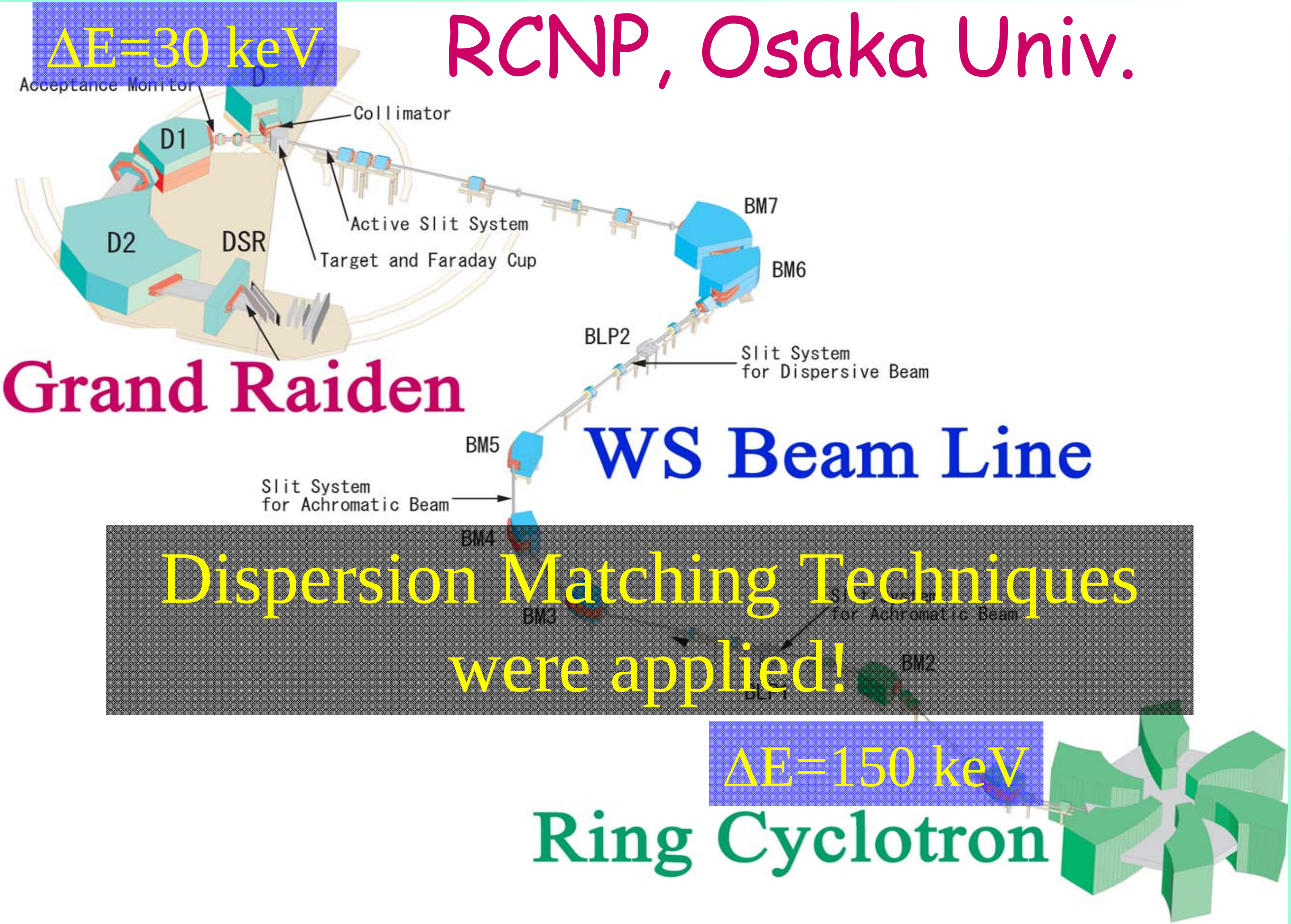
Horiz. angle resolution

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

Angular dispersion matching

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

RCNP, Osaka Univ.

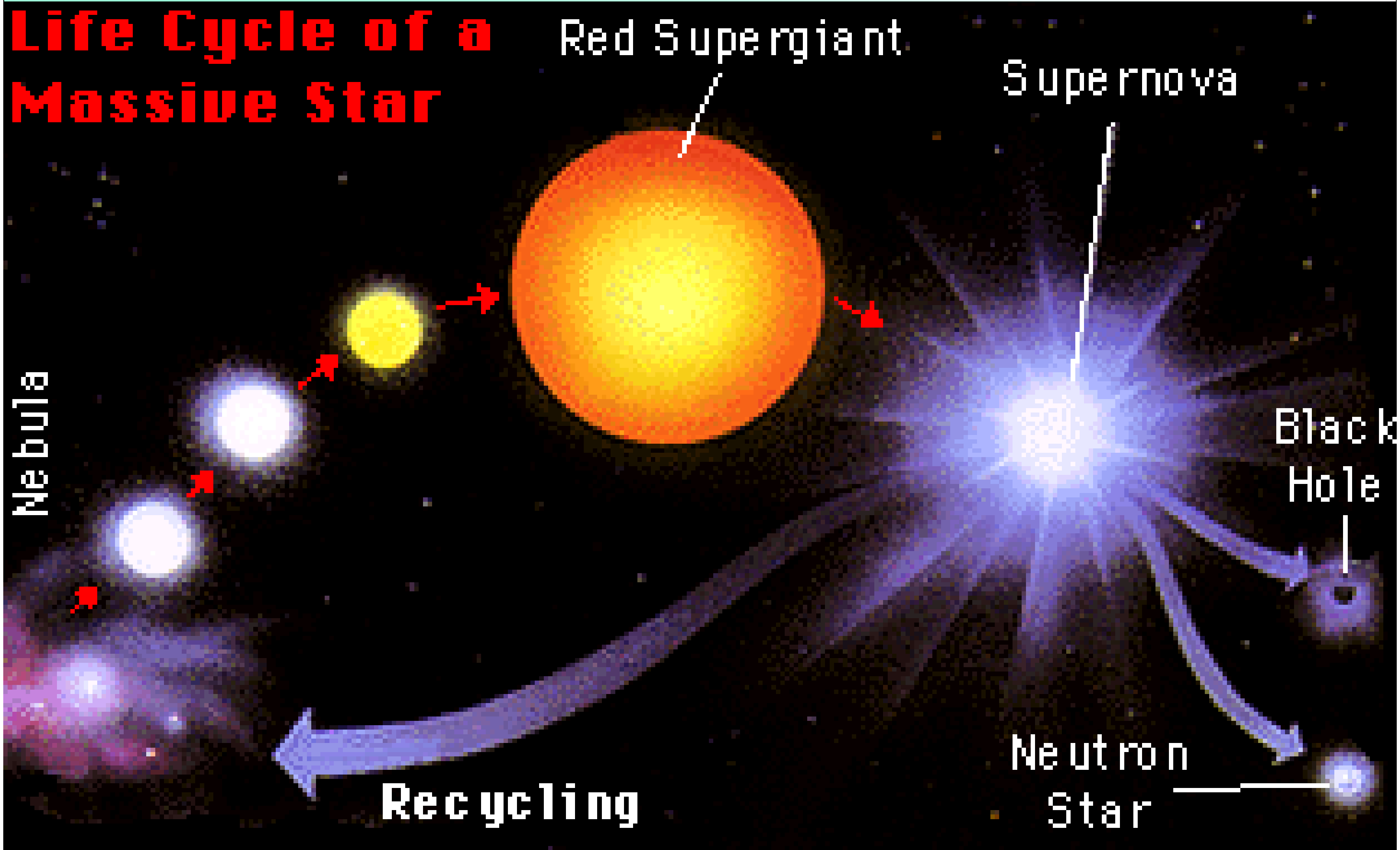


ΔE=30 keV

Dispersion Matching Techniques were applied!

