Gamow-Teller transitions: vivid nuclear weak process in the Universe

Yoshitaka FUJITA (Osaka Univ.)
Dept. Physics, University of Warsaw

March 26, 2010

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

✧Good Probe to Study the Key Part of the Nuclear Structure

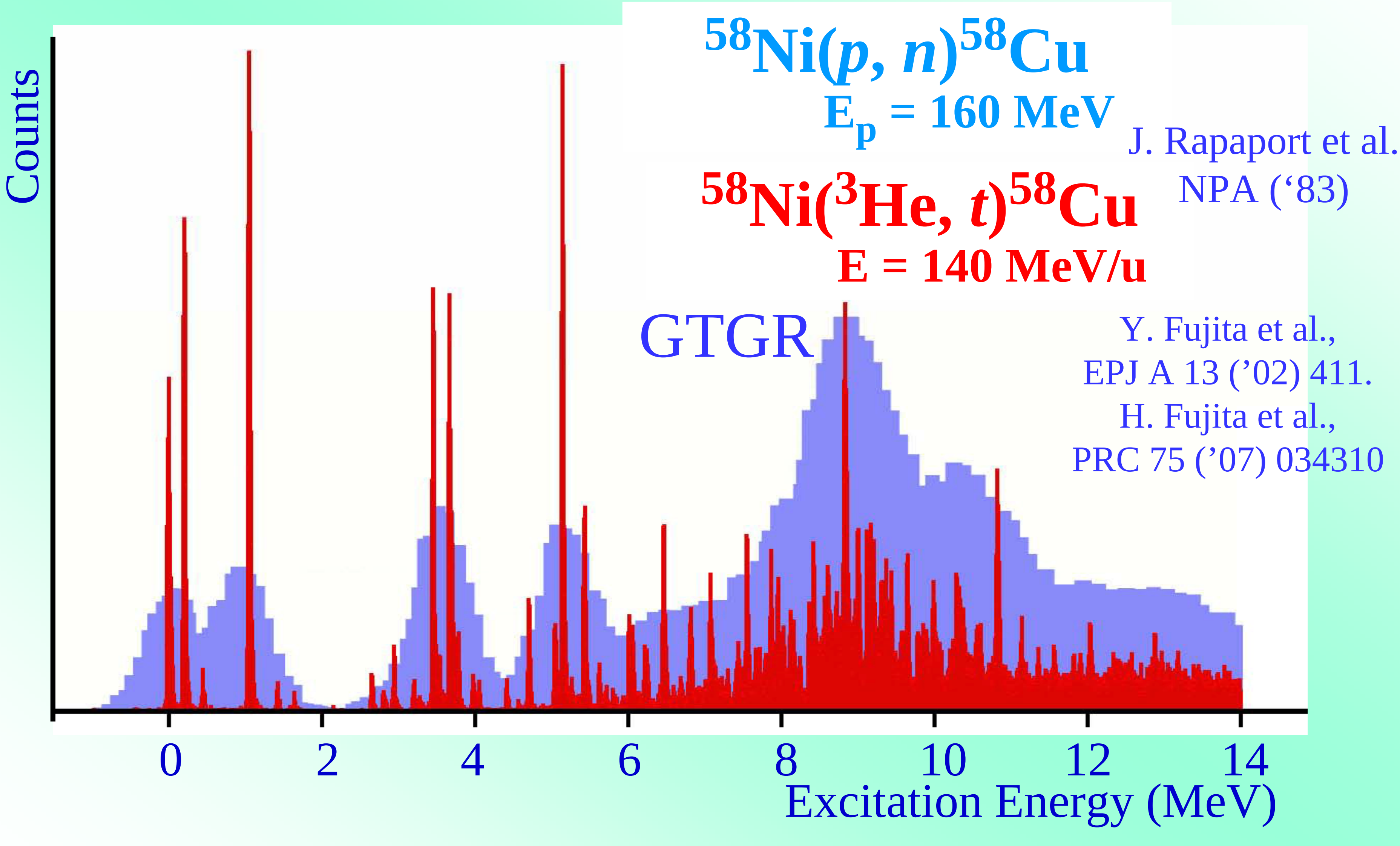
✧Astrophysical Interest

β decay : absolute *B*(GT), limited to low-lying state

(^{3}He,t) reaction : relative *B*(GT), Highly Excited States

** both are important for the GT studies!

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



Neptune driving Waves
波を操る海神ネプチューン

Neptune=**弱い相互作用**
(weak interaction)

Powerful Waves=**強い相互作用**
(strong interaction)

Neptune and the waves, or "steeds," he rides.
Walter Crane, 1892

Crucial Weak Processes during the Core Collapse

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

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

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

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

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

$$N +$$

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

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

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

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

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

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

mainly by τ & στ

↓

Gamow-Teller (GT) transitions

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

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

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

Nuclear Excitations
by
Charge Exchange Reaction
and β-Decay

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

β-decay & Nuclear Reaction

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

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

$\propto$ (matrix element)^2

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

= reaction mechanism

⊗ operator

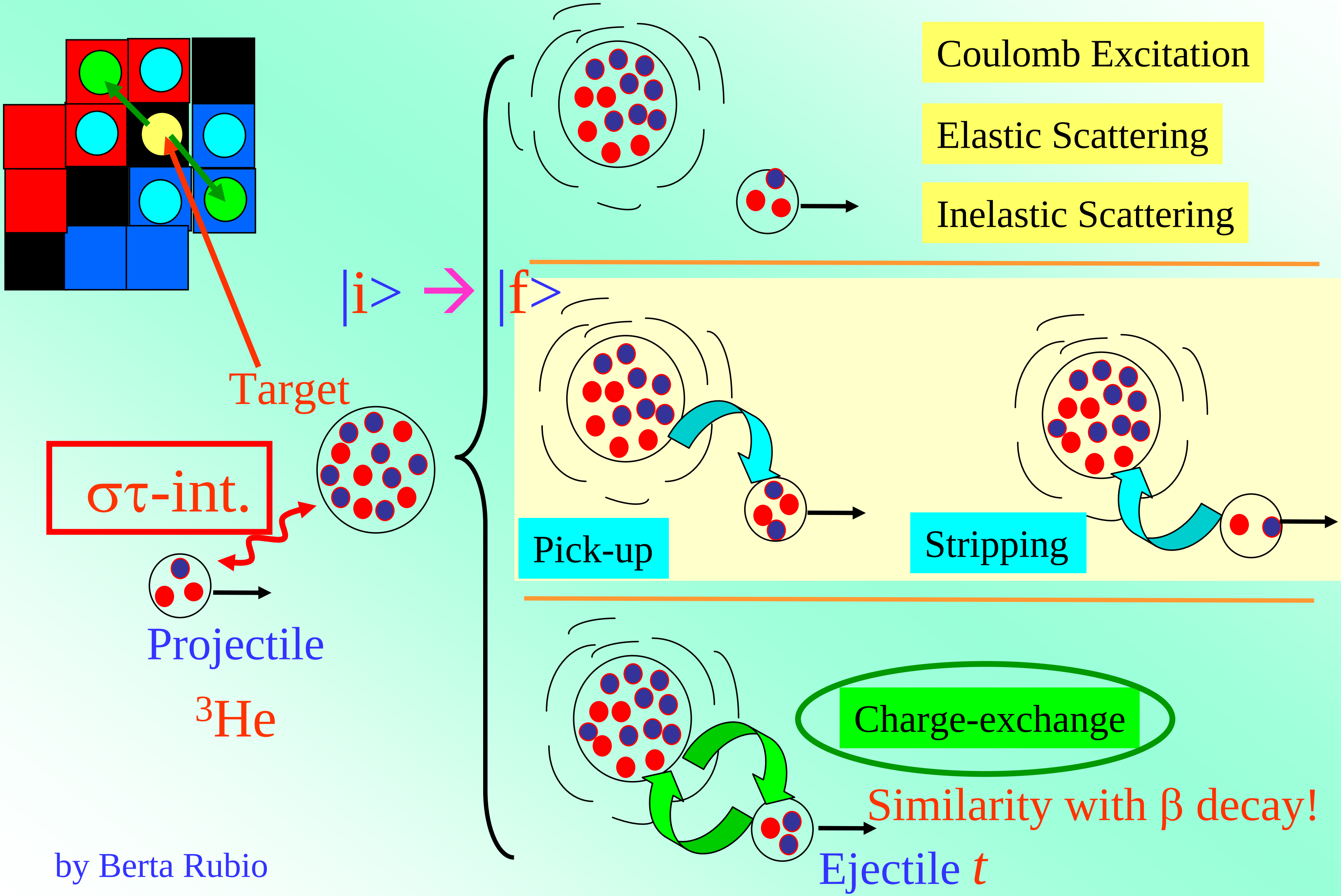
⊗ structure

=(matrix element)^2

A simple reaction mechanism should be achieved !

➡ we have to go to high incoming energy

Direct Reactions with Light Projectiles



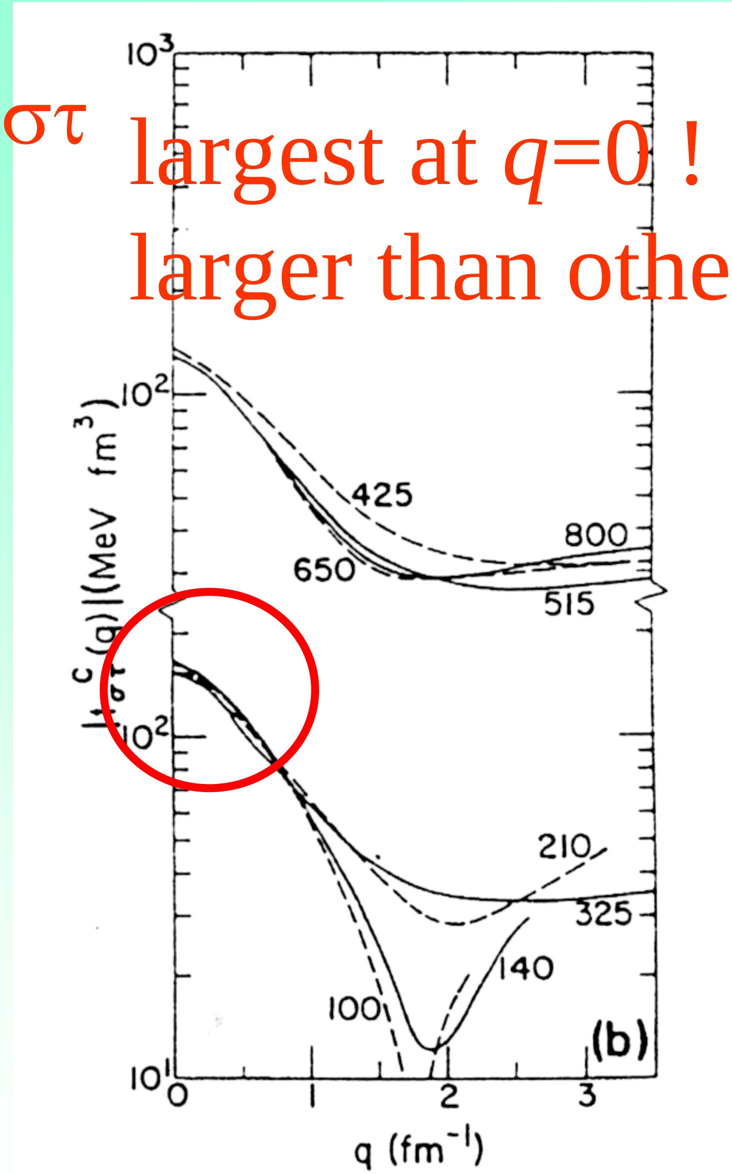
by Berta Rubio

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

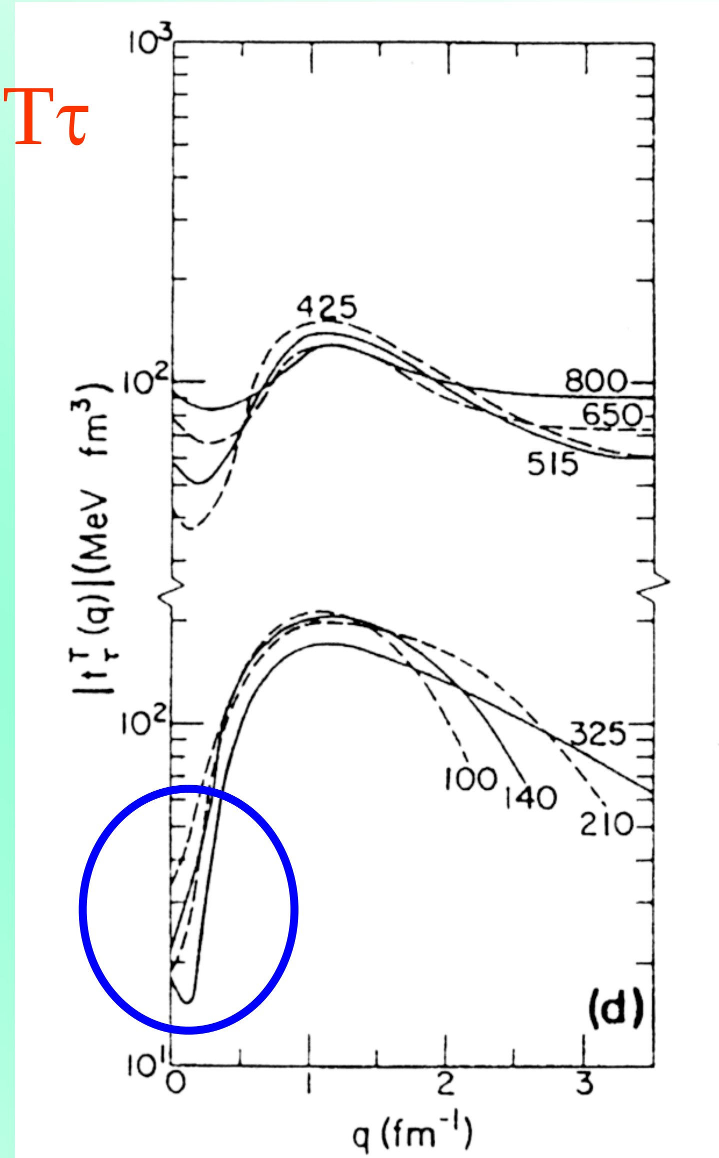
στ

largest at *q*=0 !

larger than others !



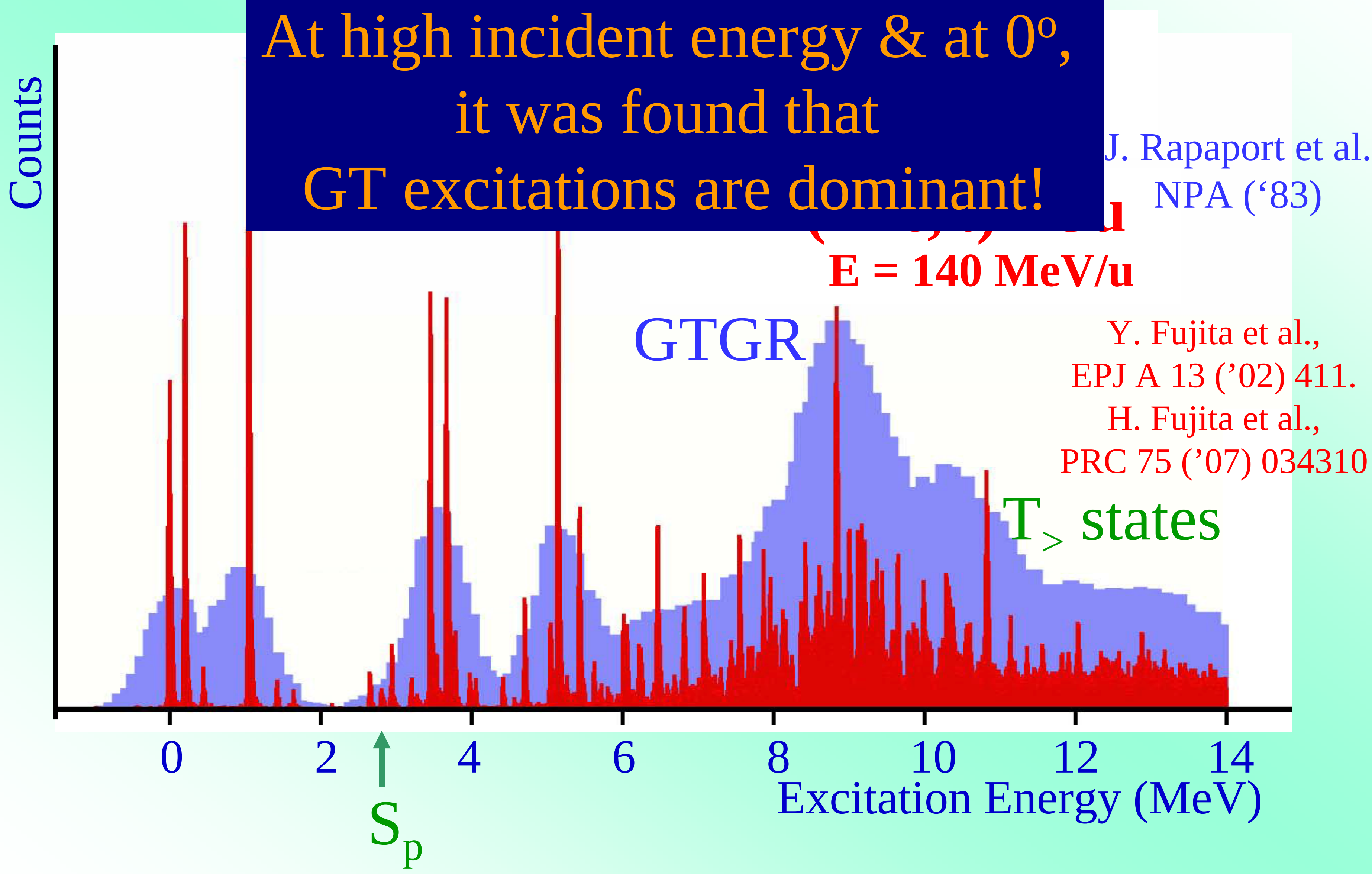
Tτ



Love & Franey PRC 24 ('81) 1073

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

At high incident energy & at 0^o,
it was found that
GT excitations are dominant!