ΔE=150 keV

Supernova Cycle



Crucial Weak Processes during the Core Collapse

$\sigma\tau$: important

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

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

$$(A,Z) + e^- \rightleftarrows (A,Z-1) + \nu_e ,$$

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

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

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

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

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

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

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

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

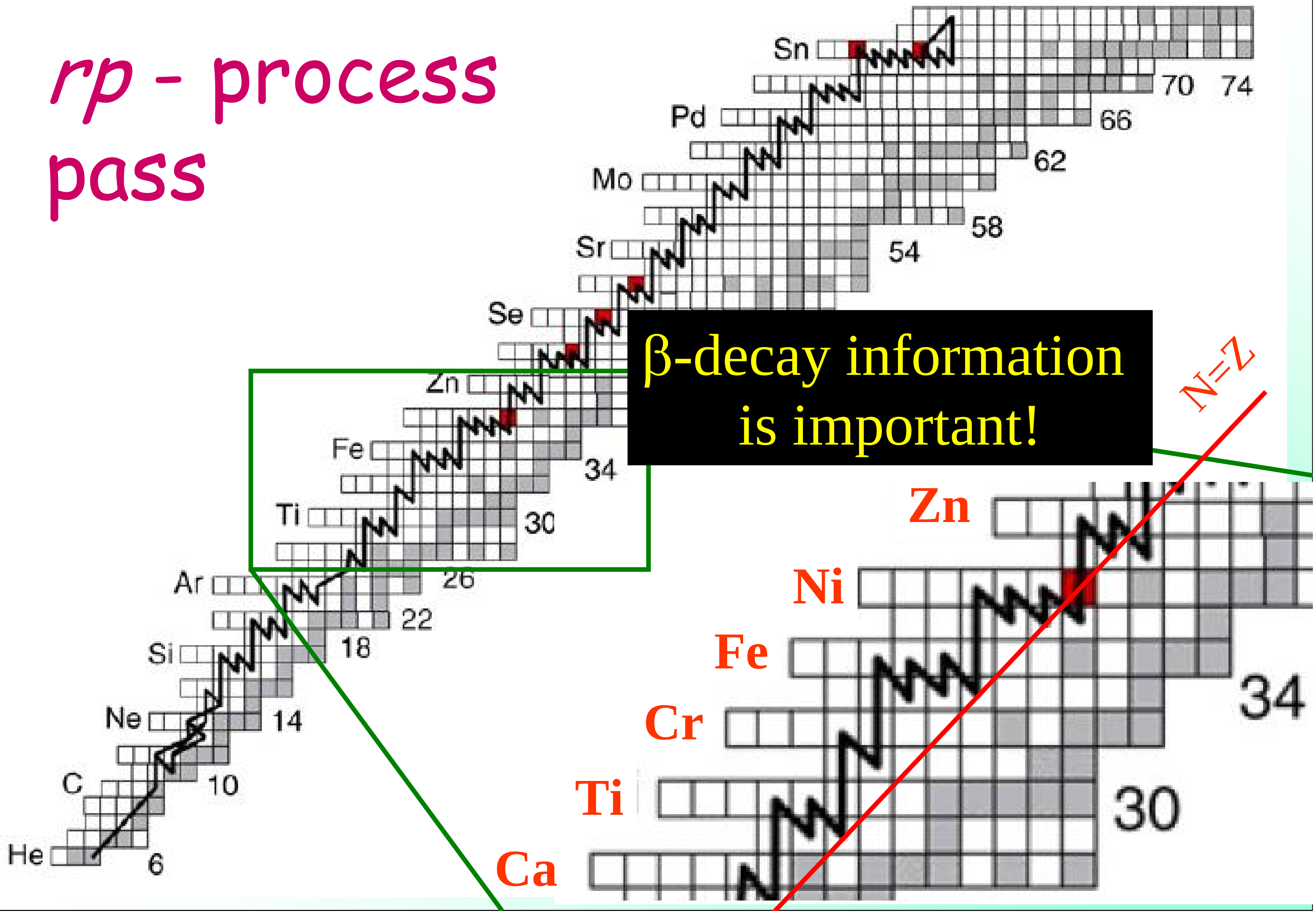
(***A***,***Z***)=nuclei in the
Cr, Mn, Fe, Co, Ni region
pf -shell Nuclei !

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

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

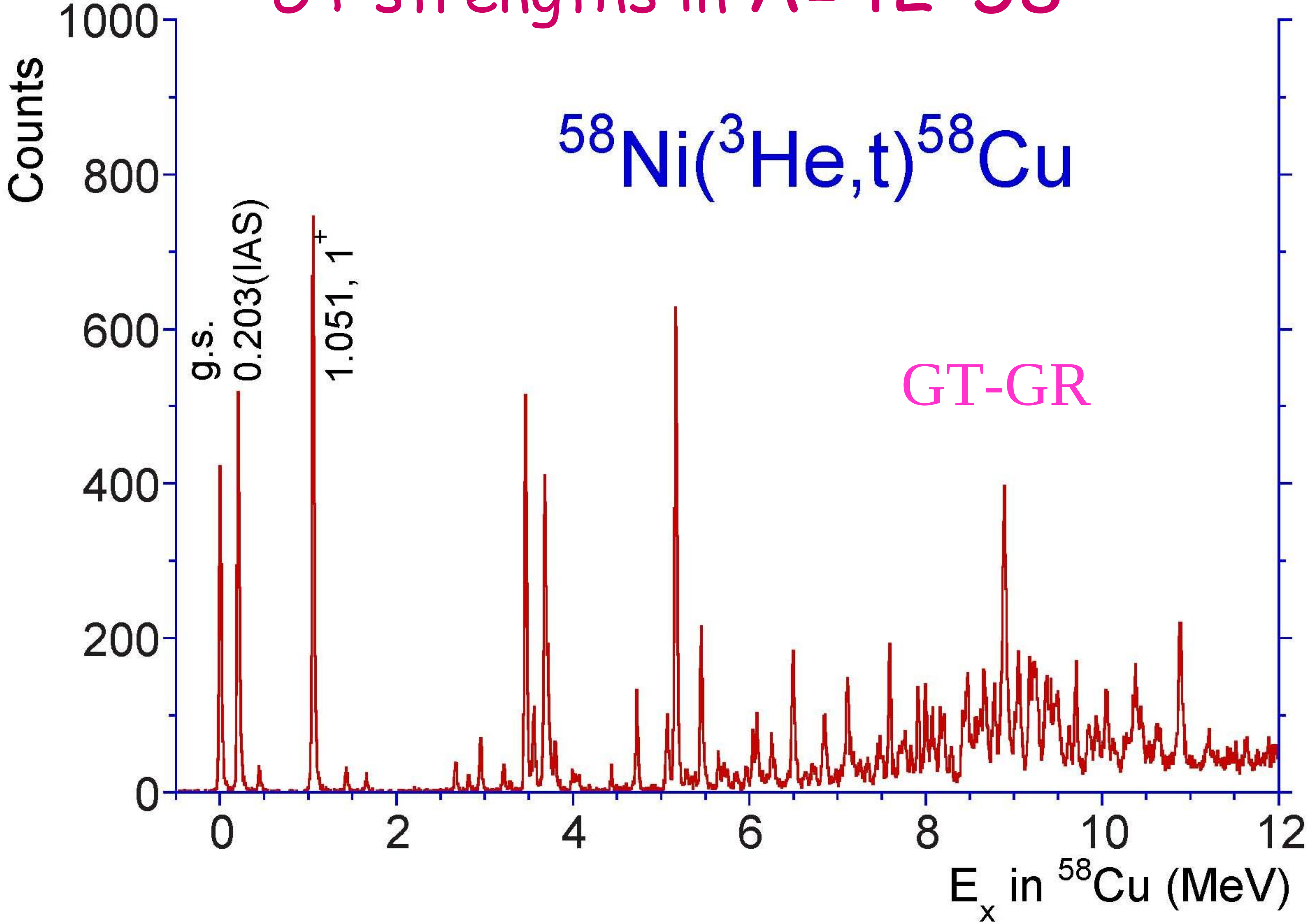
M. Wiescher et al. / Progress in Particle and Nuclear Physics 59 (2007) 51–65

rp - process pass



β-decay information is important!

GT strengths in A=42-58



***Exotic GT transitions from Unstable Nuclei

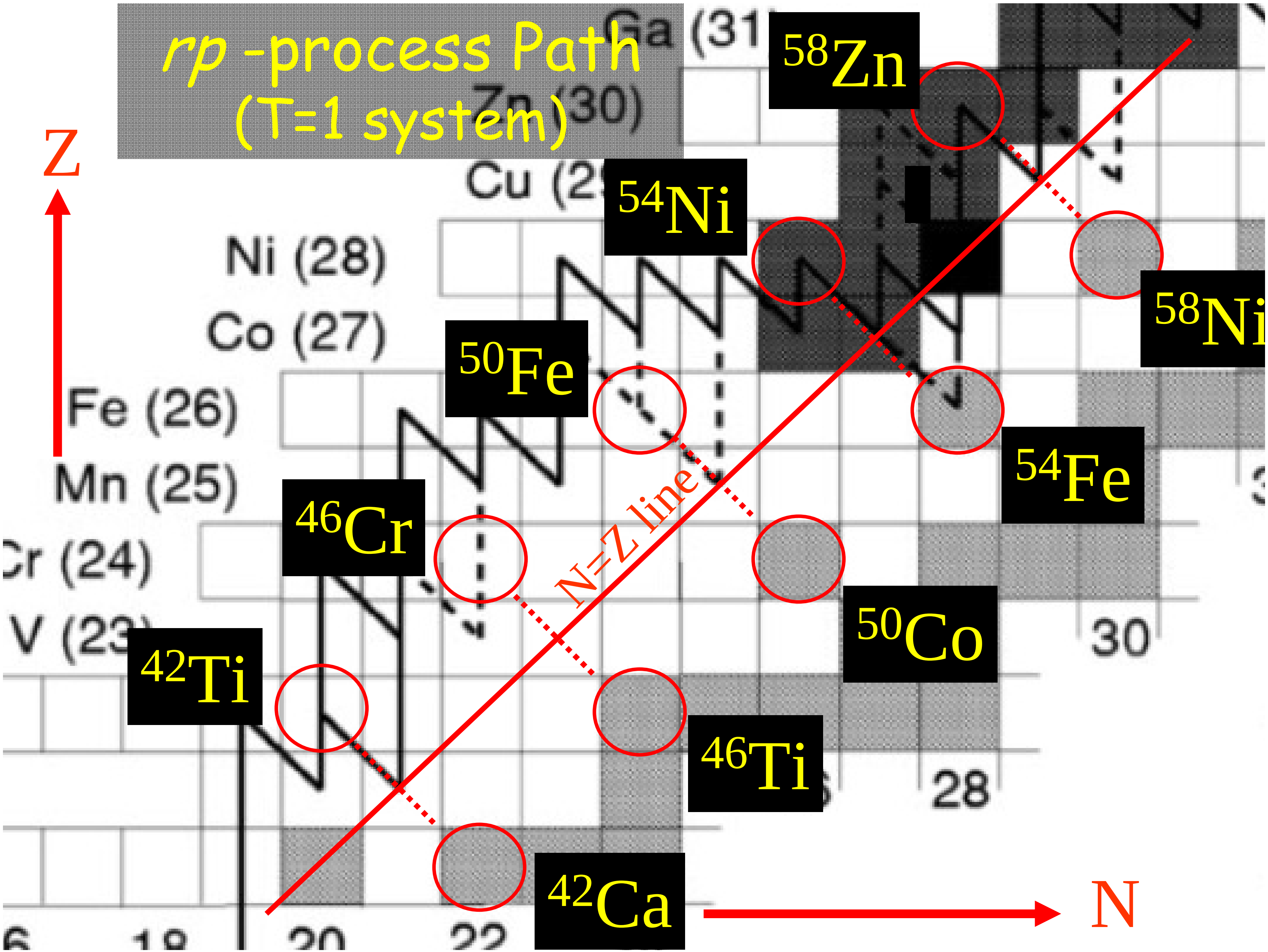
- Combined (^{3}He,t) and β-decay Study -

**Derivation of "absolute" B(GT) values

* β-decay: $T_{1/2}$ and absolute B(GT) values
  but only for the low-lying states

* (^{3}He,t) reaction: highly-excited states can be
  accessed but only the relative B(GT) values

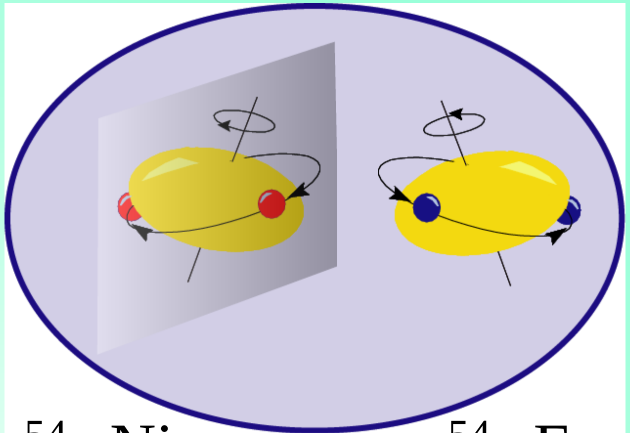
Let's combine CE reaction and β-decay data
starting from mirror nuclei !

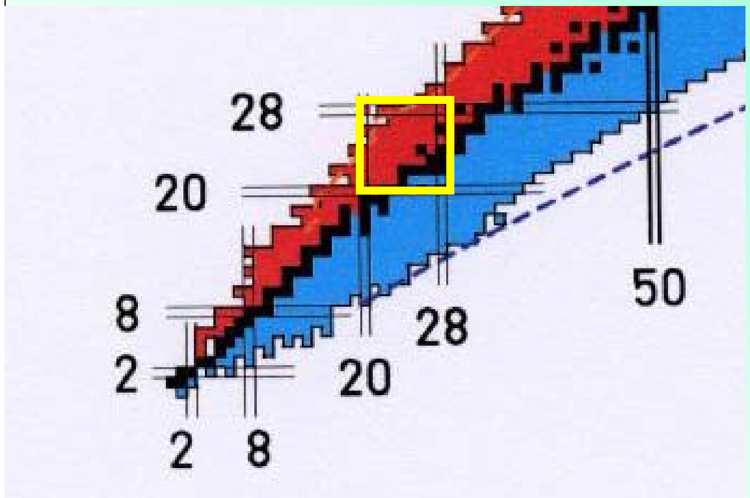


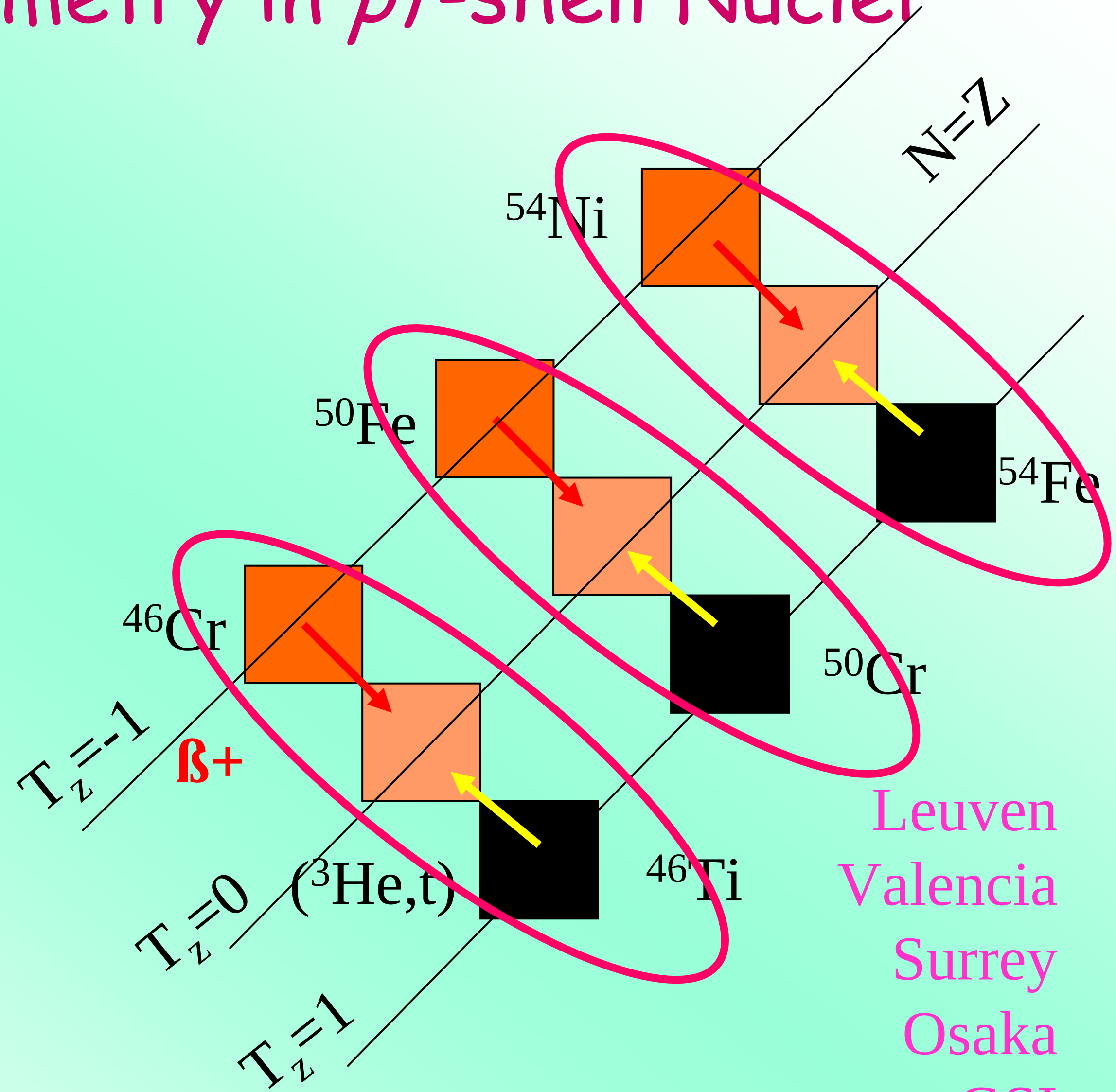
rp -process Path
(T=1 system)
Z
N
N=Z line
58Zn
54Ni
50Fe
46Cr
42Ti
58Ni
54Fe
50Co
46Ti
42Ca
Ni (28)
Co (27)
Fe (26)
Mn (25)
Cr (24)
Zn (30)
20
22
28
30