β-decay & Nuclear Reaction

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

ngth

n)

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

ⓧ operator

ⓧ structure

$=(\text{matrix element})^2$

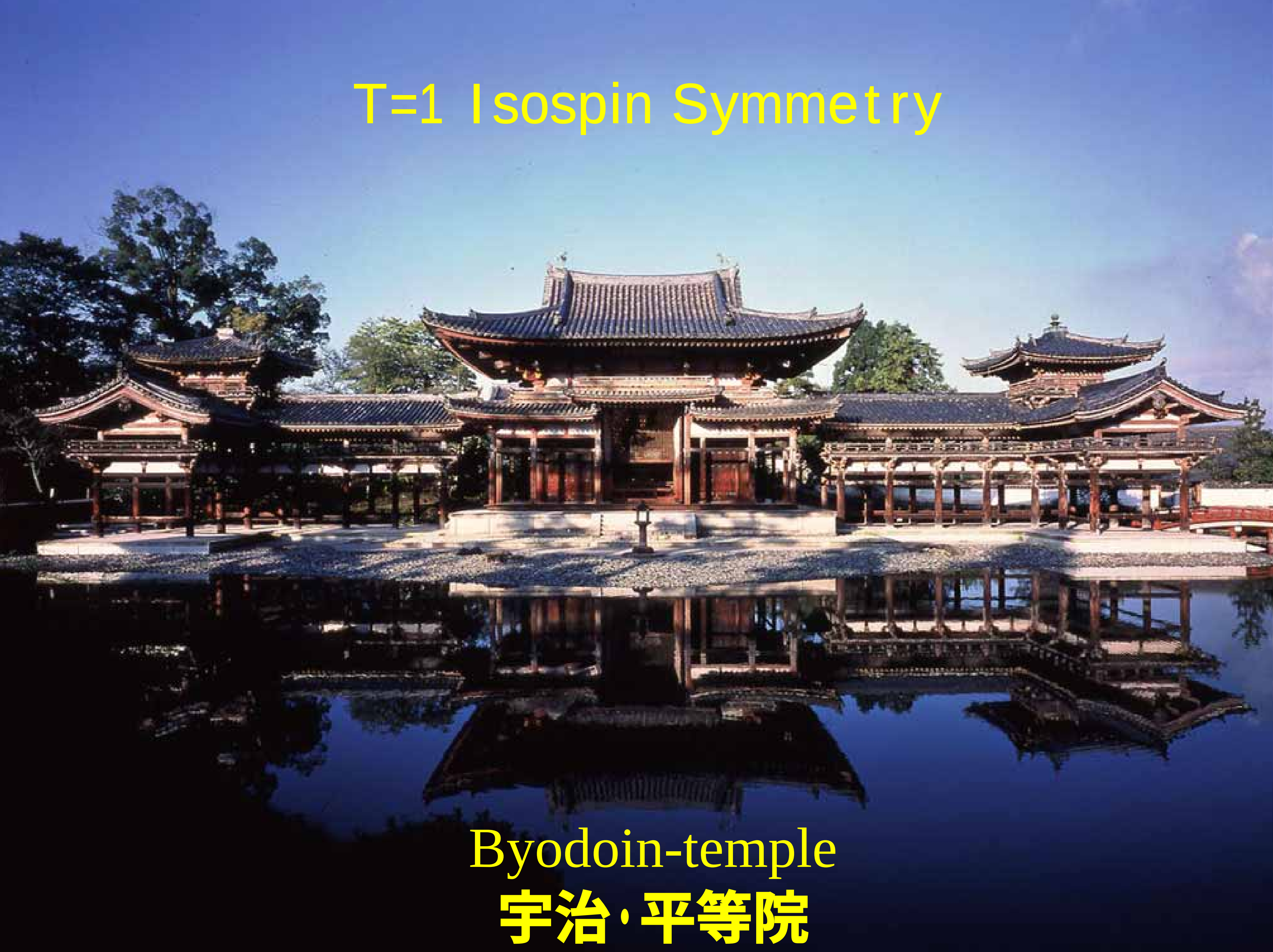
A simple reaction mechanism should be achieved !

→ we have to go to high incoming energy

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

by means of
Isospin Symmetry

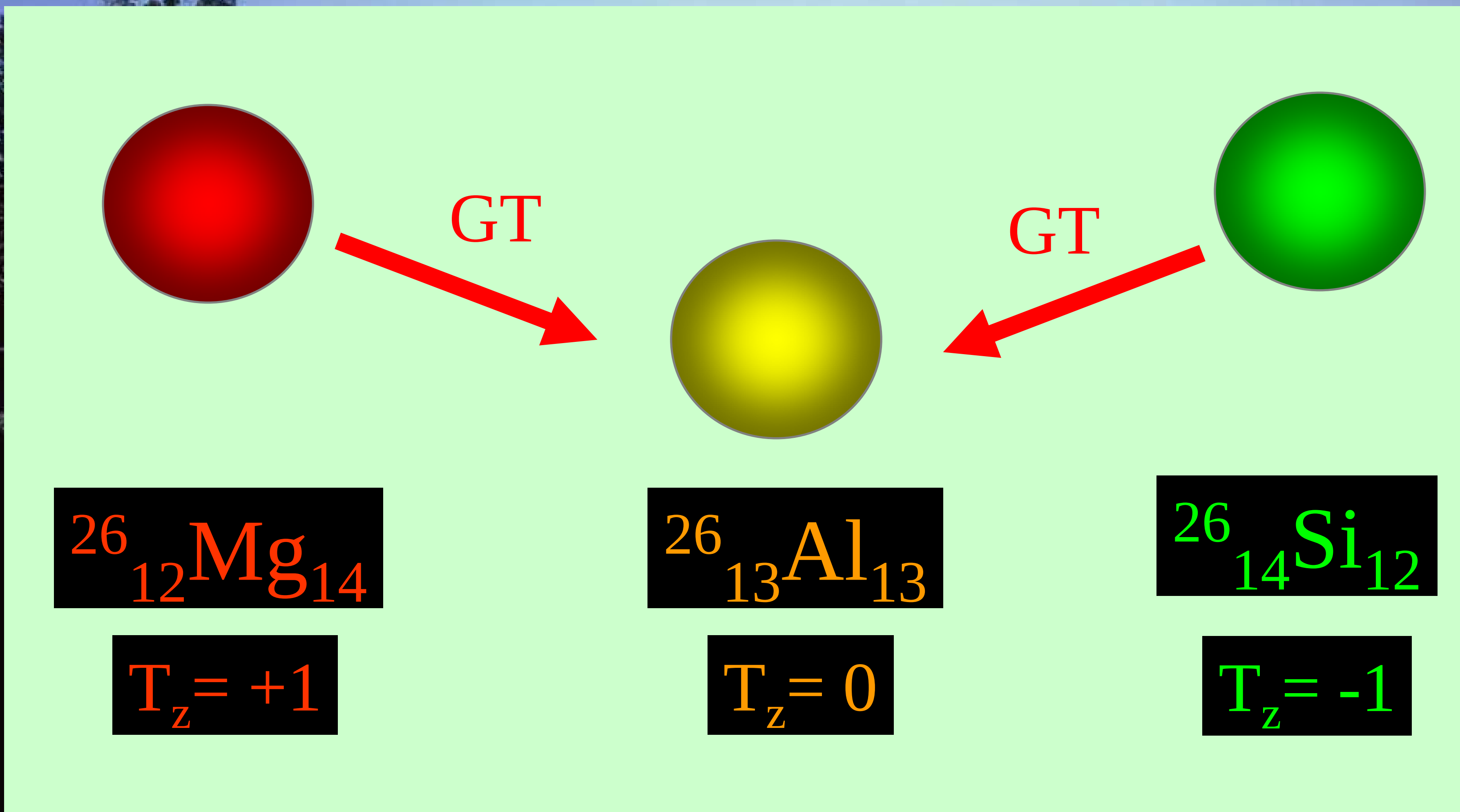
T=1 Isospin Symmetry



Byodoin-temple

宇治·平等院

T=1 Isospin Symmetry



Transitions in real & isospin space (T=1)

Symmetry Transitions from T=1 Nuclei

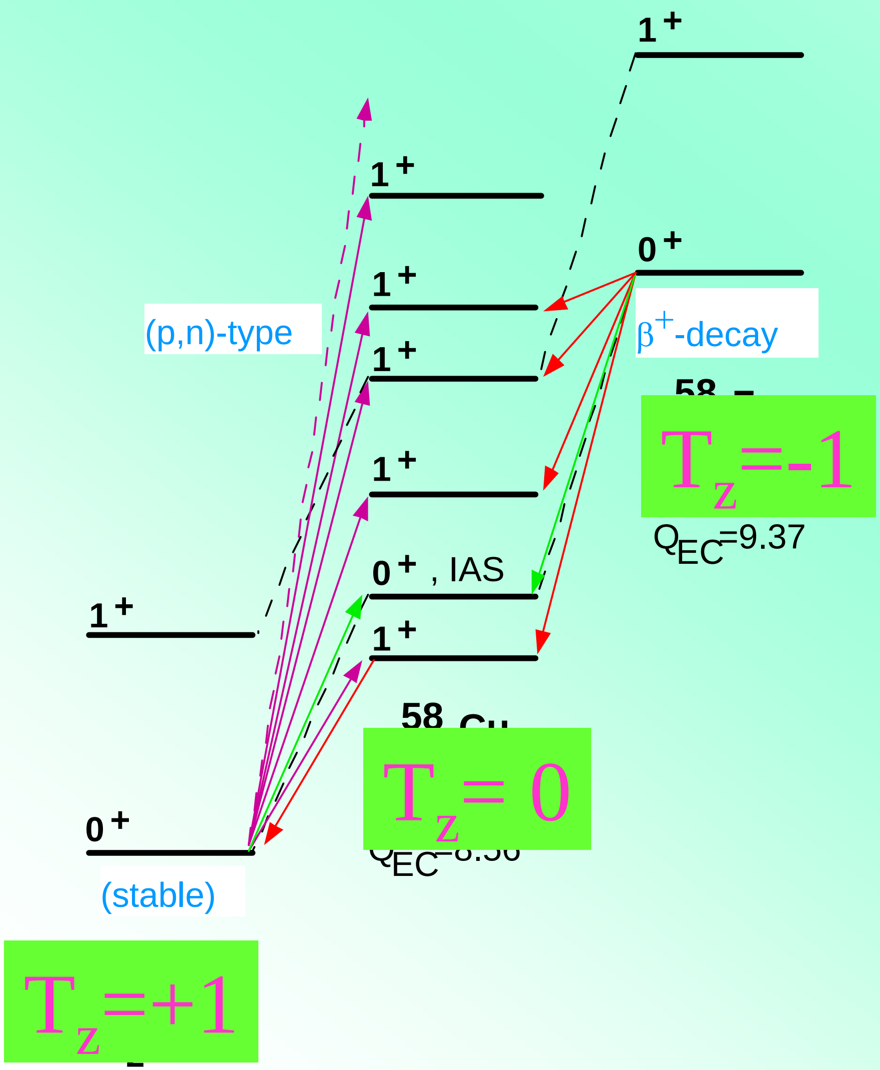
$T_z=+1 \rightarrow T_z=0 \leftarrow T_z=-1$

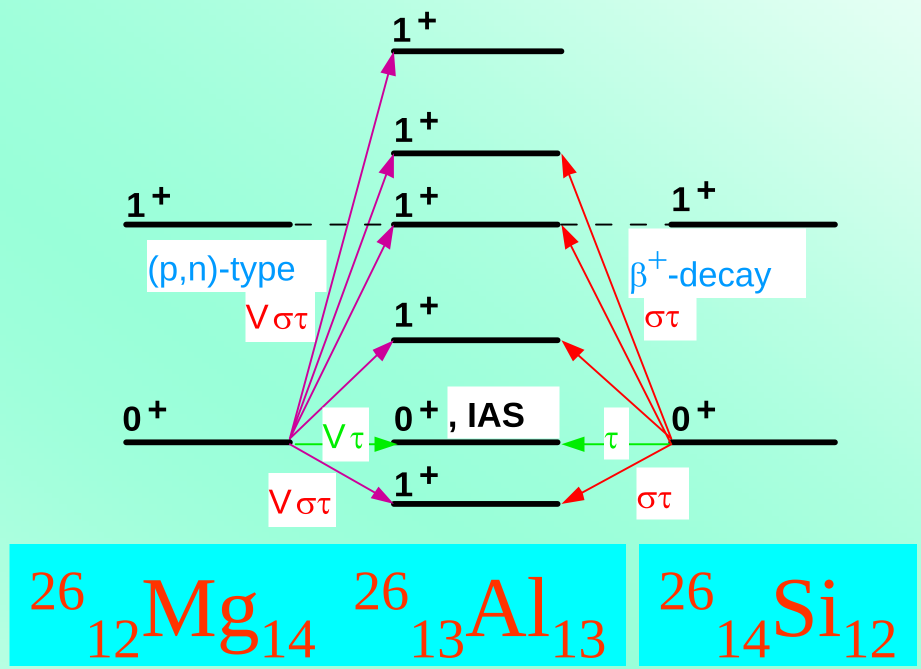
(in real energy space)

Symmetry Transitions from T=1 Nuclei

$T_z=+1 \rightarrow T_z=0 \leftarrow T_z=-1$

(in isospin symmetry space*)