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

Mirror nuclei





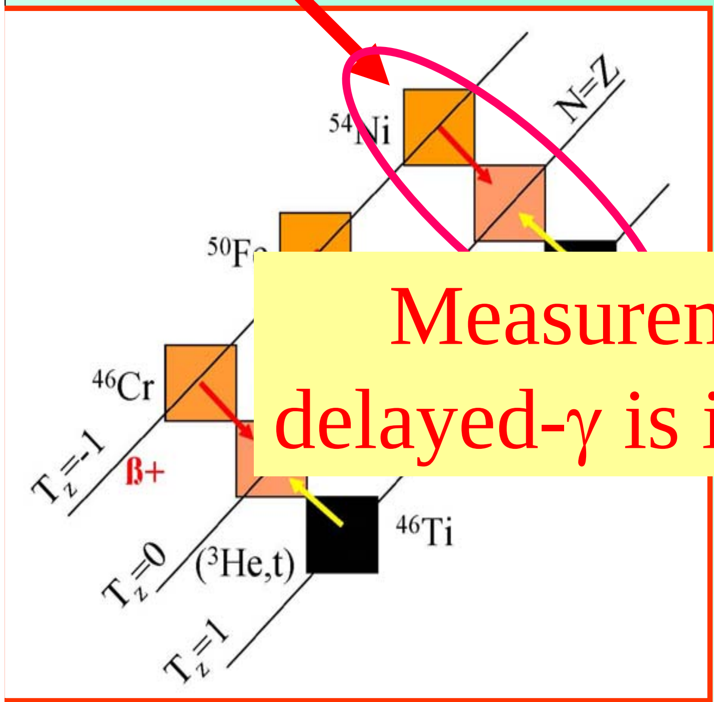


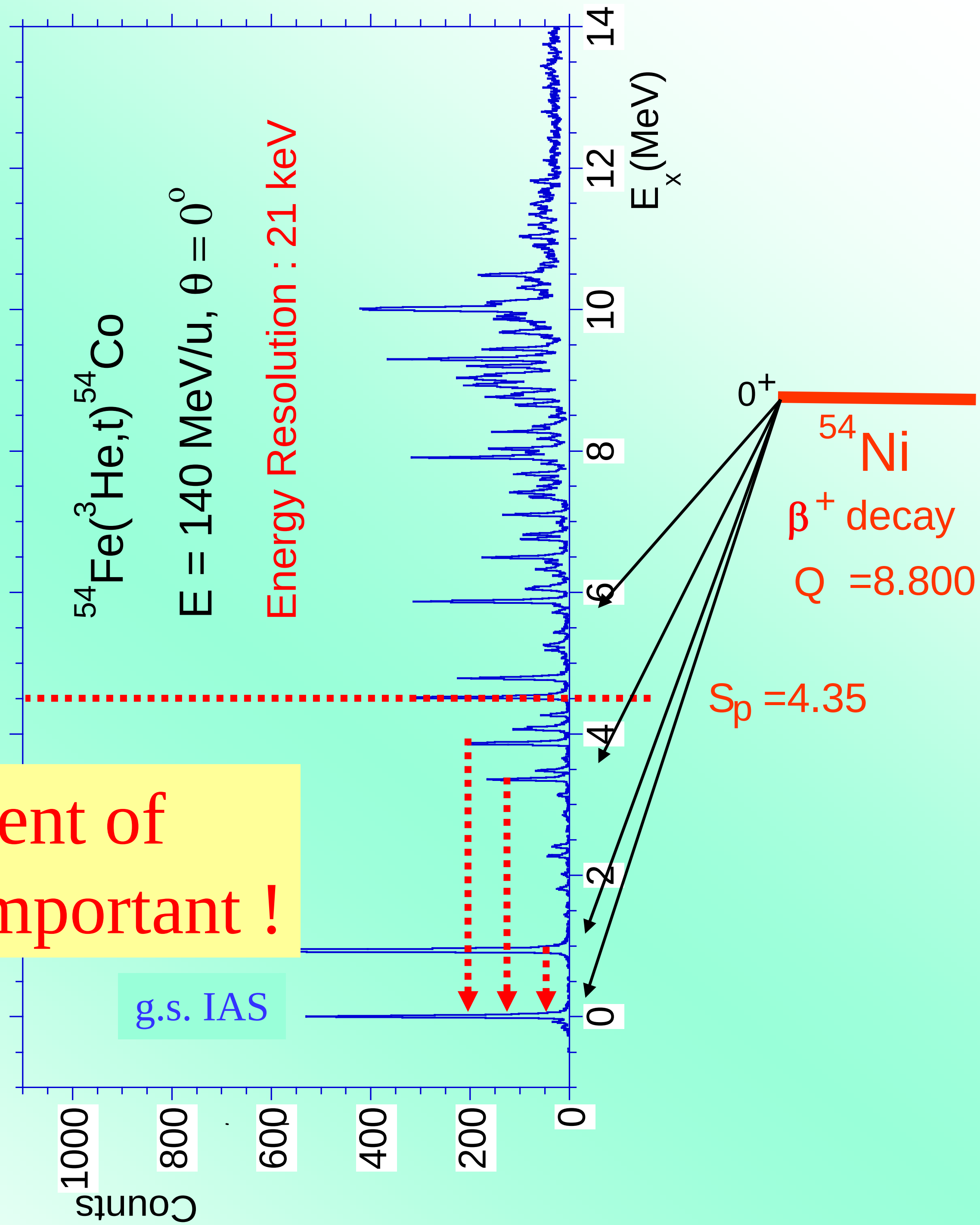
by B. Rubio

Leuven
Valencia
Surrey
Osaka
GSI
CNS

^{54}Ni β-decay measurement

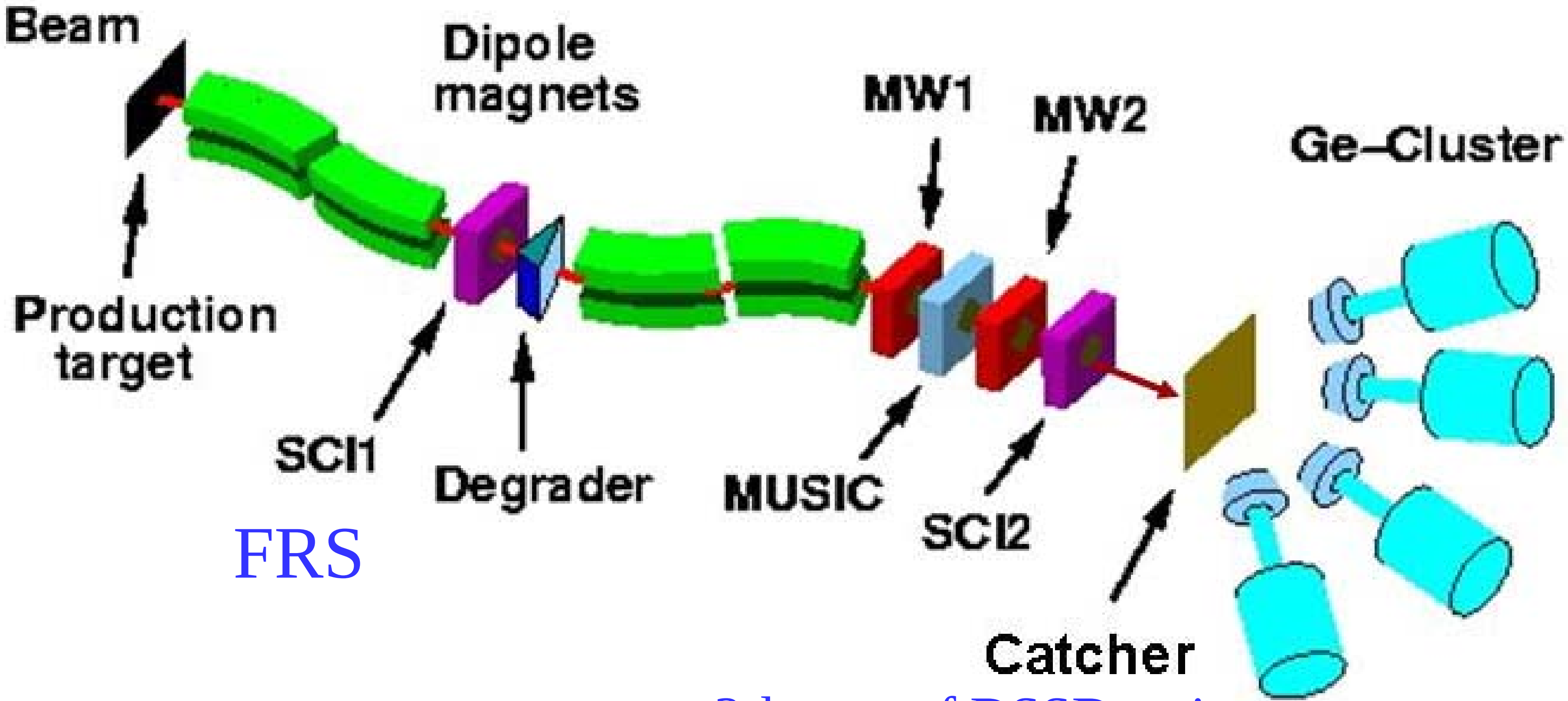
- at GSI (FRS facility)
- RISING (stopped beam campaign)





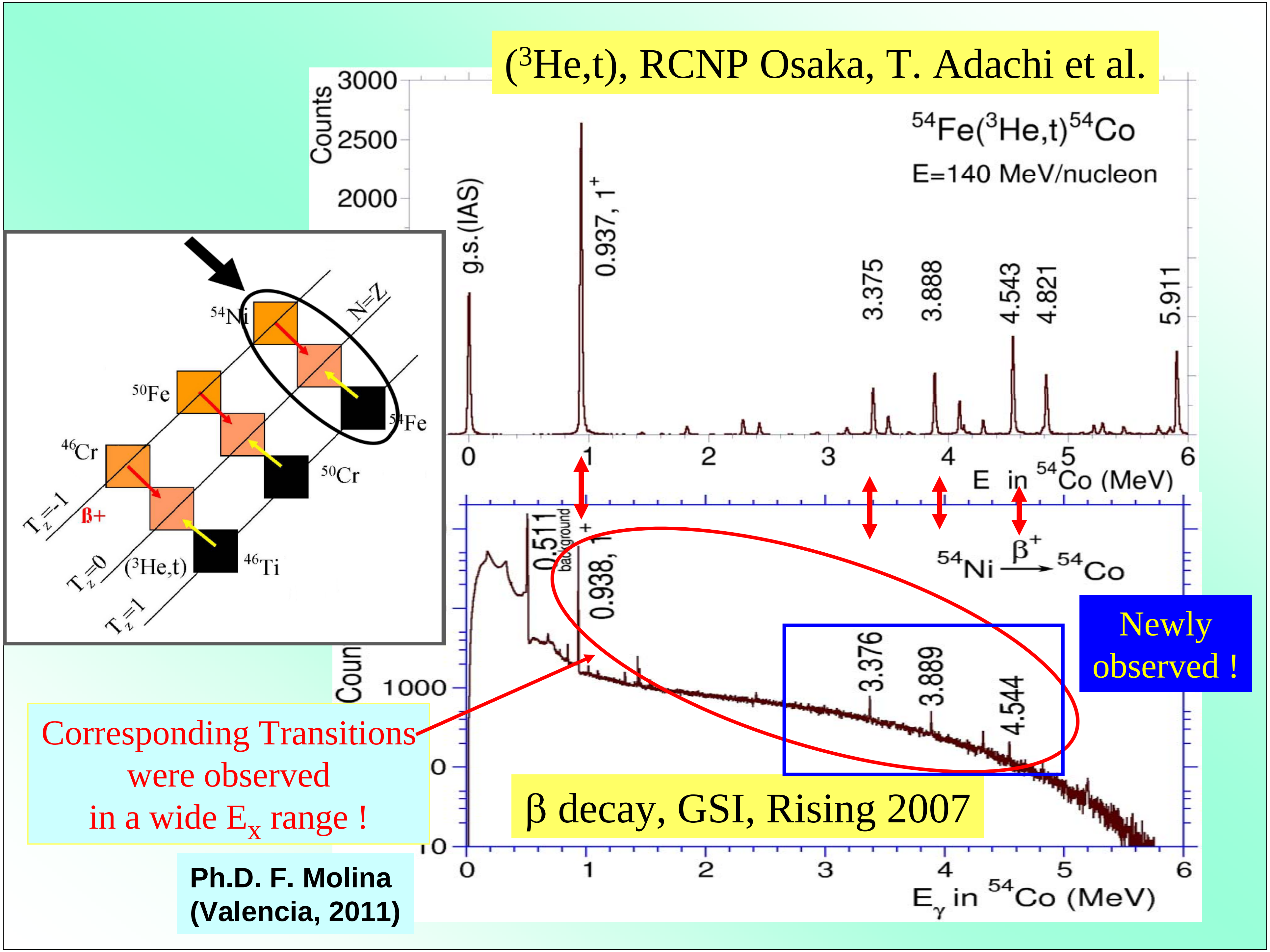
Measurement of delayed-γ is important !