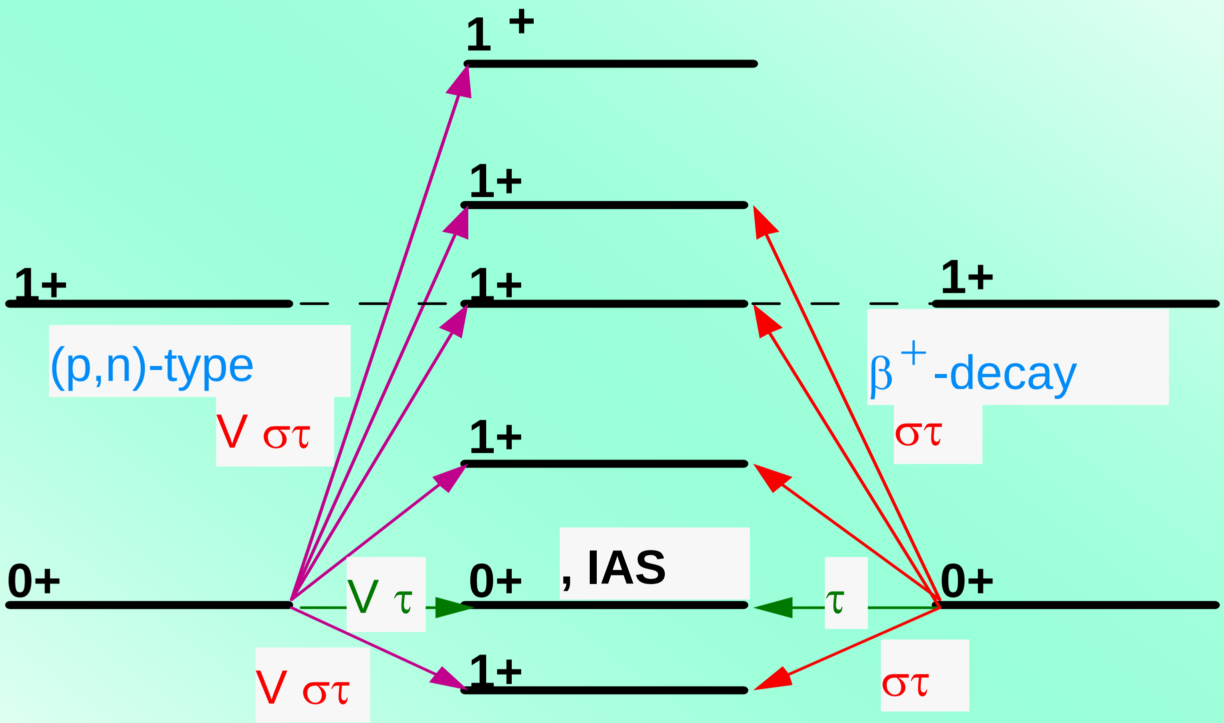


*after the correction of
Coulomb displacement energy

T=1 symmetry : Structures & Transitions

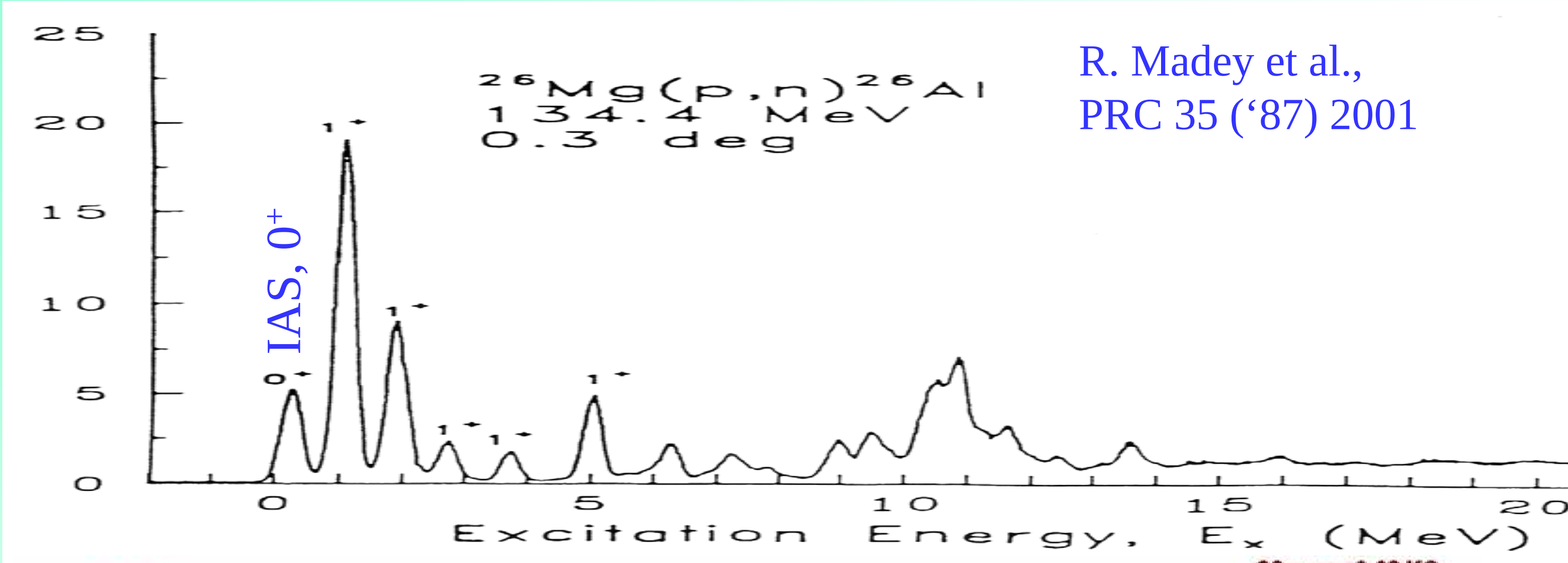
T_z=+1 → T_z=0 ← T_z=-1

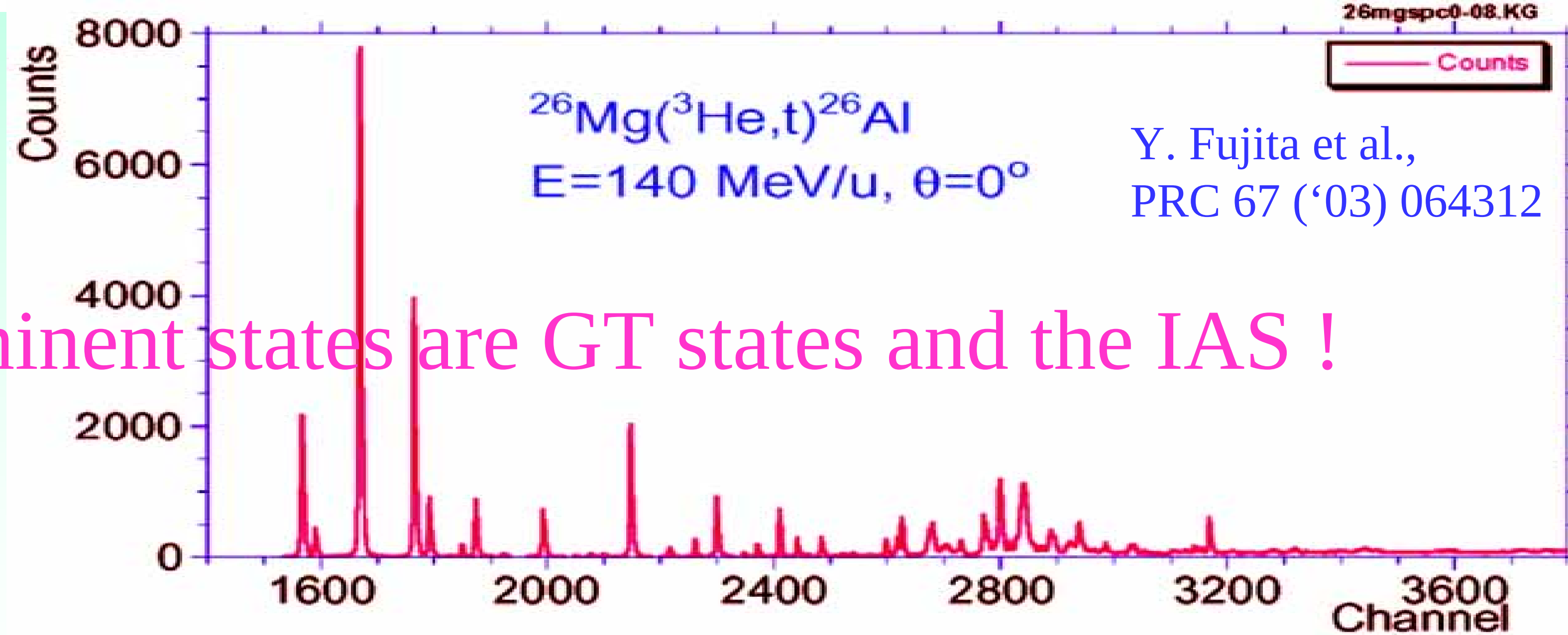
(in isospin symmetry space*)



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

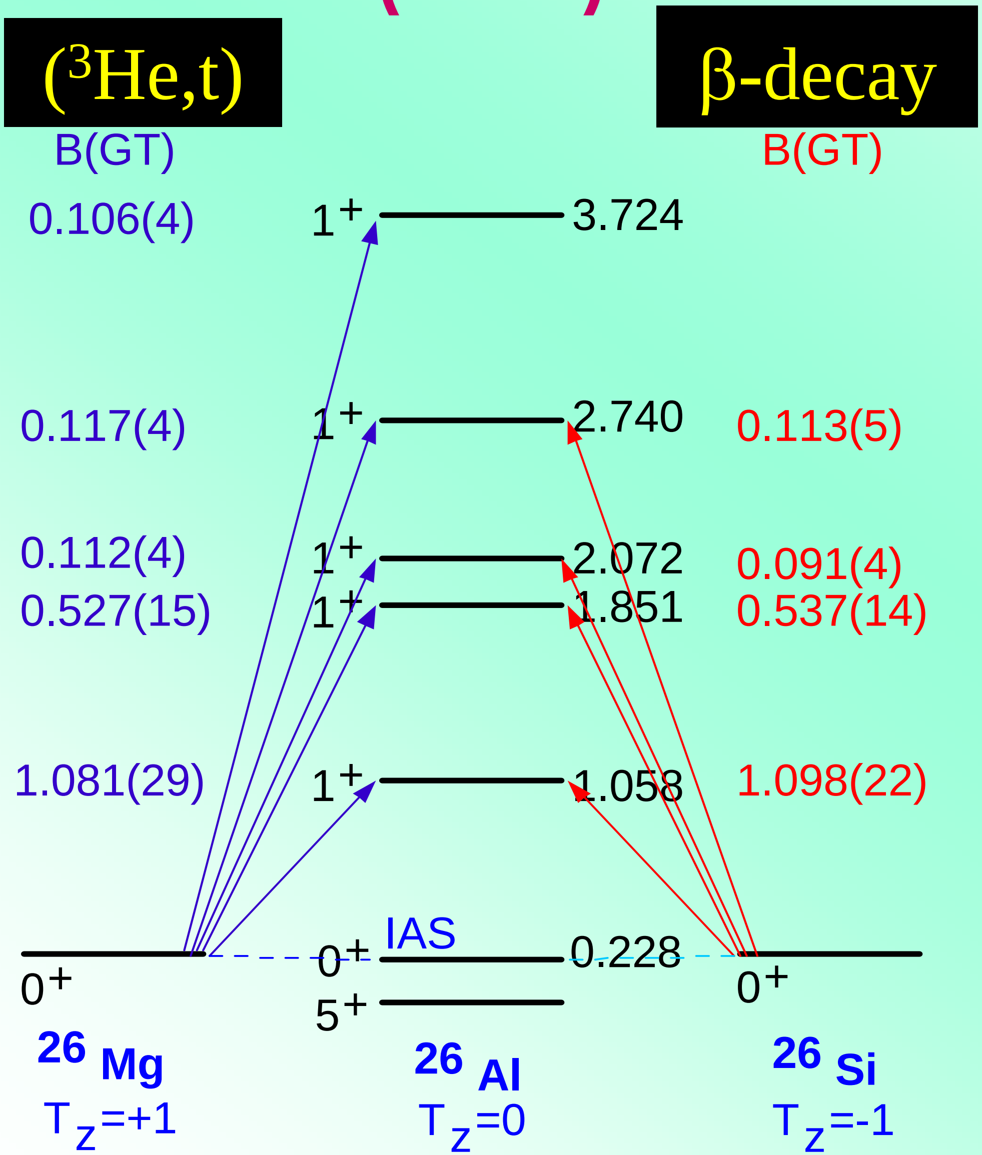
^{26}Mg(p, n)^{26}Al & ^{26}Mg(^{3}He,t)^{26}Al spectra

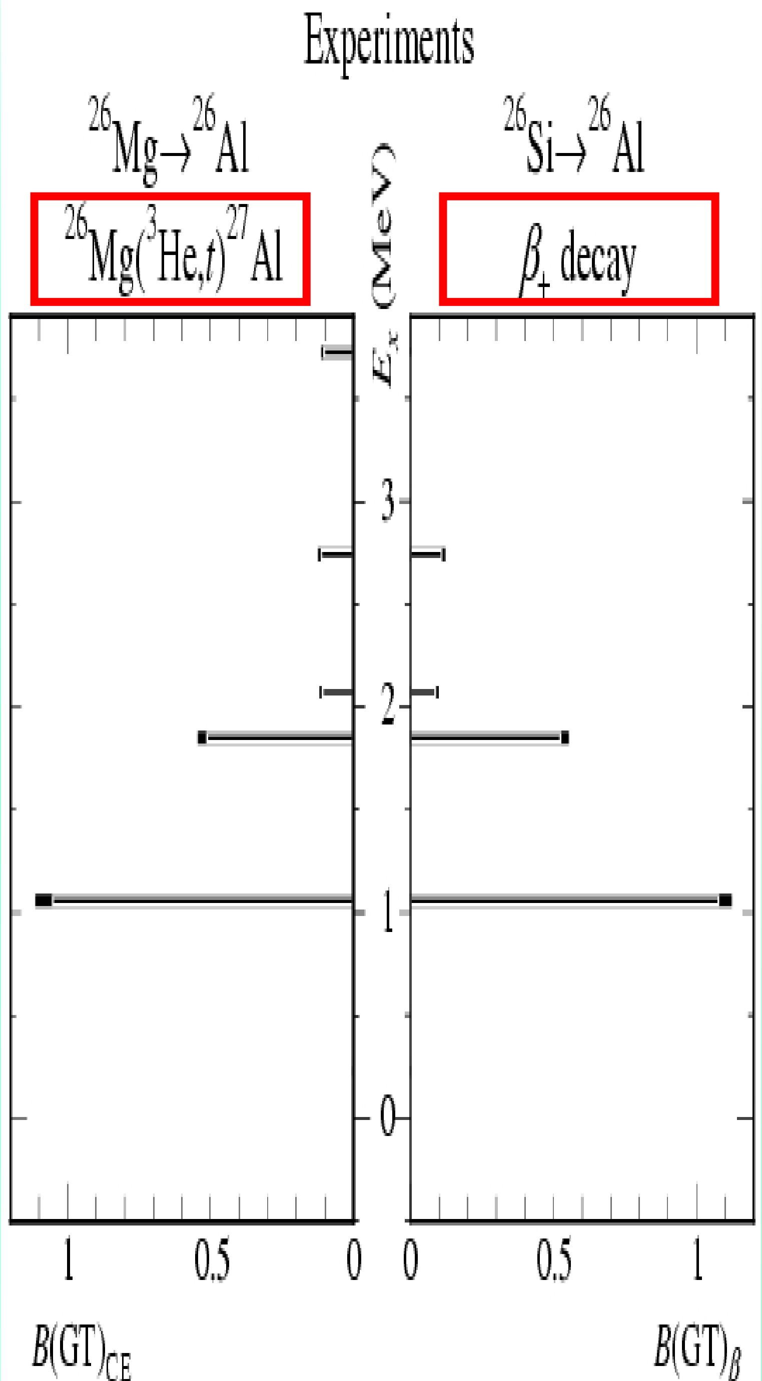




Prominent states are GT states and the IAS !

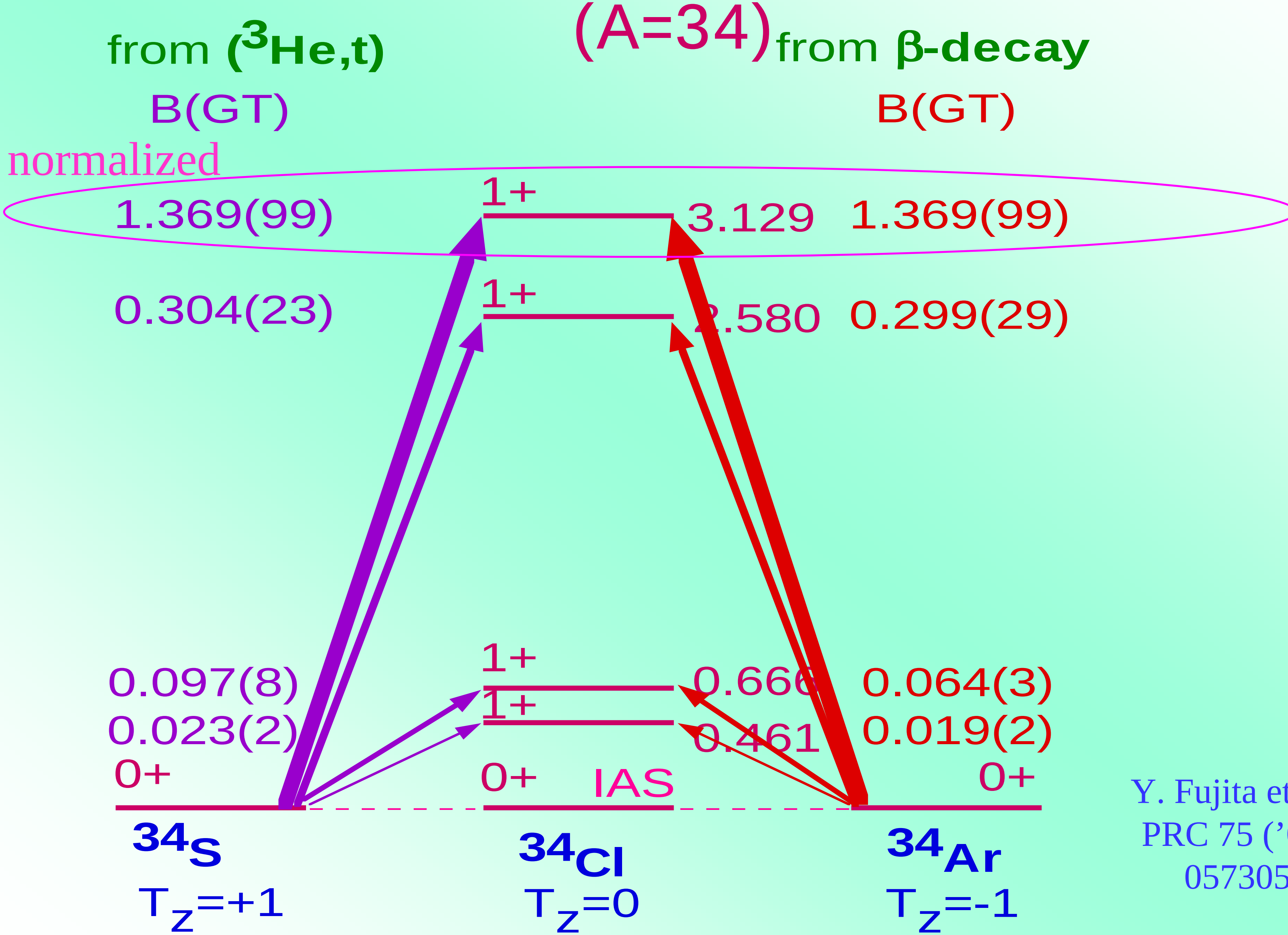
B(GT) values from Symmetry Transitions (A=26)





Y. Fujita et al., PRC 67 (‘03) 064312

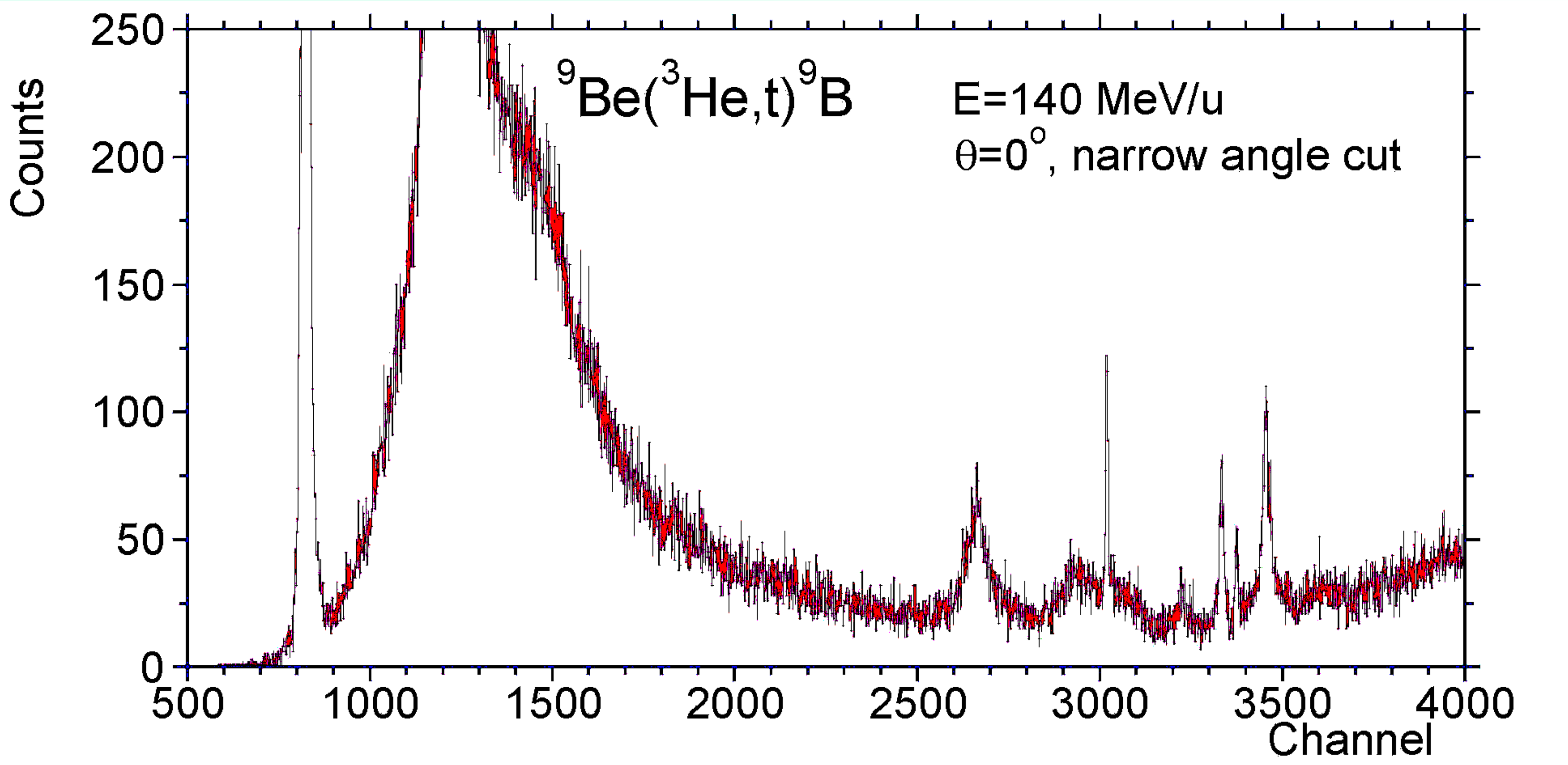
B(GT) values from Symmetry Transitions (A=34)



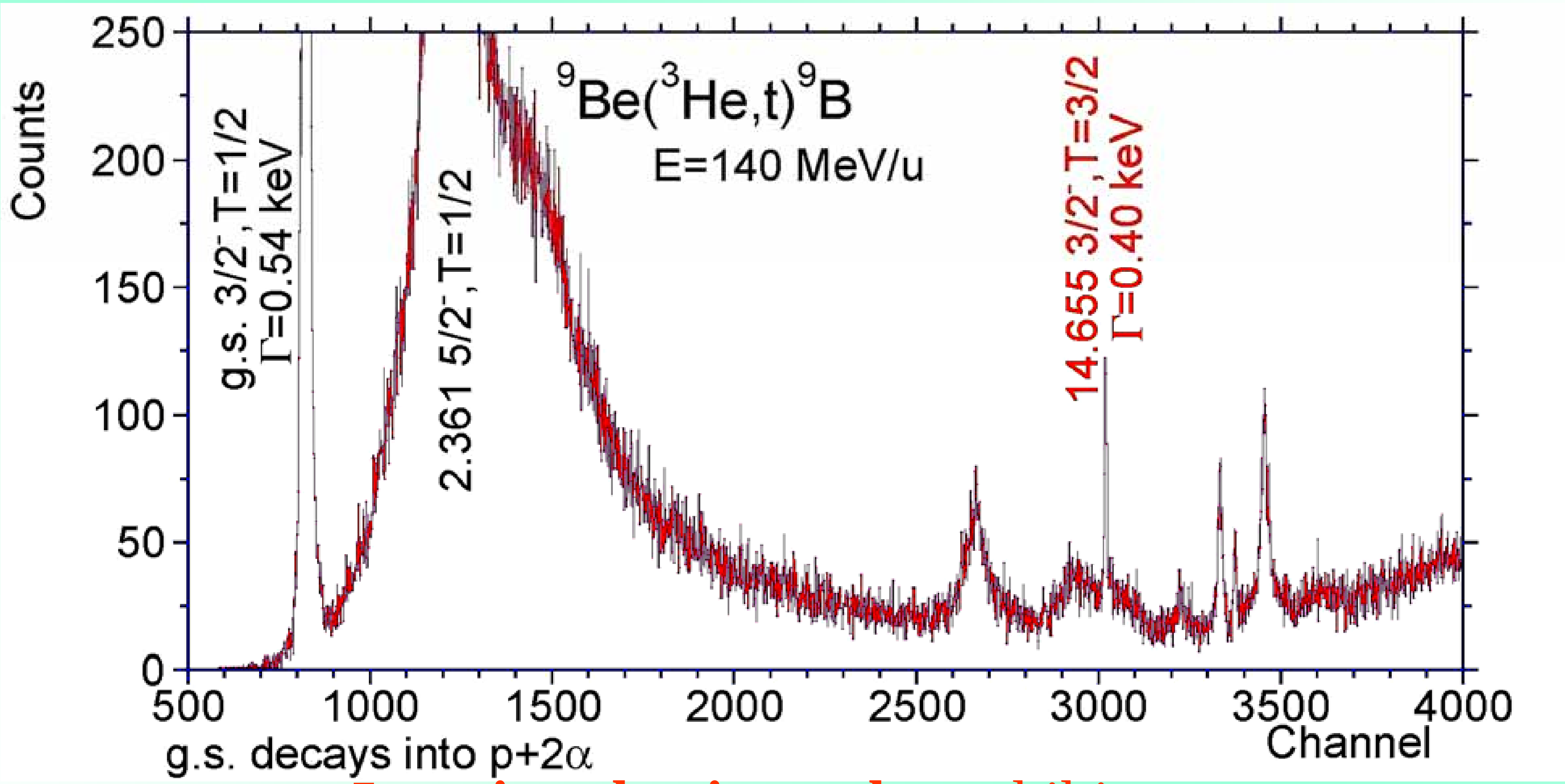
Y. Fujita et al., PRC 75 (’07) 057305

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

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



$^{9}Be(^{3}He,t)^{9}B$ 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 $\Gamma = \Delta E$

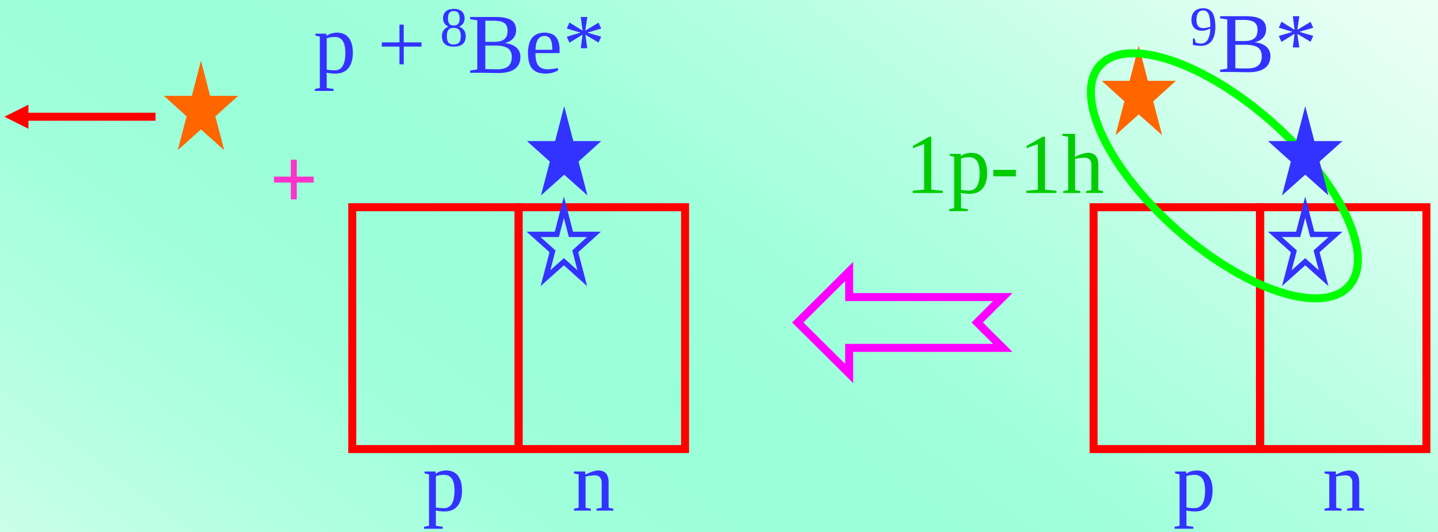
*if: Decay is Fast,

then: Width of a State is Wider !

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

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

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



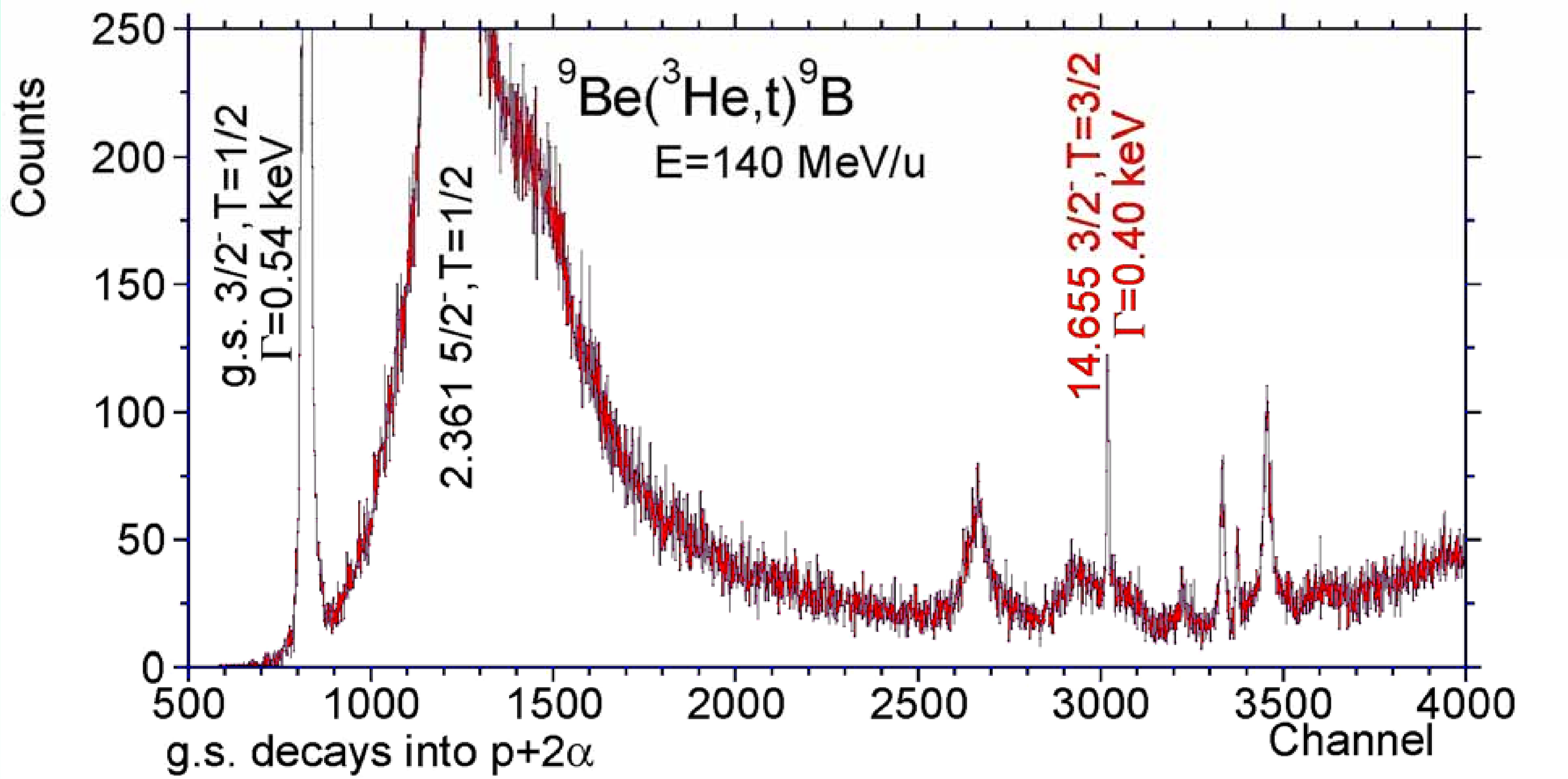
T_z : -1/2 + 0 = -1/2

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

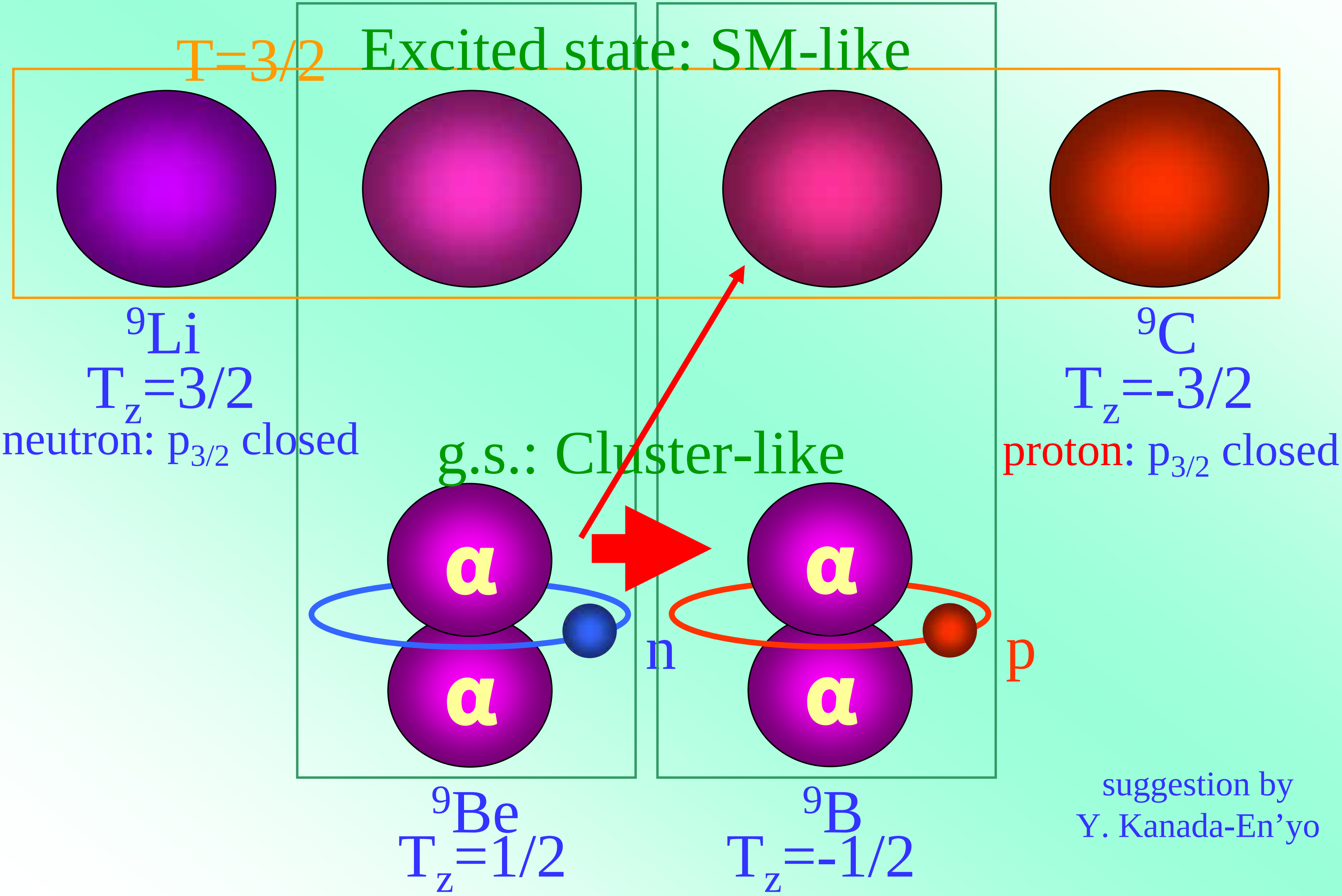
^{9}Be(^{3}He,t)^{9}B spectrum (III)