GSI: RISING set up
- active stopper campaign -

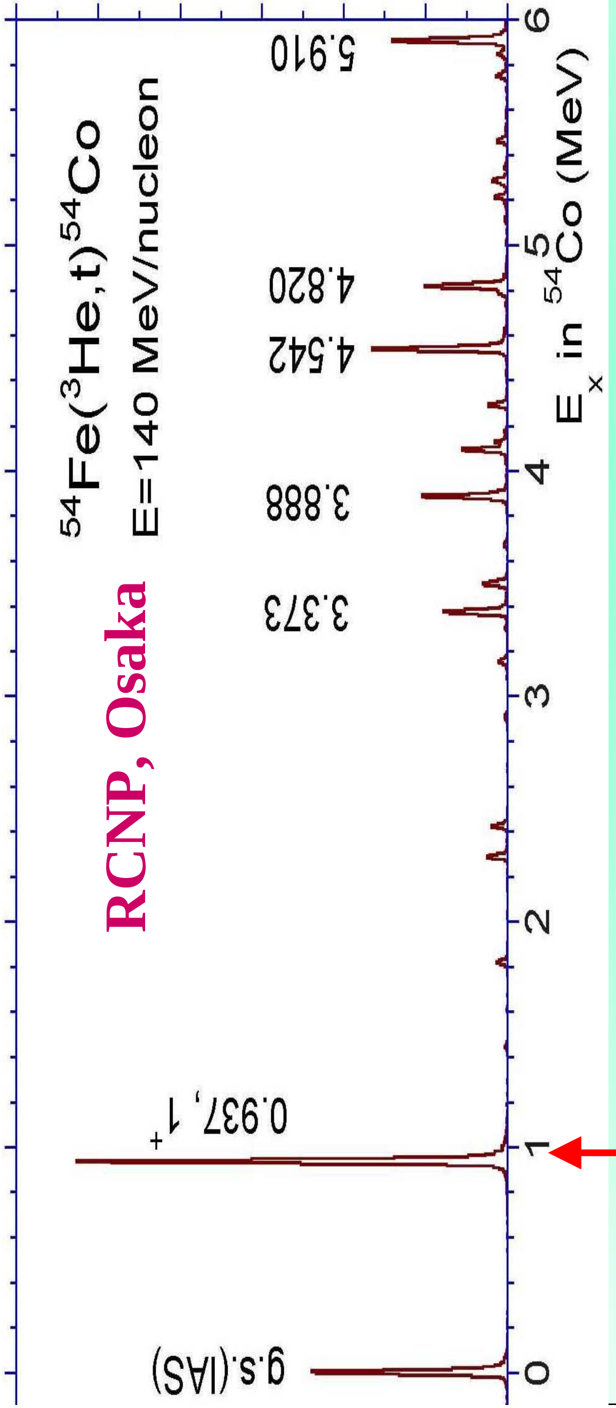


FRS

3-layors of DSSD active stopper

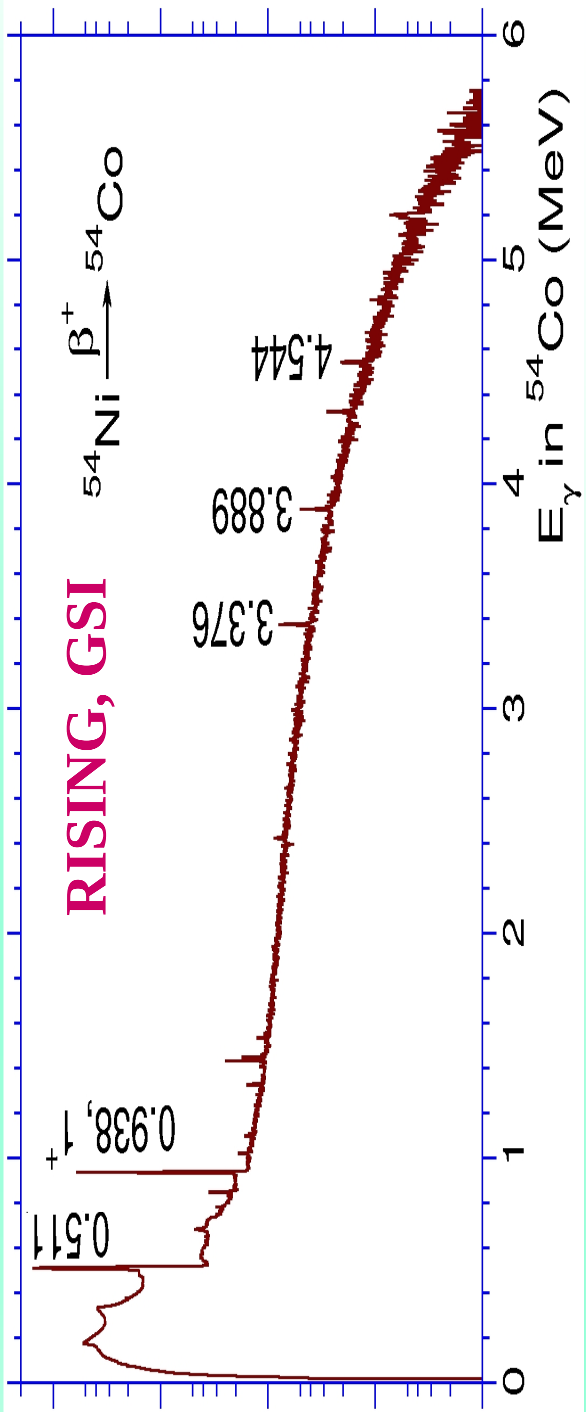


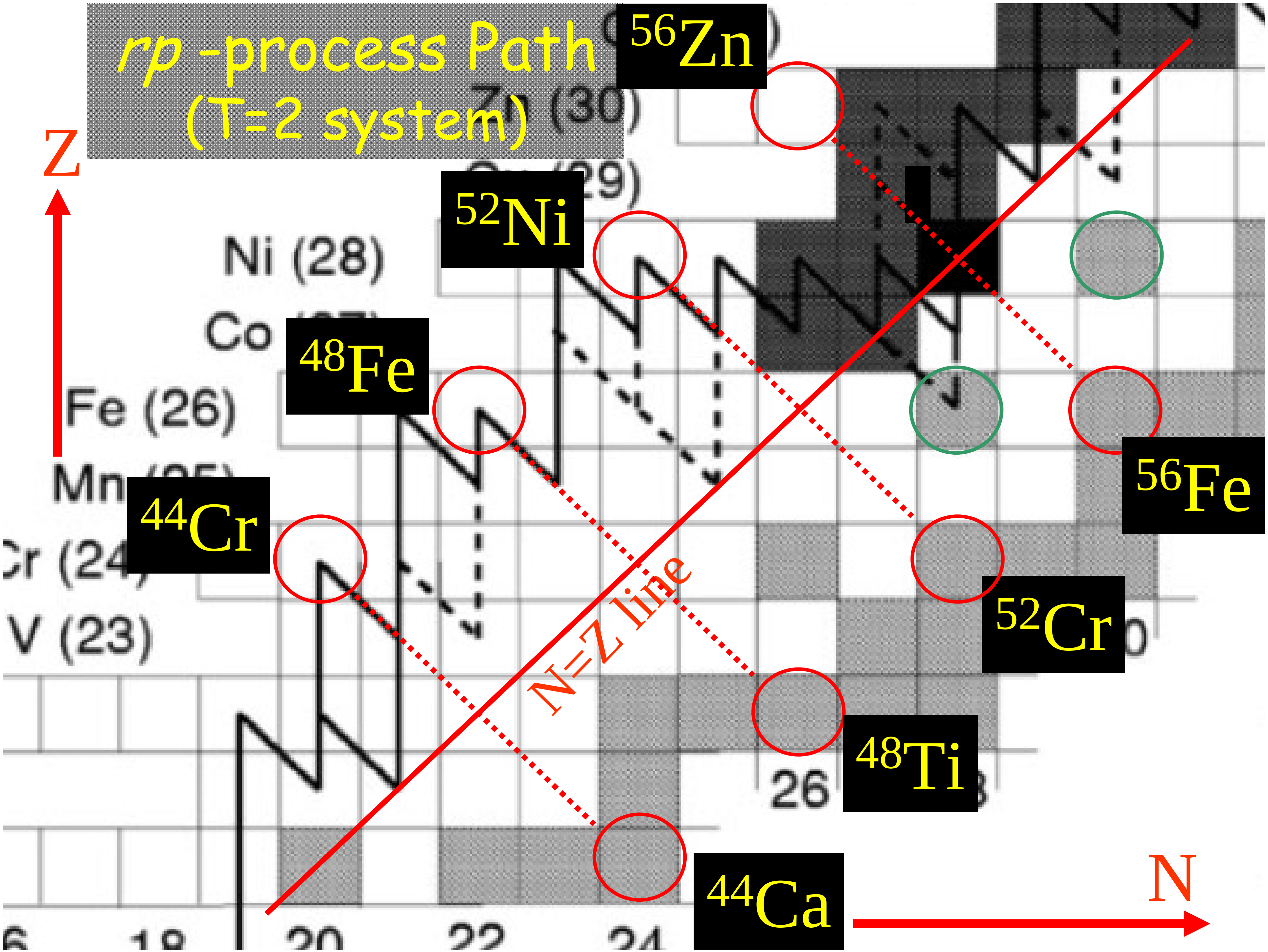
(3He,t), RCNP Osaka, T. Adachi et al.
54Fe(3He,t)54Co
E=140 MeV/nucleon
Counts
g.s.(IAS)
0.937, 1+
3.375
3.888
4.543
4.821
5.911
E in 54Co (MeV)
54Ni
50Fe
46Cr
54Fe
50Cr
46Ti
N=Z
Tz=-1
Tz=0
Tz=1
ß+
(3He,t)
54Ni β+ → 54Co
0.511 background
0.938, 1+
3.376
3.889
4.544
1000
Eγ in 54Co (MeV)
Newly observed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