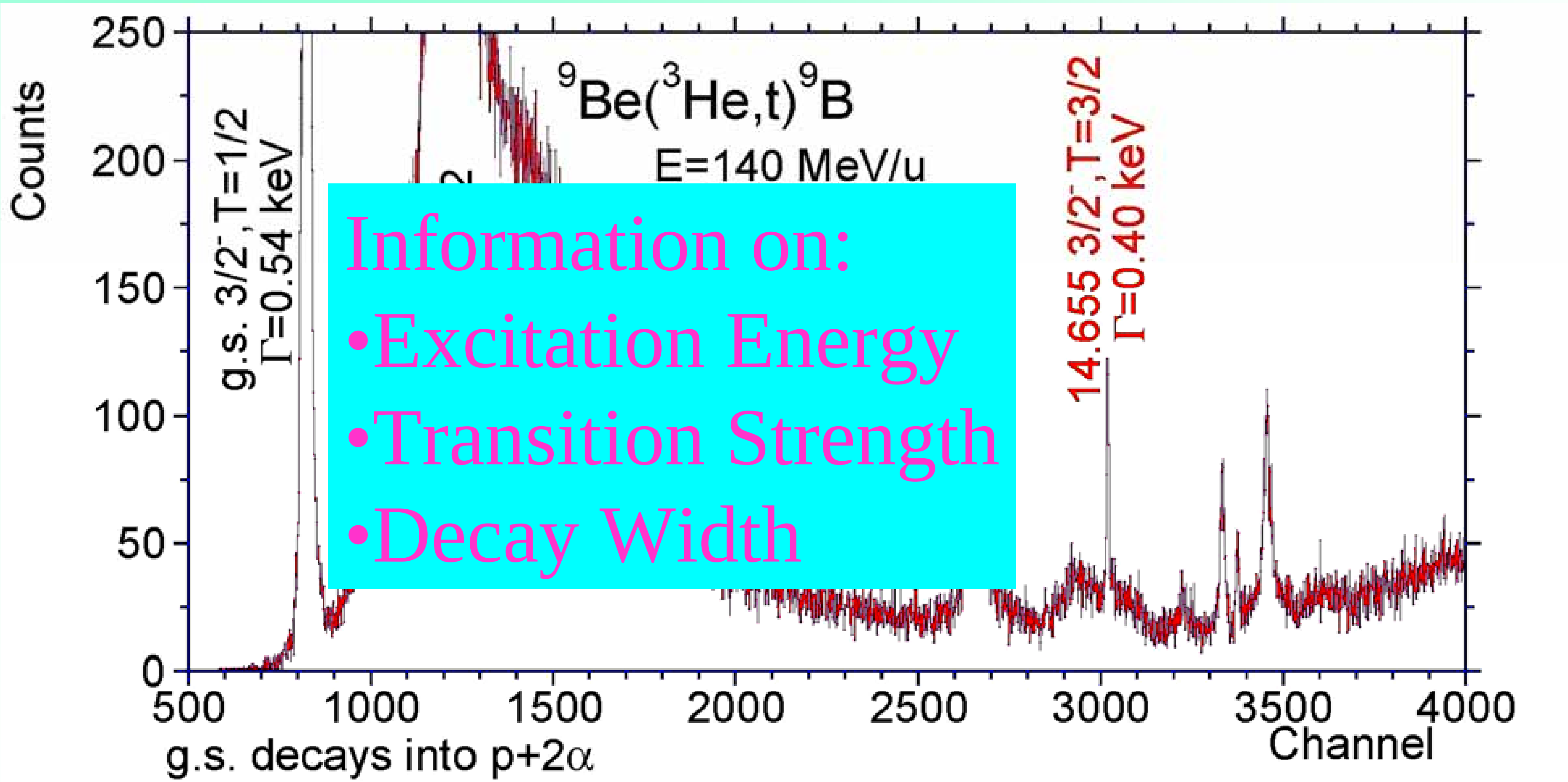
14.7 MeV T=3/2 state is very weak!

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

Shell Structure and Cluster Structure



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

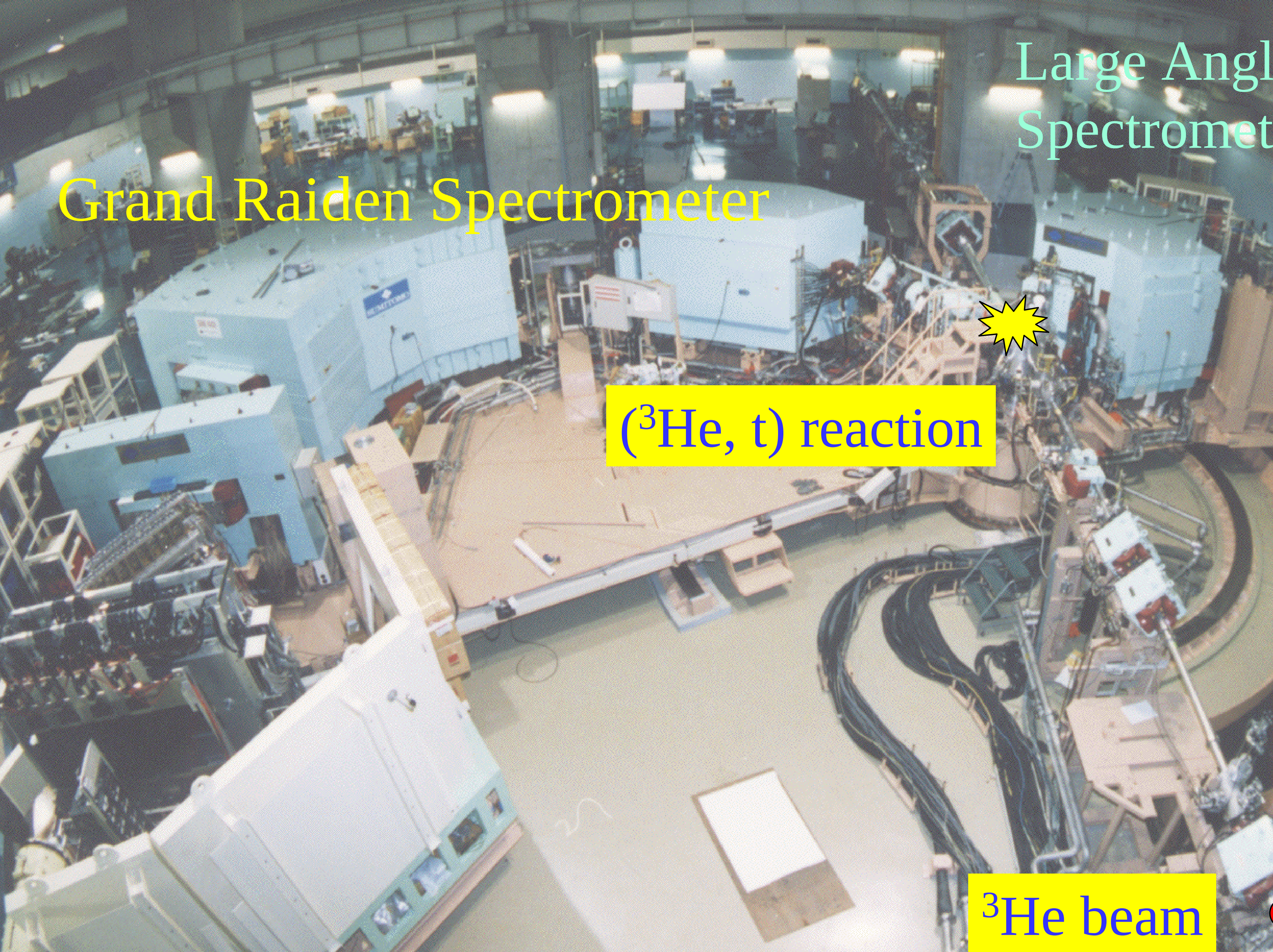
High-resolution Experiment

-beam matching techniques-

(dispersion matching techniques)

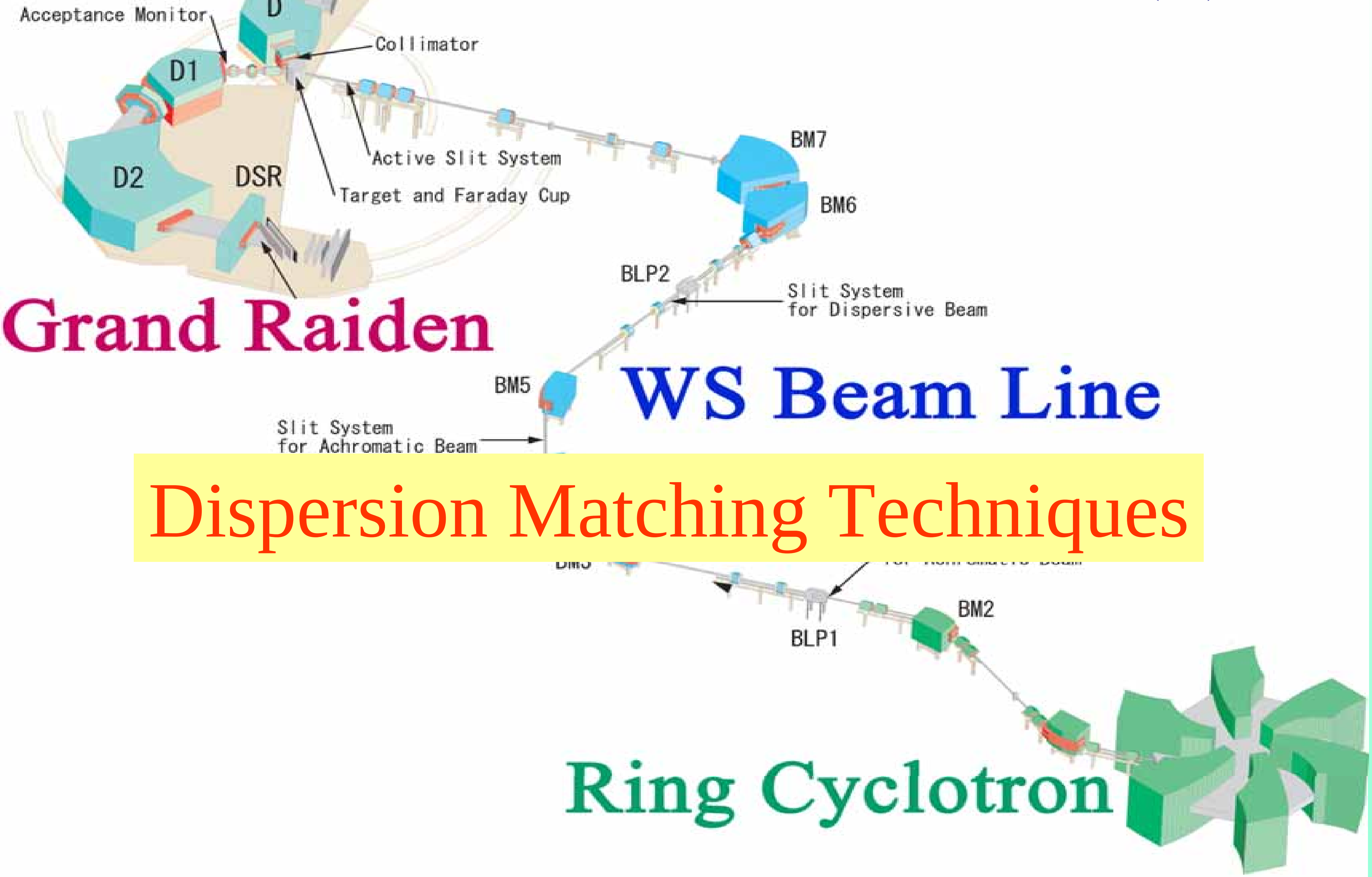
RCNP Ring Cyclotron

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


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

Beam line WS-course at RCNP

T. Wakasa et al., NIM A482 ('02) 79.

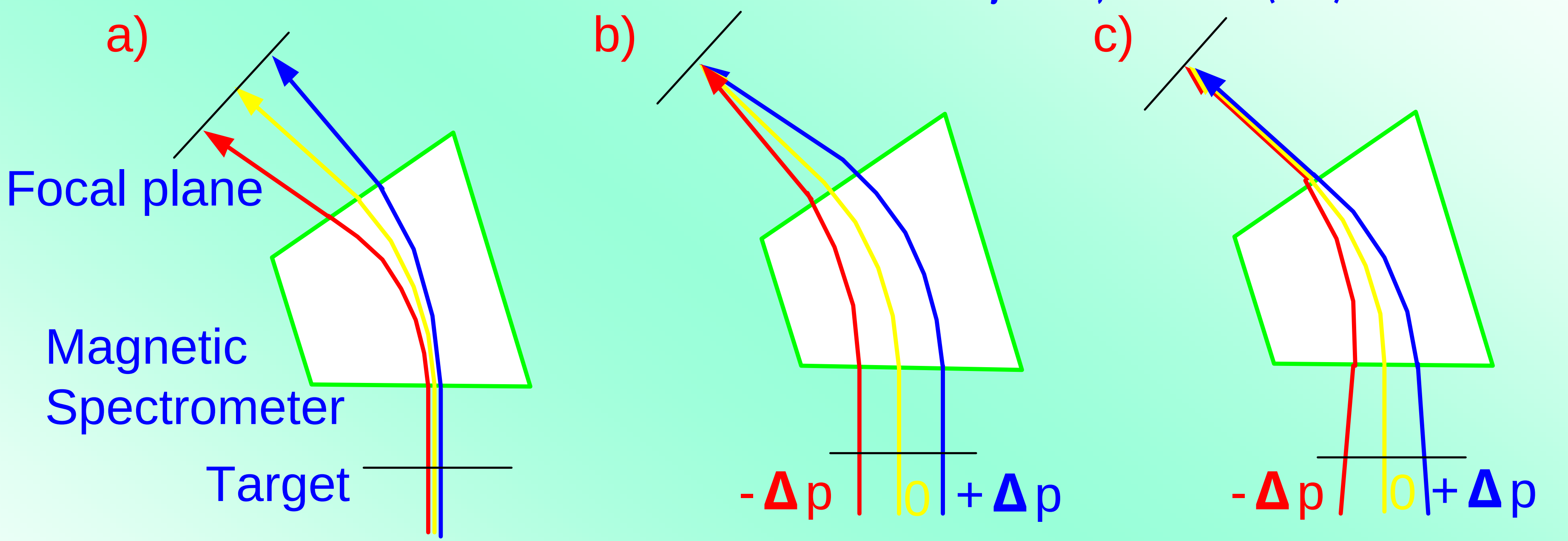


Dispersion Matching Techniques

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

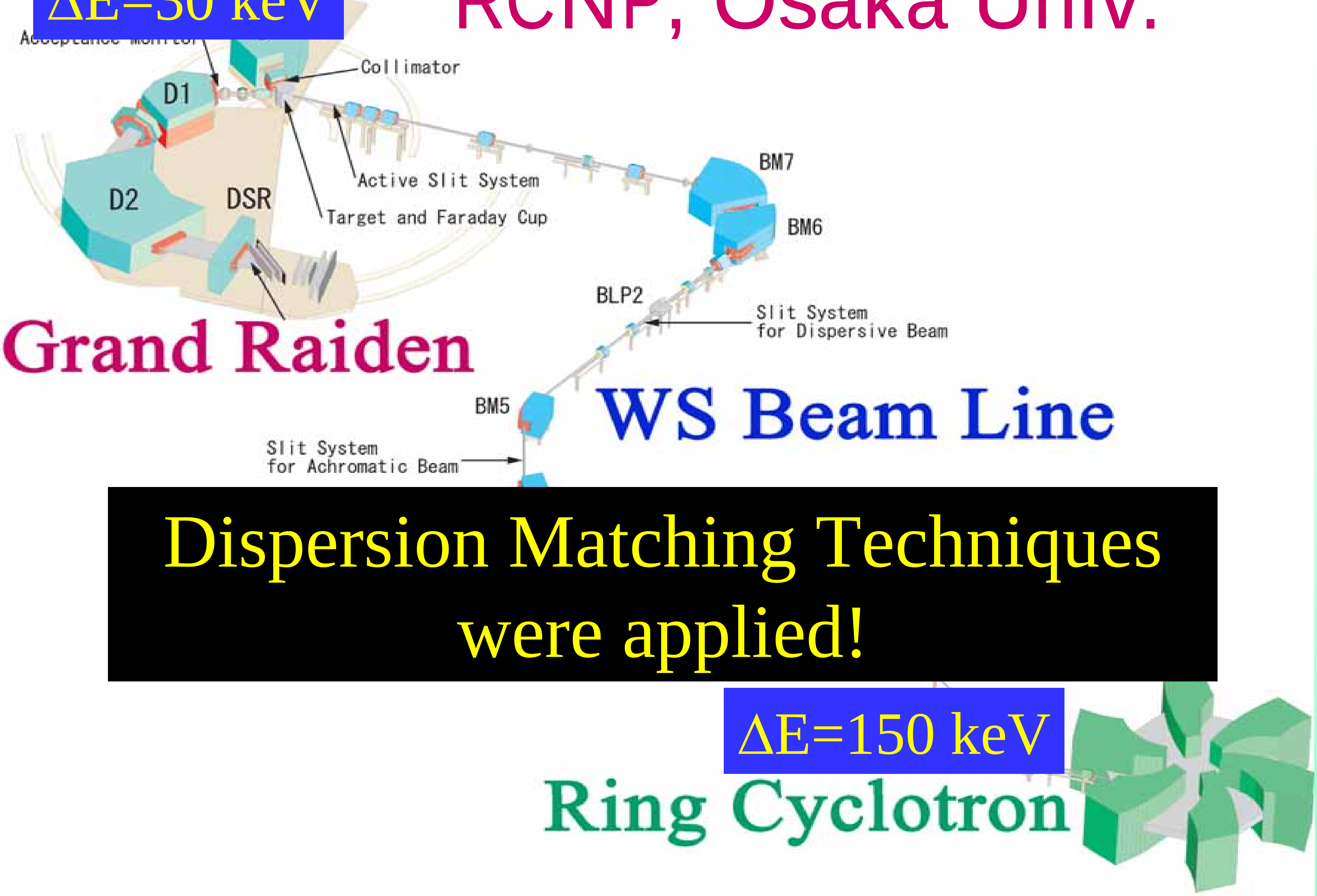
$\Delta\theta_{sc} > 15$mrad

Angular dispersion matching

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

RCNP, Osaka Univ.

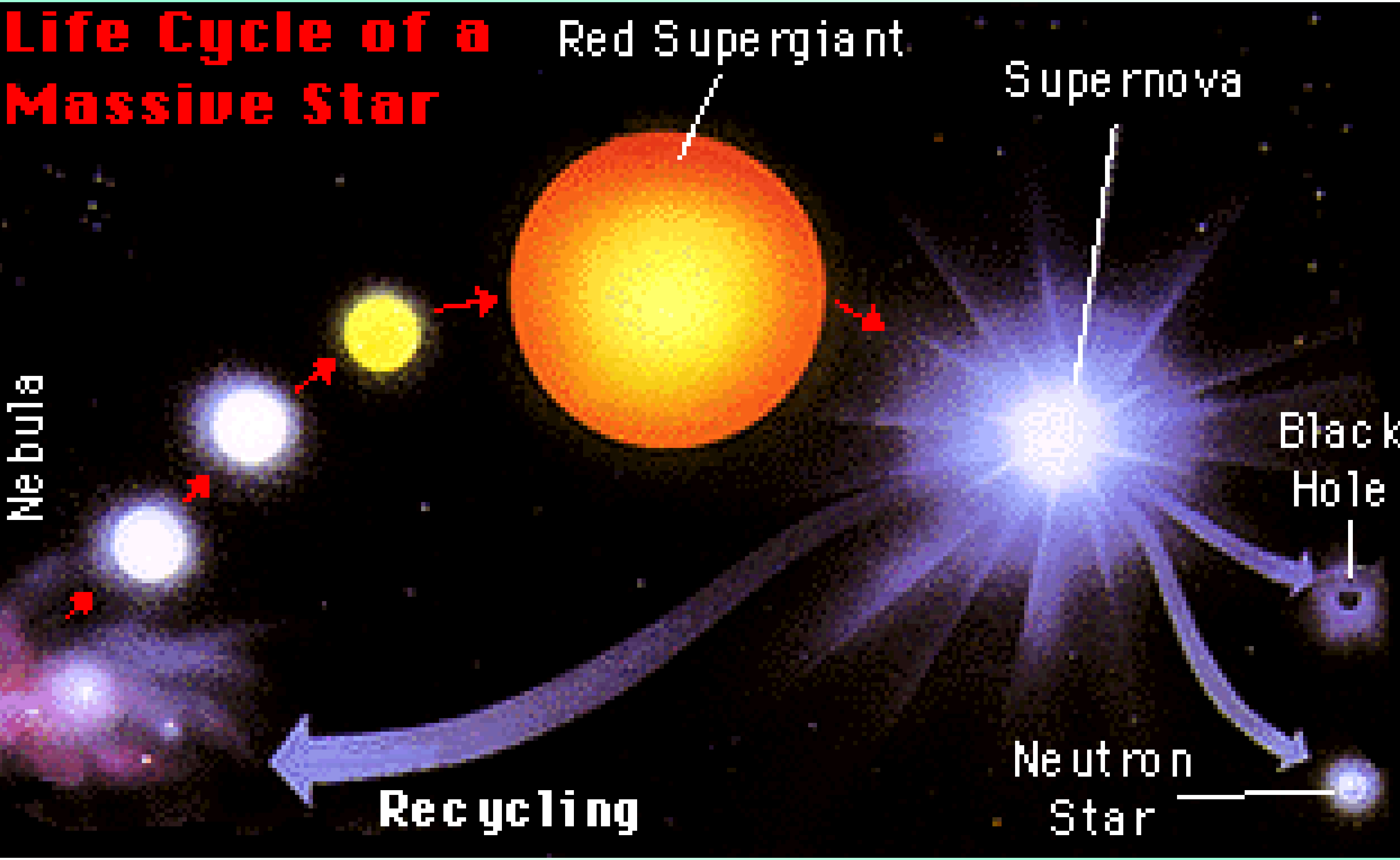
ΔE=30 keV



Dispersion Matching Techniques were applied!

ΔE=150 keV

Supernova Cycle



Crucial Weak Processes during the Core Collapse

$\sigma\tau$: important

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

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

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

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

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

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

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

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

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

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

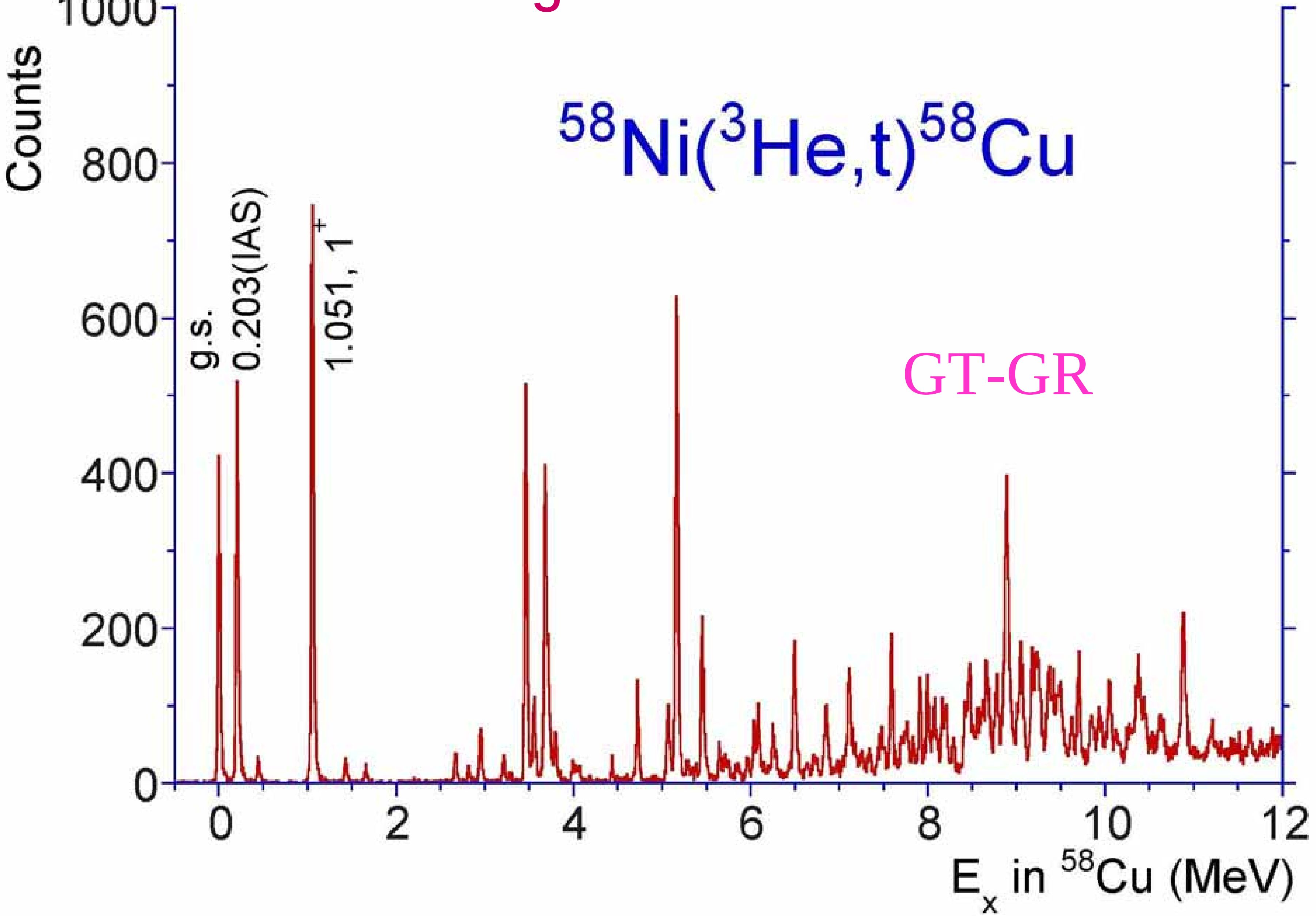
$$(A,Z)^* \rightleftarrows (A,Z) + \nu + \bar{\nu}.$$

(***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

GT strengths in A=42-58



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

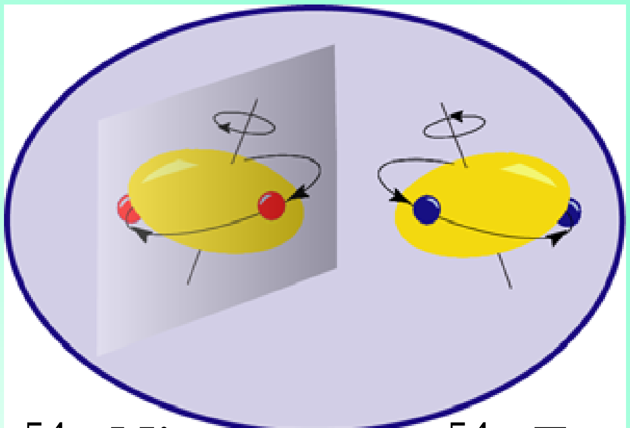
*β-decay: $T_{1/2}$ and absolute B(GT) values
but only for the low-lying states

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

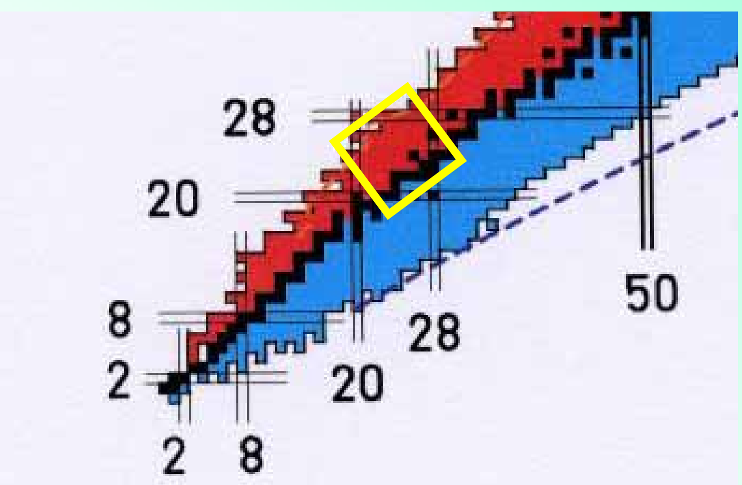
Let's combine these data !

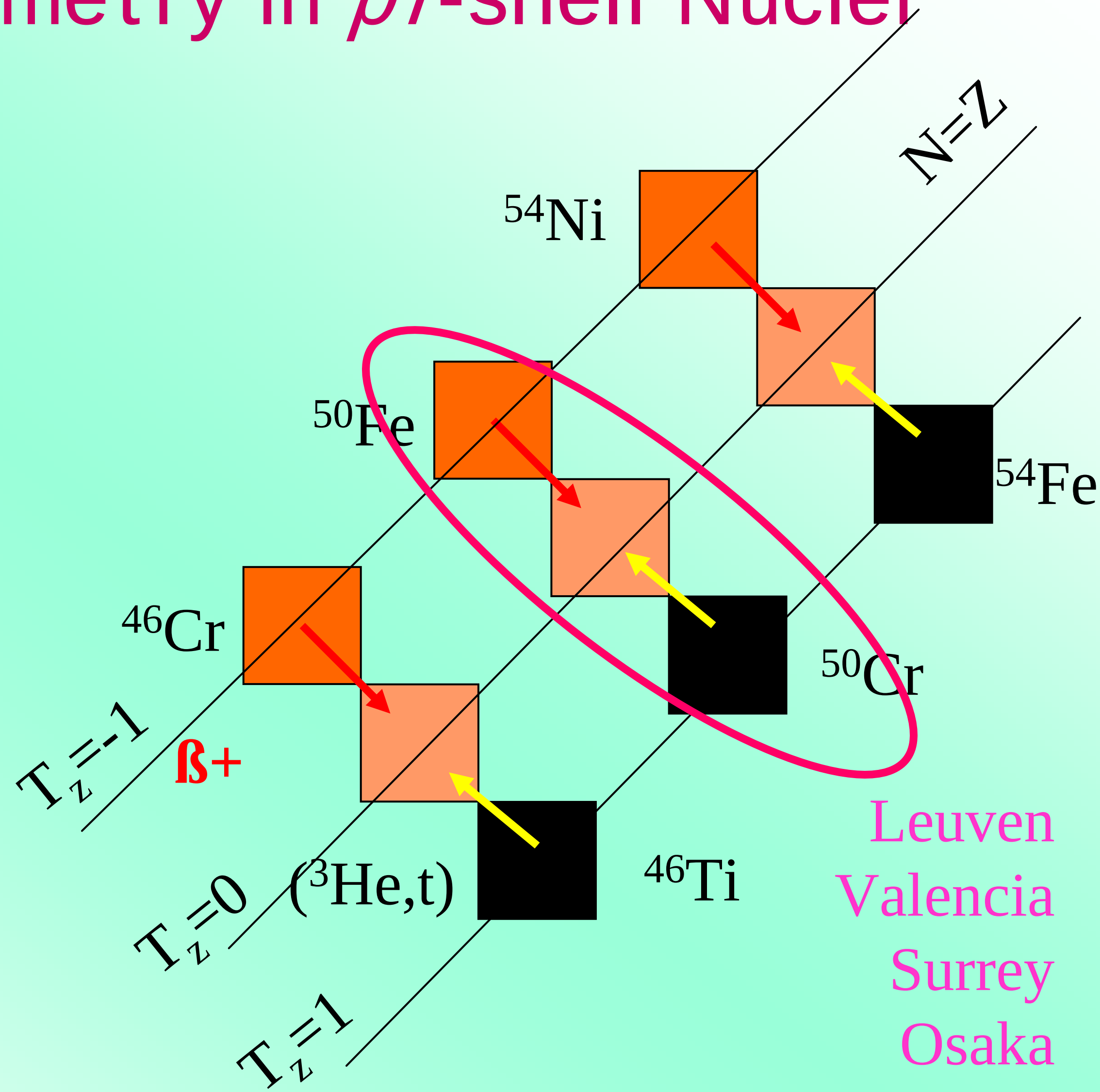
T=1 Isospin Symmetry in *pf*-shell Nuclei