Comparison

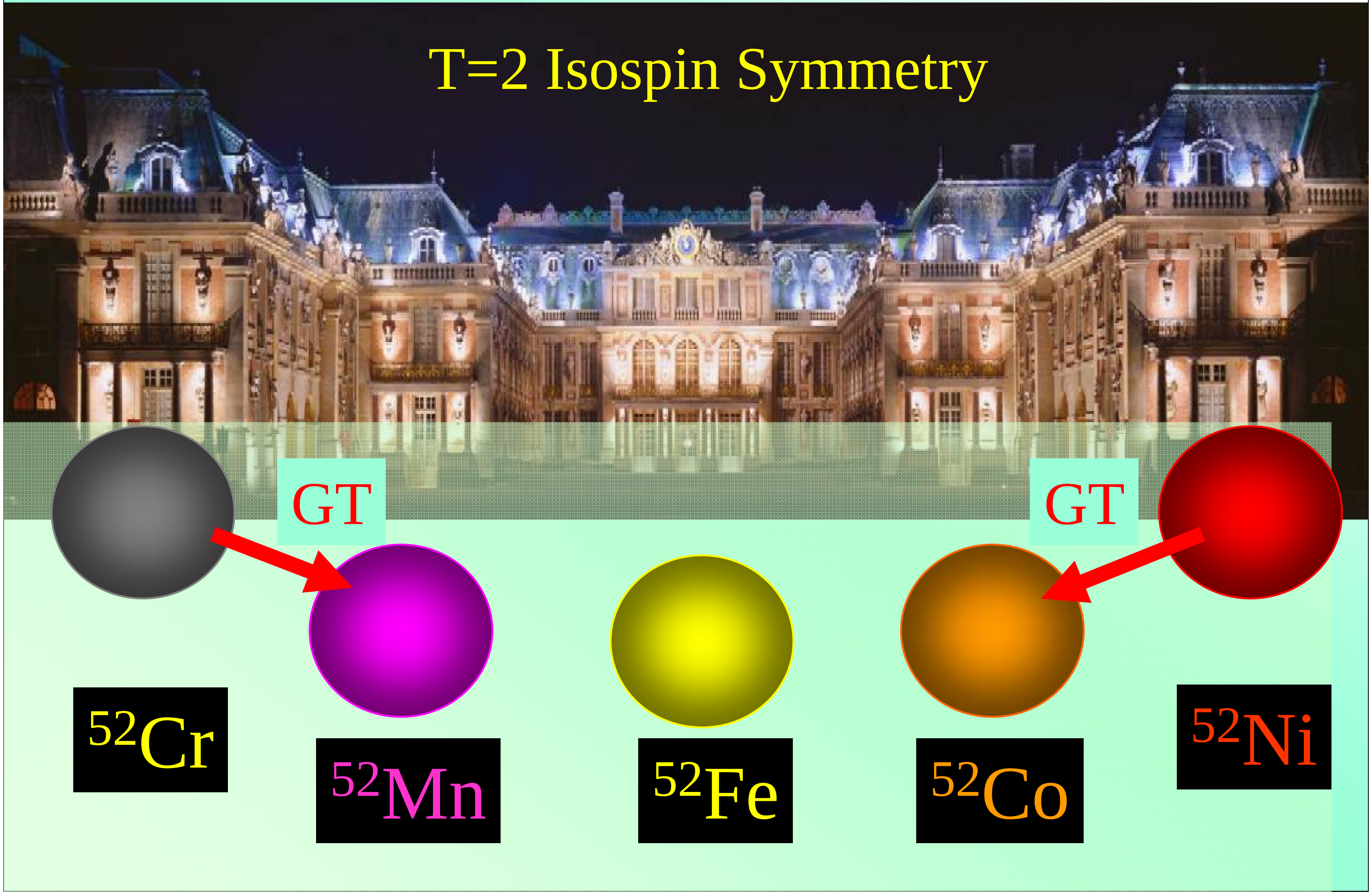
B(GT) $(^{3}He,t)$	B(GT) β-decay
0.09	0.07
0.07	0.07
0.46	0.48



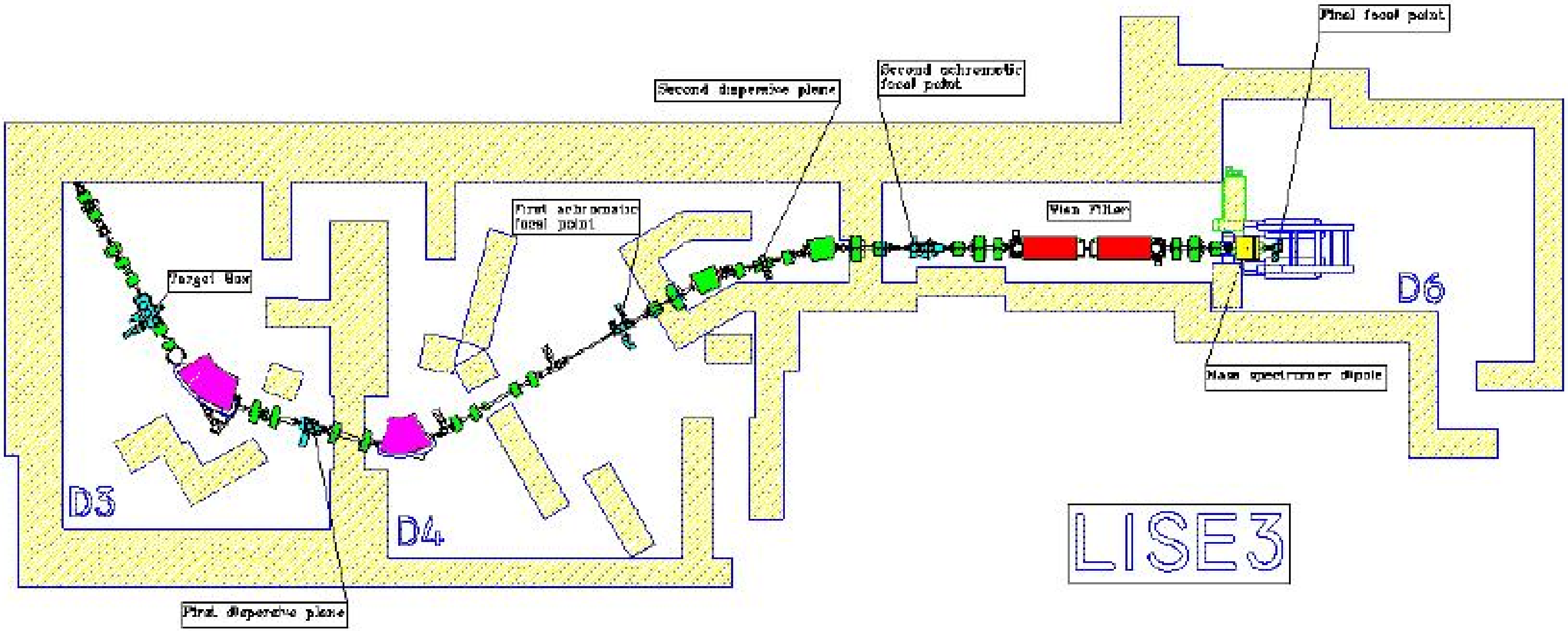


rp -process Path
(T=2 system)
Z
N
N=Z line
56Zn
52Ni
48Fe
44Cr
56Fe
52Cr
48Ti
44Ca
Zn (30)
Ni (28)
Co
Fe (26)
Cr (24
V (23)
20
22
24
26

Chateau de Versailles



GANIL LISE3 fragment separator

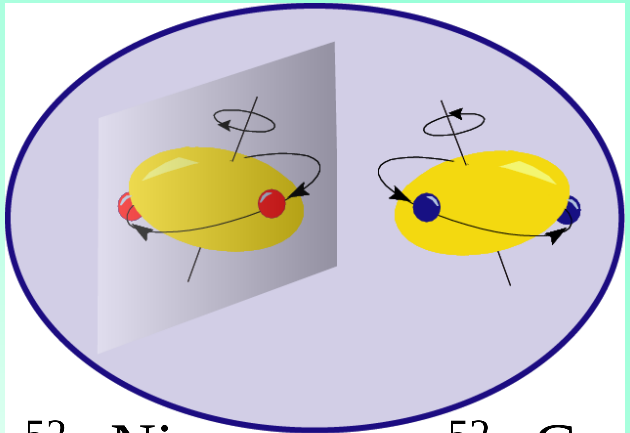


^{58}Ni beam: ~ 79MeV/u, 3.5 eμA, production target: Ni

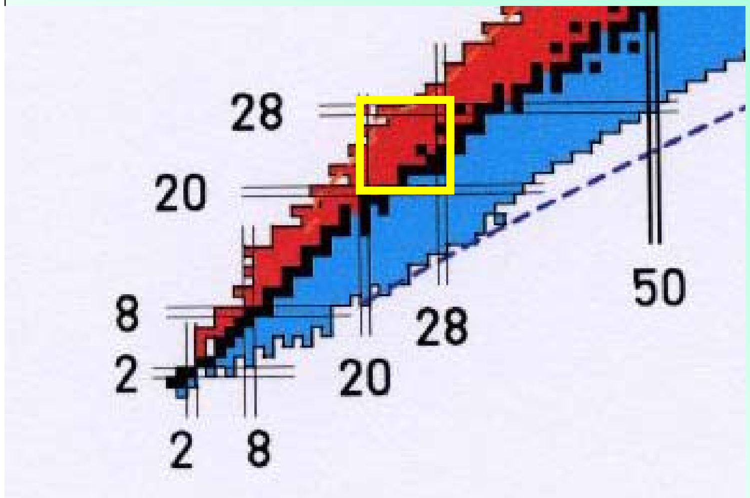
p-decay: by DSSD, γ-decay: by Ge detectors