Mirror nuclei



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

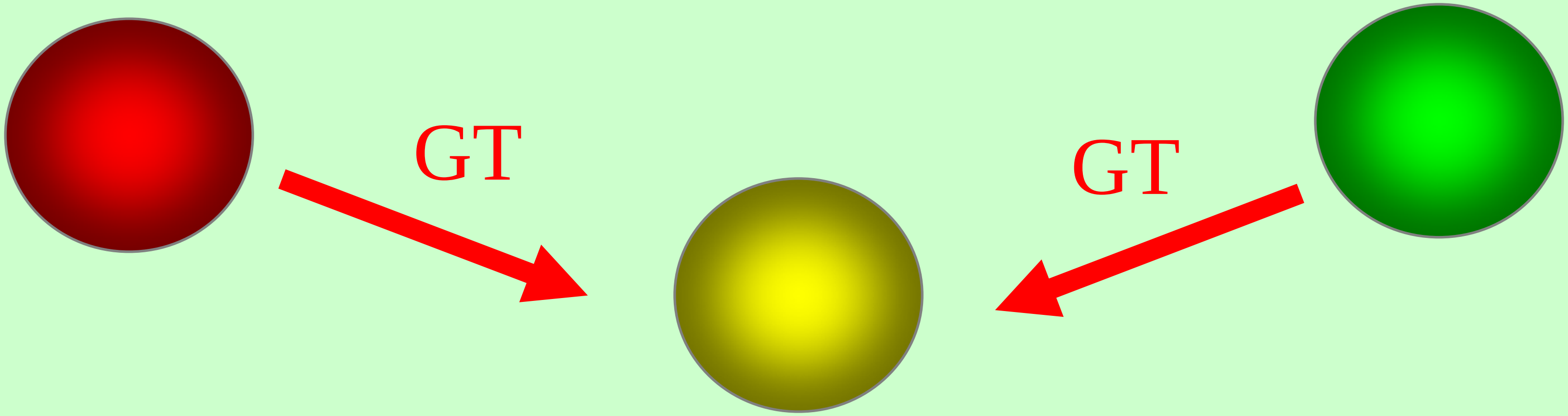




Leuven
Valencia
Surrey
Osaka
GSI

by B. Rubio

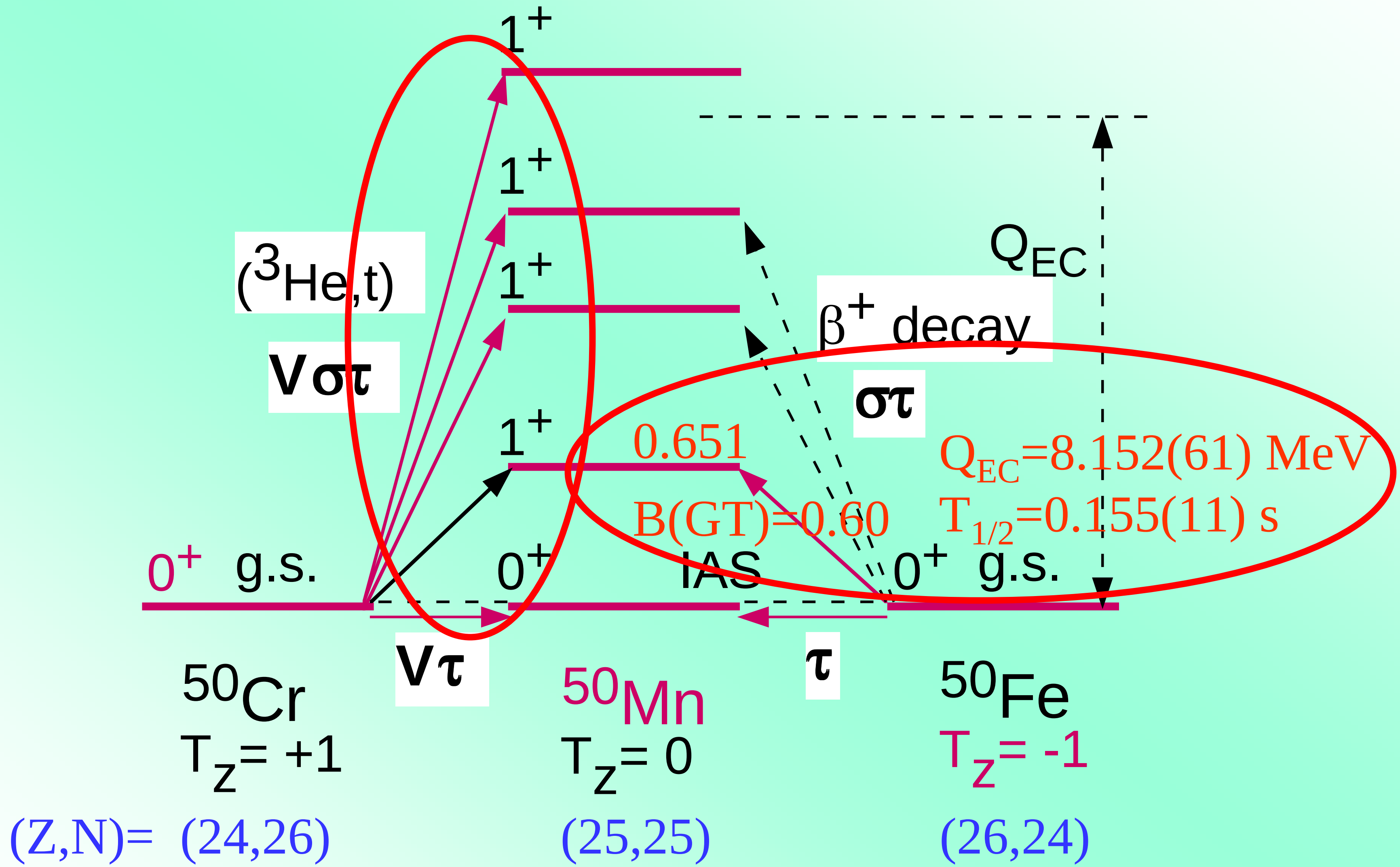
T=1 Isospin Symmetry



$^{50}_{24}Cr_{26}$ $\quad$ $^{50}_{25}Mn_{25}$ $\quad$ $^{50}_{26}Fe_{46}$

$T_z = +1$ $\quad$ $T_z = 0$ $\quad$ $T_z = -1$

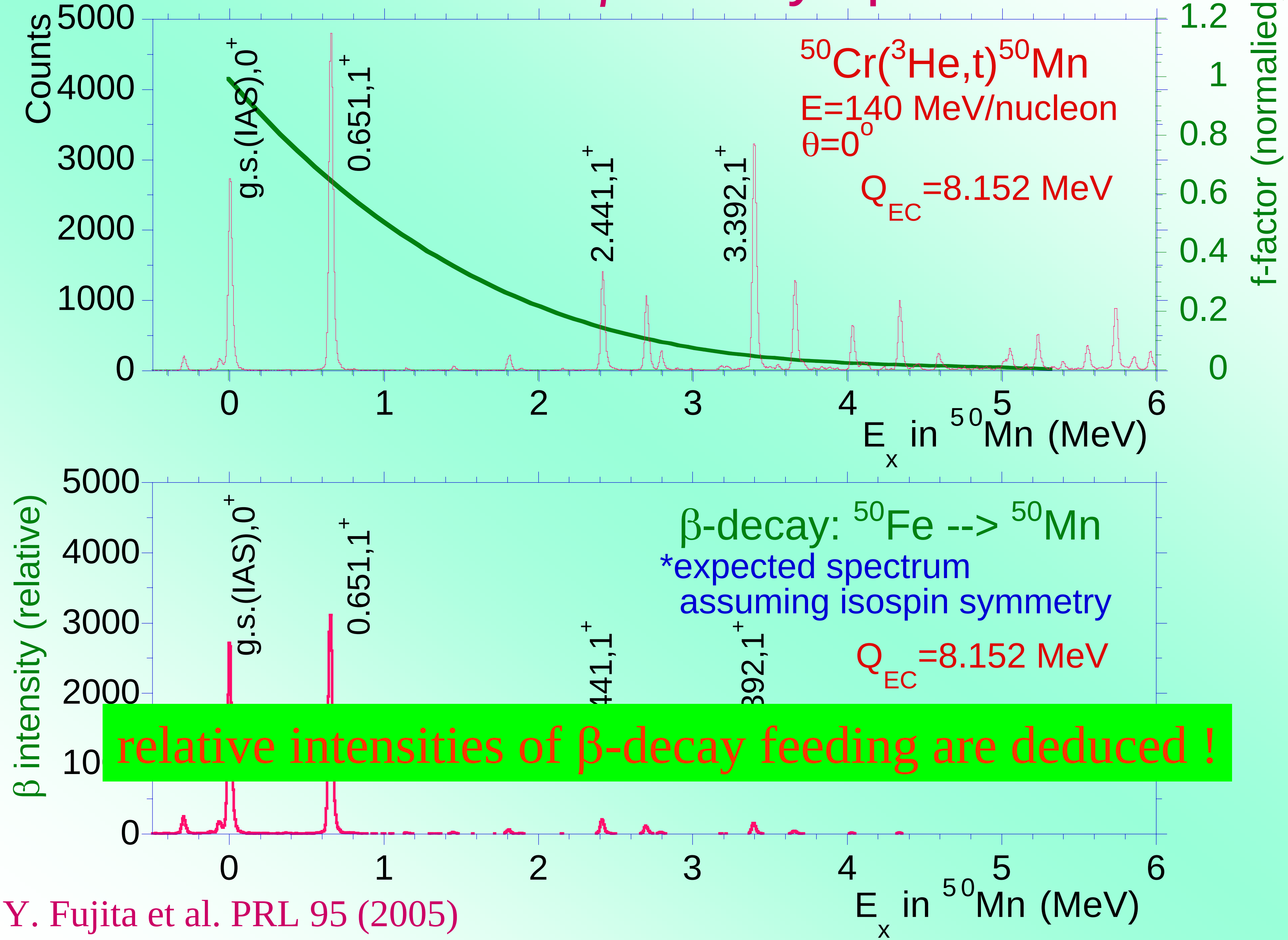
Isospin Symmetry Transitions:
$^{50}Cr(^{3}He,t) \rightarrow$ ^{50}Mn $\leftarrow \beta$-decay ^{50}Fe



**Reconstruction of β decay from (^{3}He,t)

---assuming isospin symmetry ---

Simulation of β-decay spectrum



relative intensities of β-decay feeding are deduced !

Y. Fujita et al. PRL 95 (2005)

Absolute B(GT) values
-via reconstruction of β-decay spectrum-

Tra.Strengh $\propto 1/t_i$ t_i =partial half-life

$$\frac{1}{T_{1/2}} = \frac{1}{t_{Fermi}} + \sum_{i=GT} \frac{1}{t_i}$$

β-decay experiment

$T_{1/2}$=0.155(11) s

B(F)=N-Z

Relative feeding intensity from (^{3}He,t)

Absolute intensity: B(GT)

GT tra. to the 0.65 MeV state

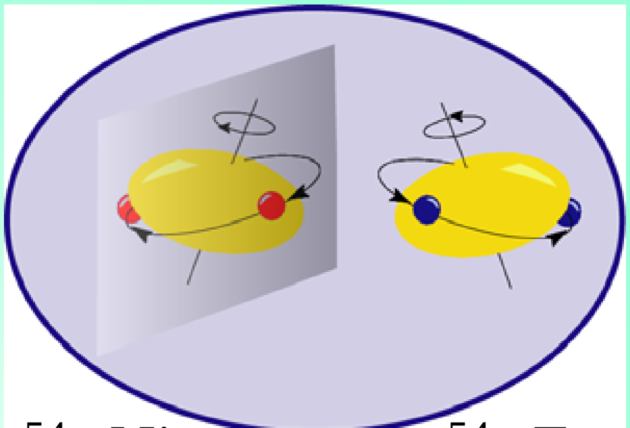
New value B(GT)=0.50(13)

*20% smaller than deduced in the β-decay: 0.60(16)

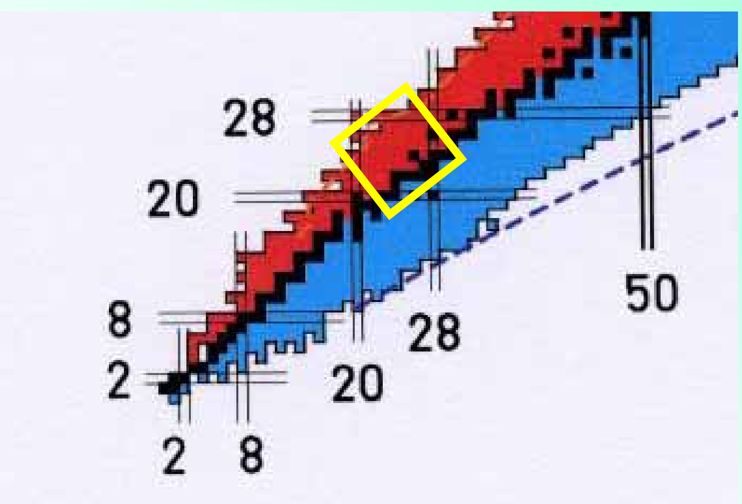
Y. Fujita et al.
PRL 95 (2005)

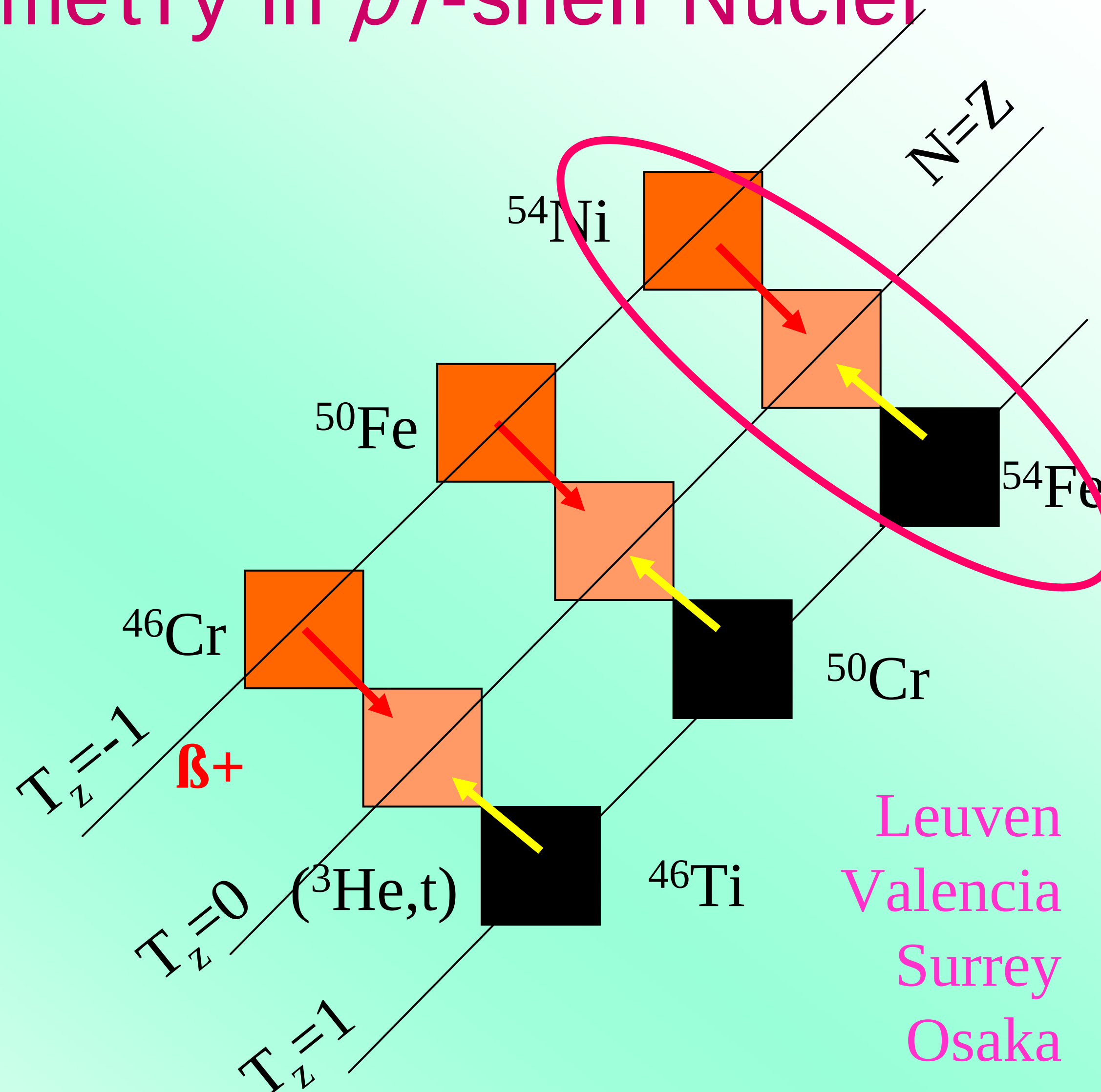
T=1 Isospin Symmetry in *pf*-shell Nuclei