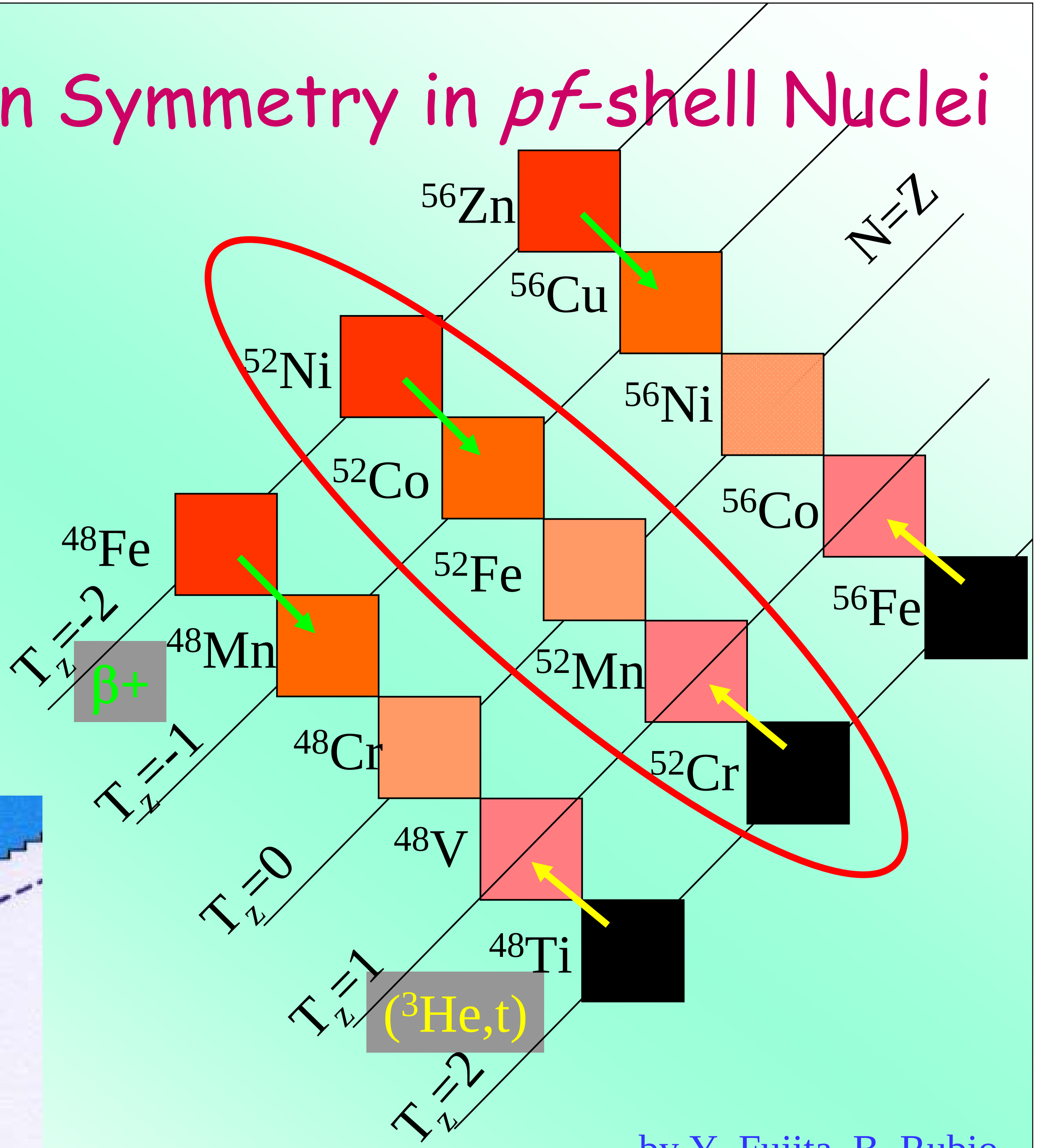
T = 2 Isospin Symmetry in *pf*-shell Nuclei

Mirror nuclei



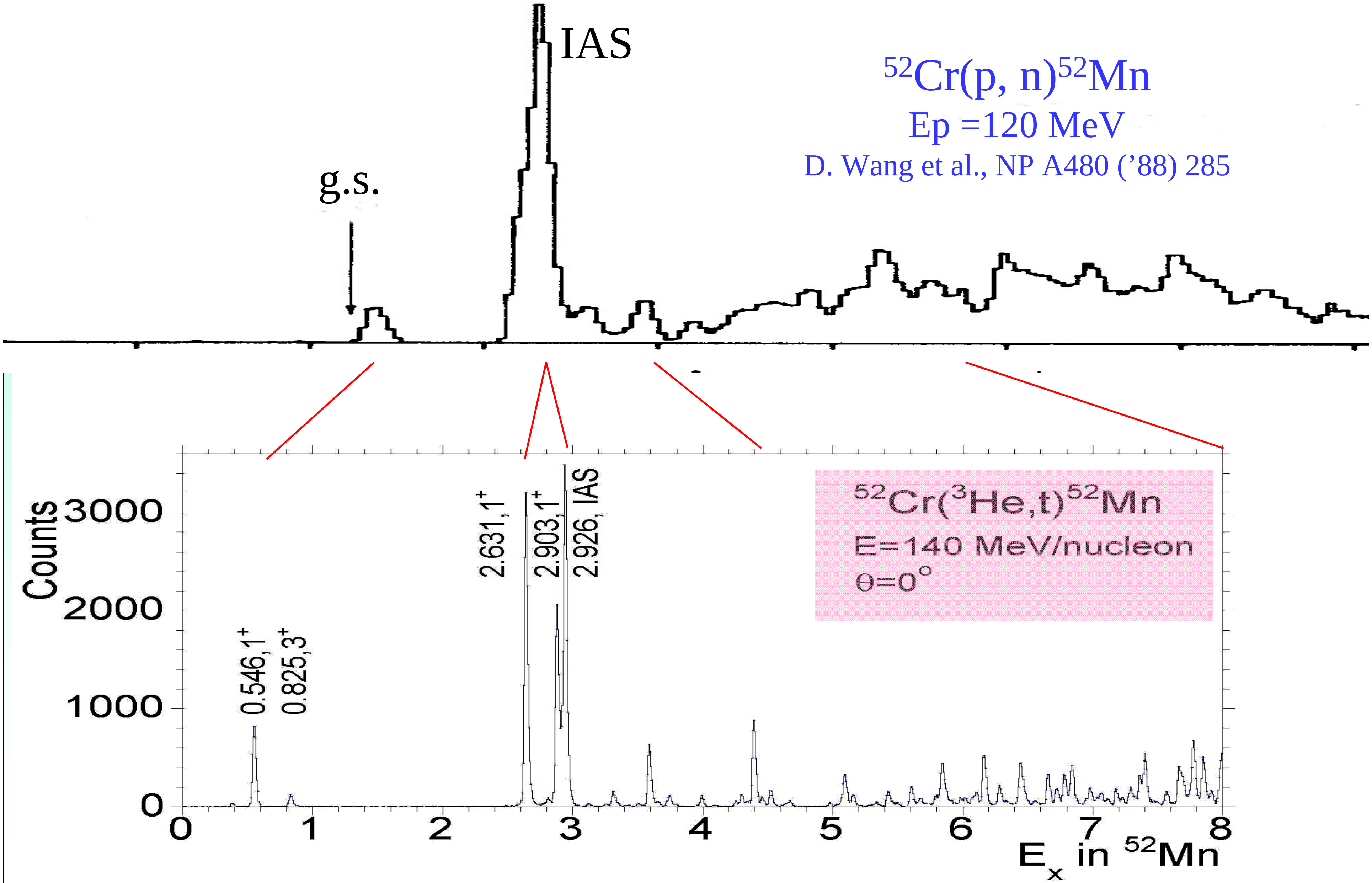
$^{52}_{28}Ni_{24}$ $^{52}_{24}Cr_{28}$



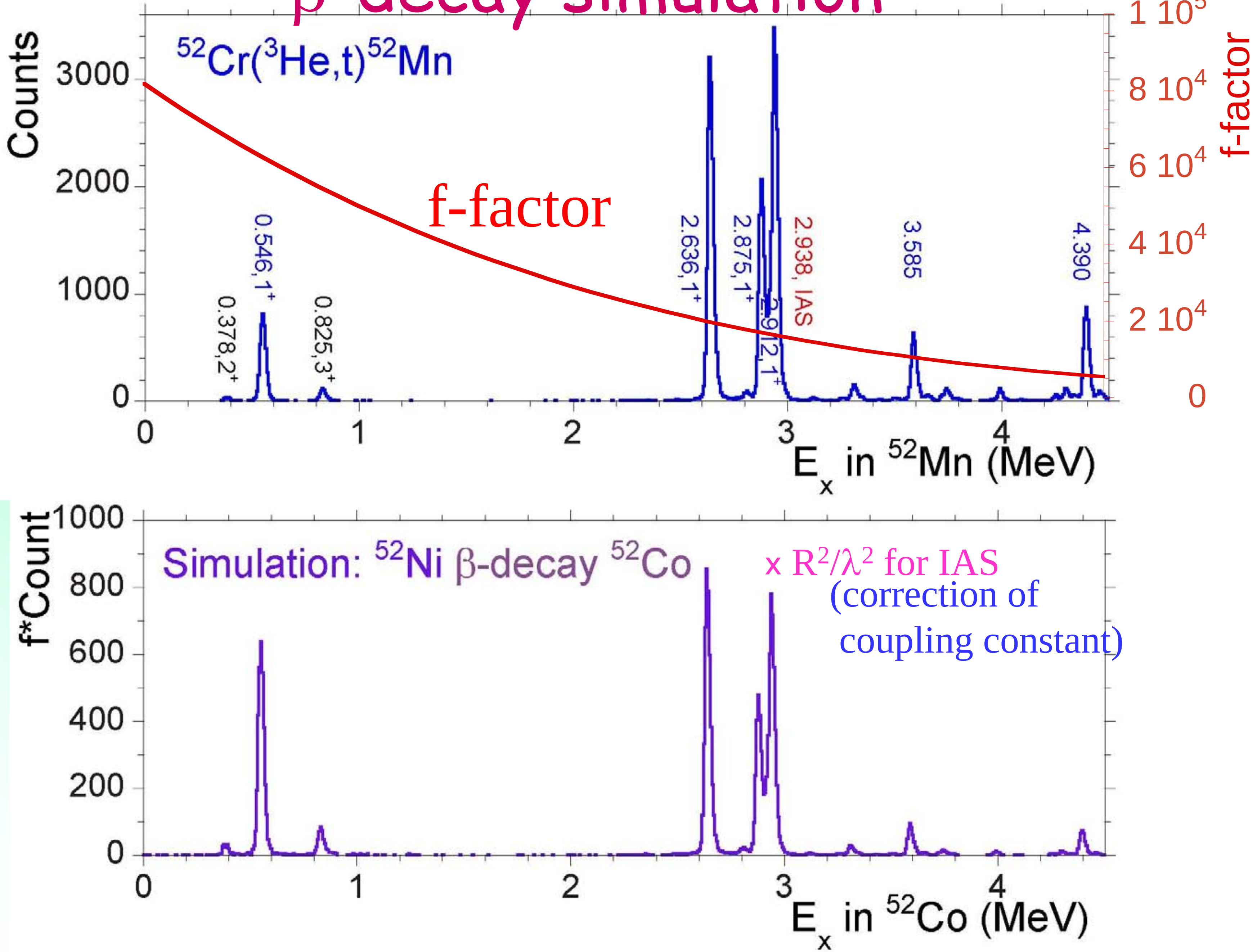


by Y. Fujita, B. Rubio

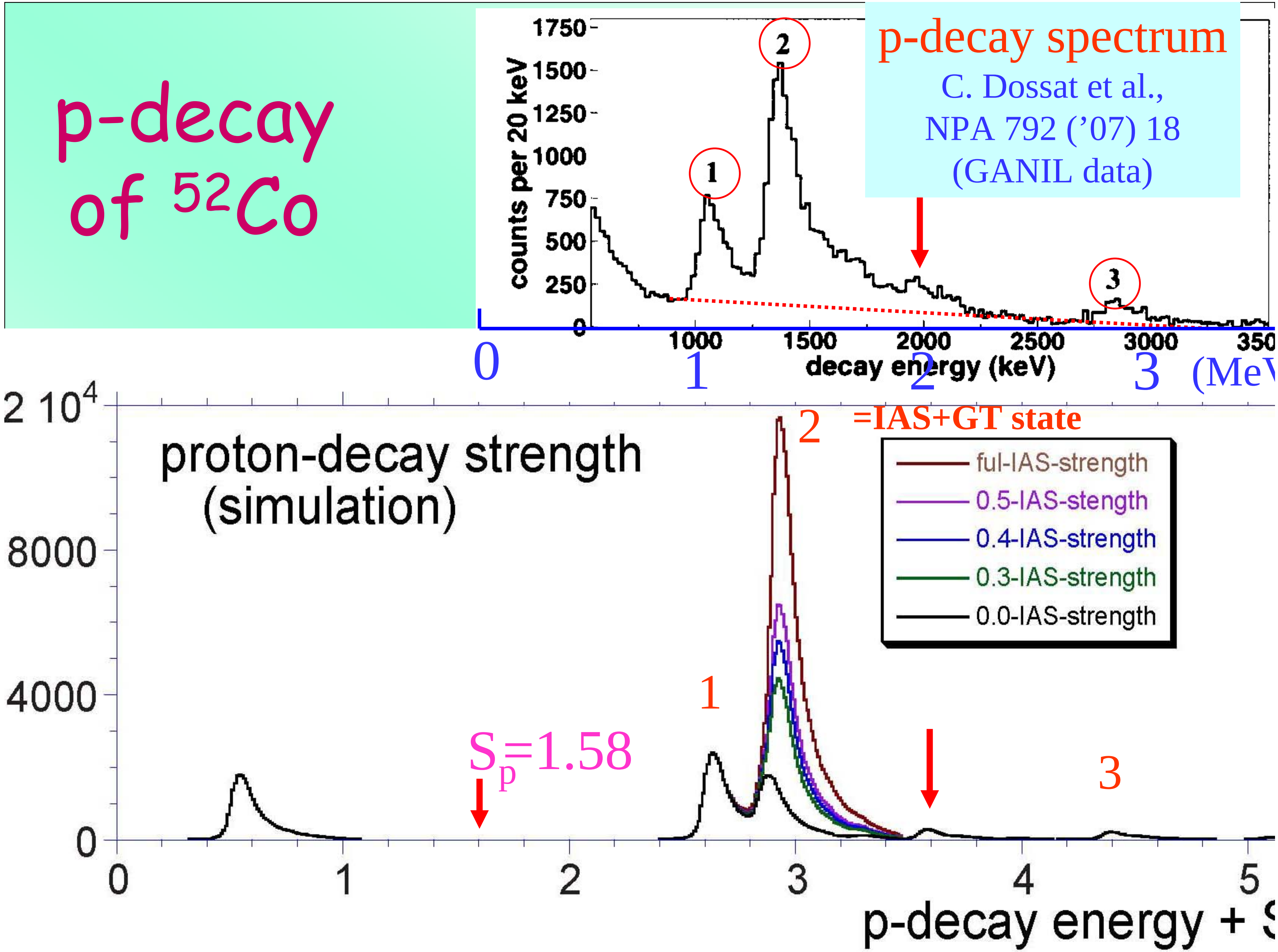
Comparison: (p, n) and (^{3}He,t)



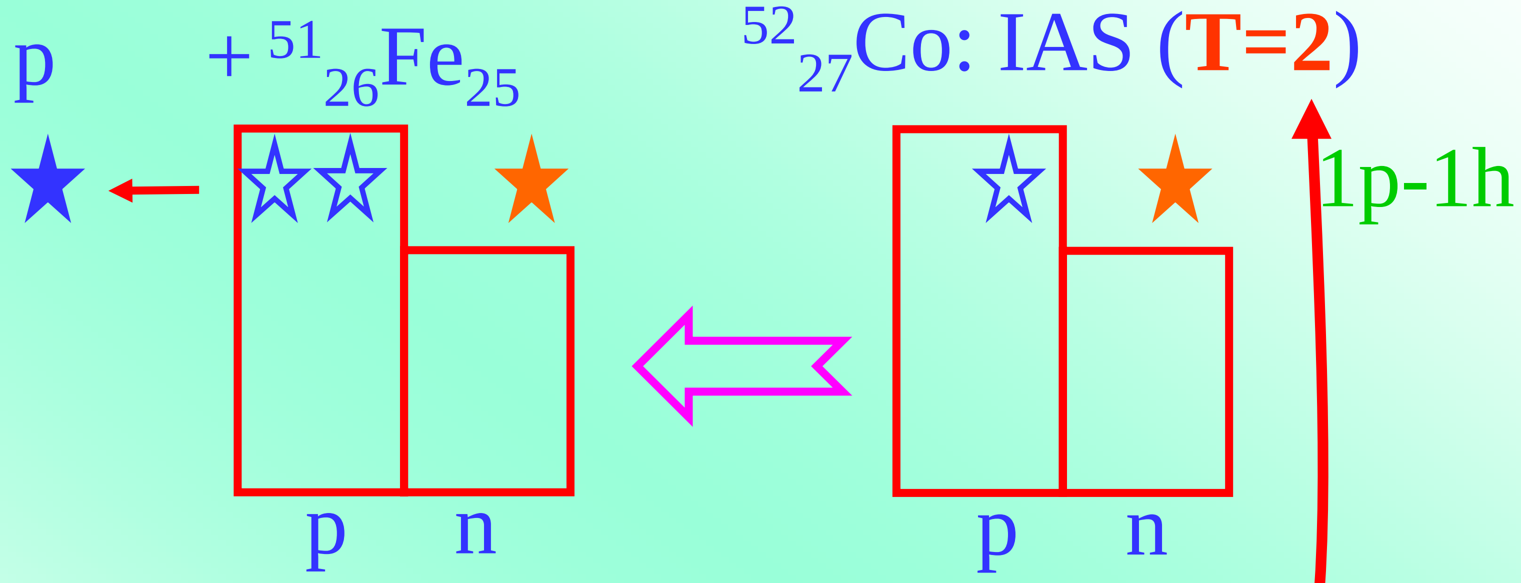
β-decay simulation



p-decay of ^{52}Co



Isospin Selection Rule : *p*-decay of IAS in ^{52}Co



T_z : -1/2 + (-1/2) = -1

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

Therefore, delayed ***p***-decay of the IAS is forbidden!

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 !
➔ Vital part of the Nuclear Structure is revealed !

GT transitions:
- transitions with full of personality -

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Review

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

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(2011) 549-606

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