Mirror nuclei



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



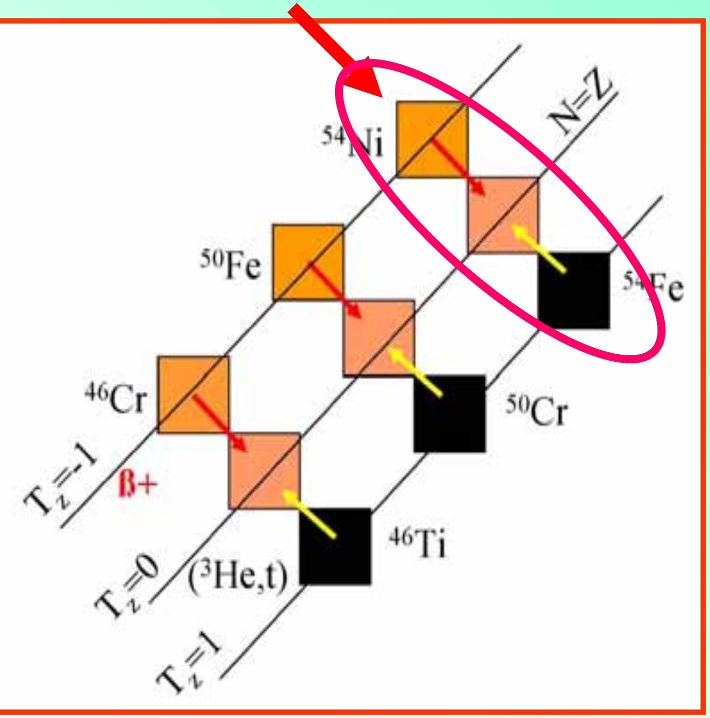


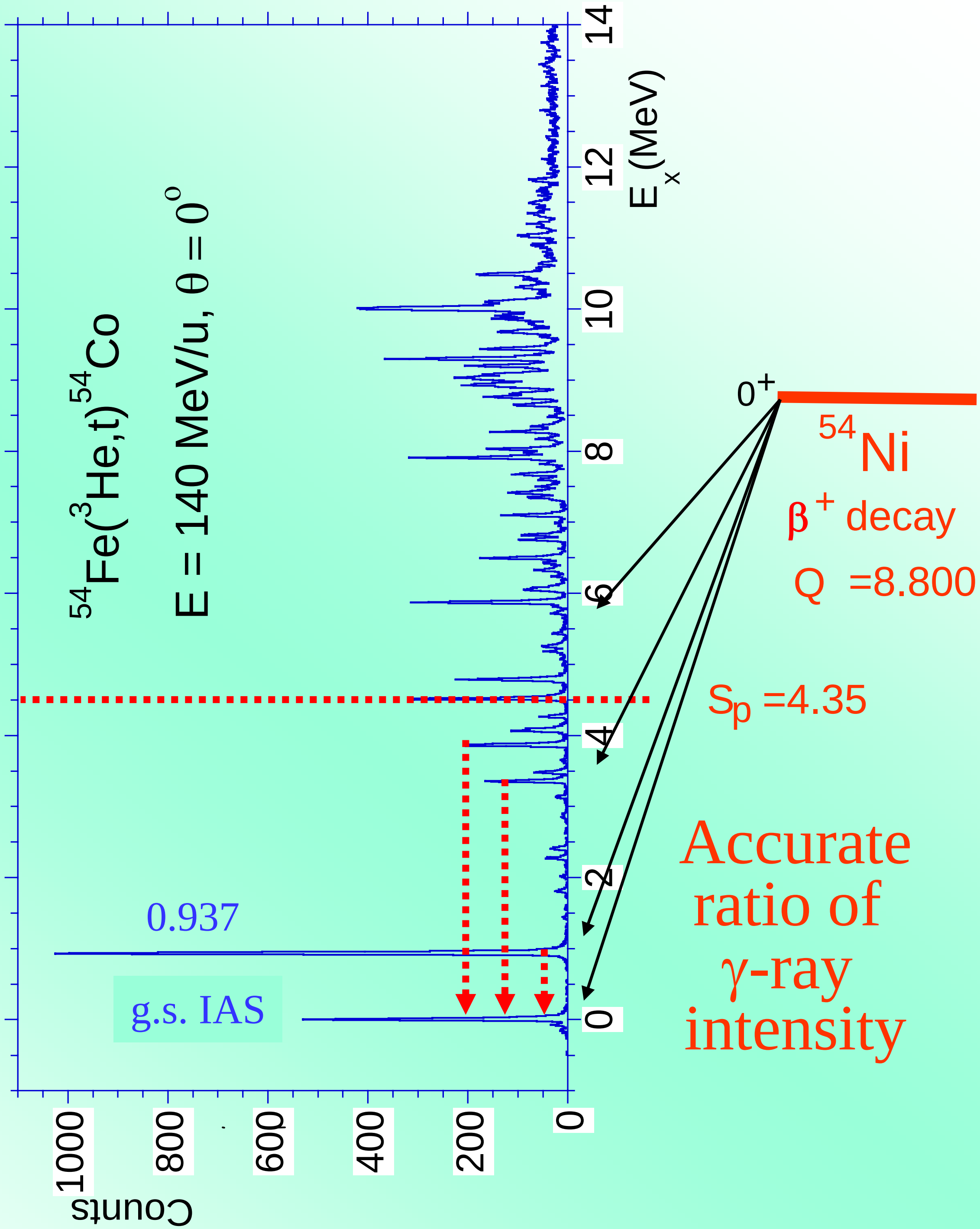
by B. Rubio

Leuven
Valencia
Surrey
Osaka
GSI
CNS

^{54}Ni β-decay measurement

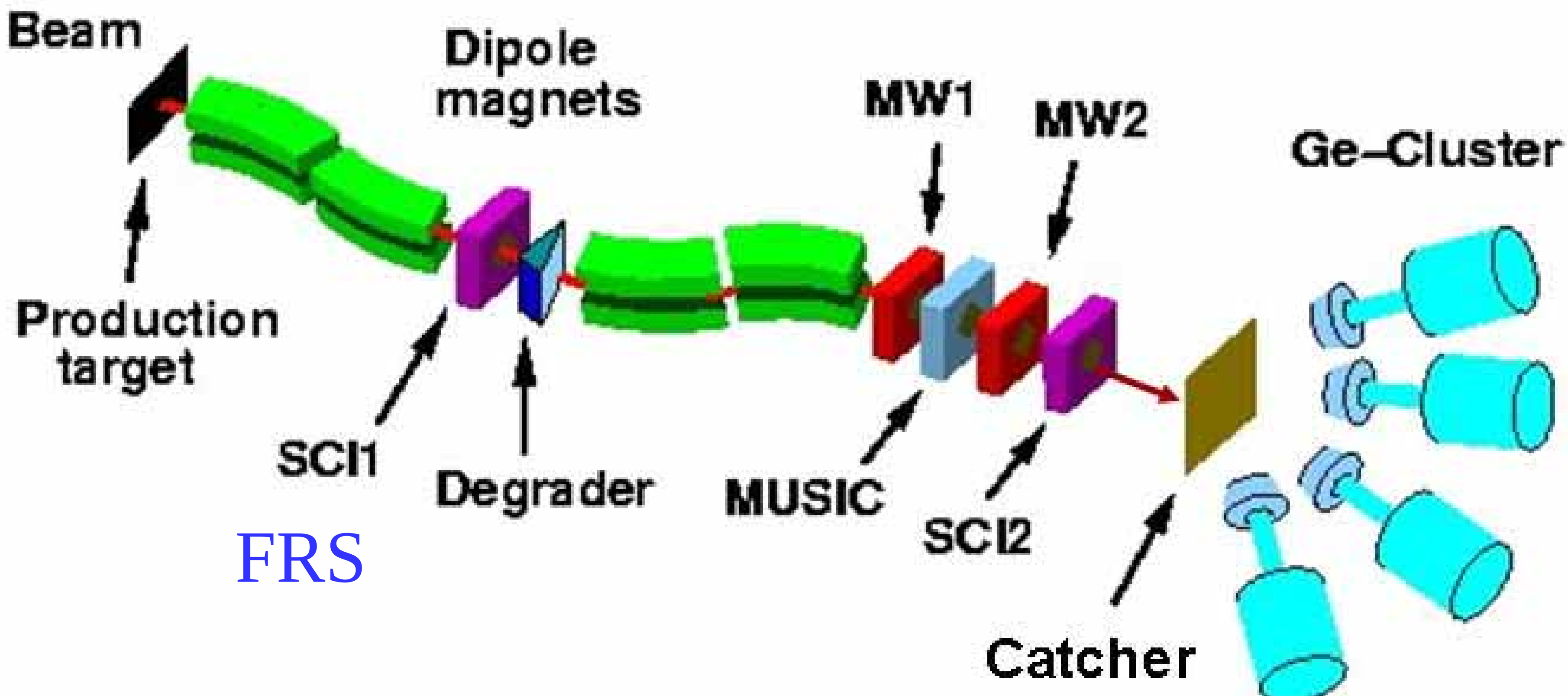
- at Louvain la Neuve (ISOL facility)
- at GSI (FRS facility)



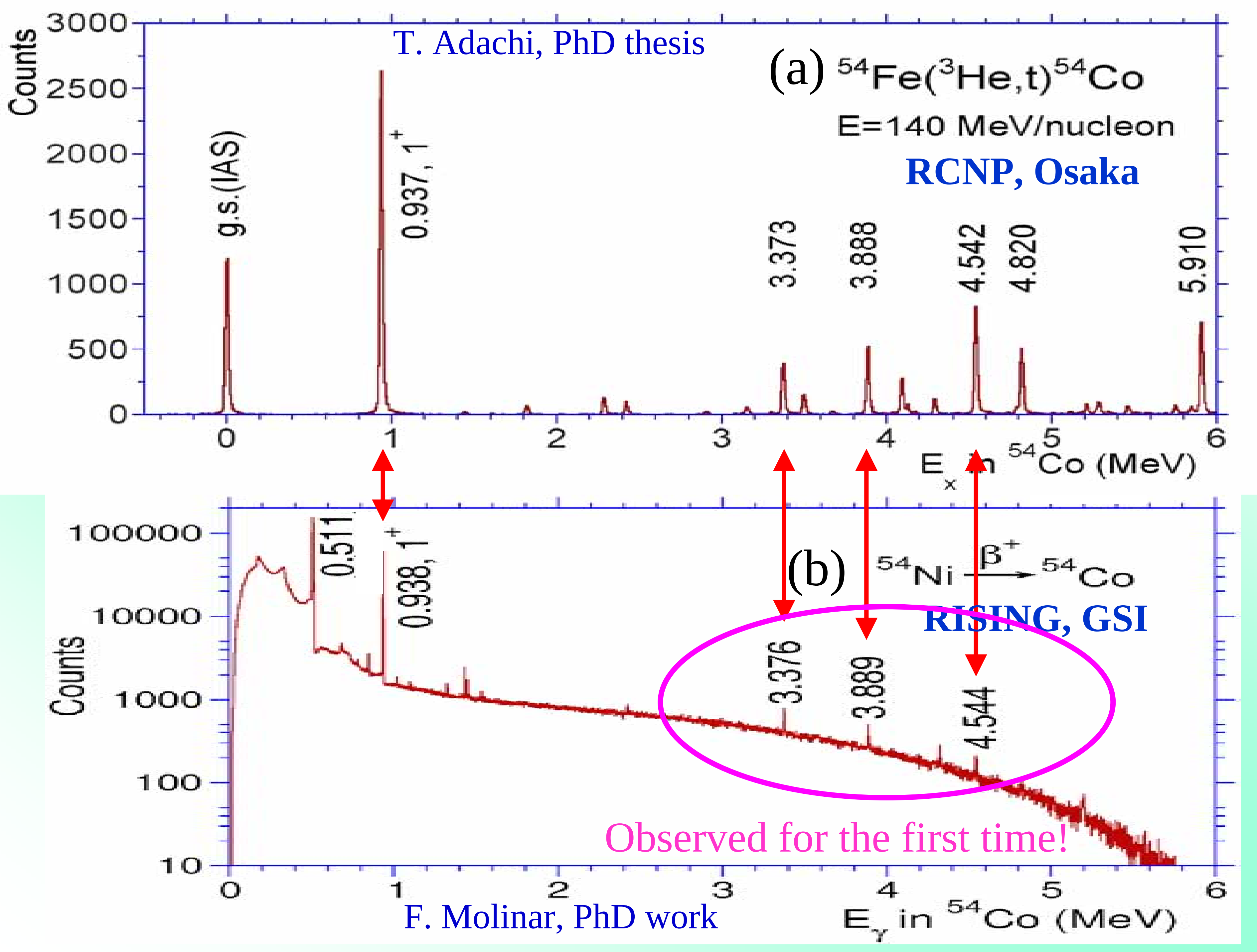


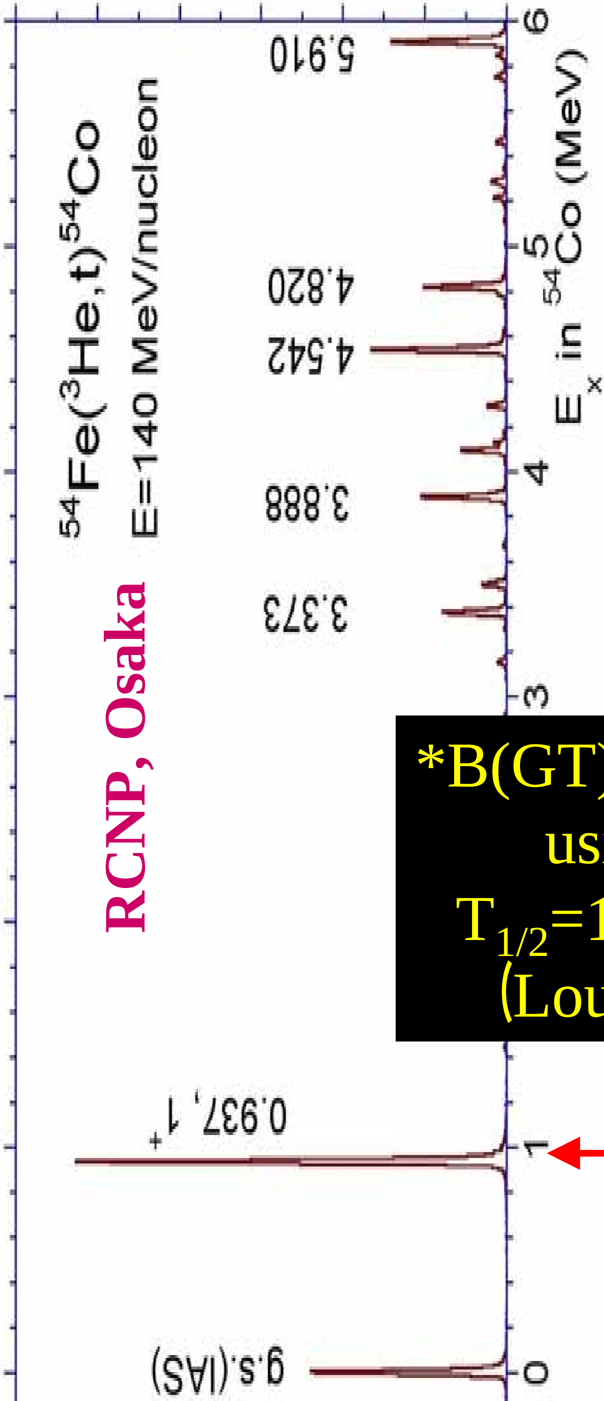
Accurate ratio of γ-ray intensity

GSI: RISING set up
- active stopper campaign -



3-layors of DSSD active stopper

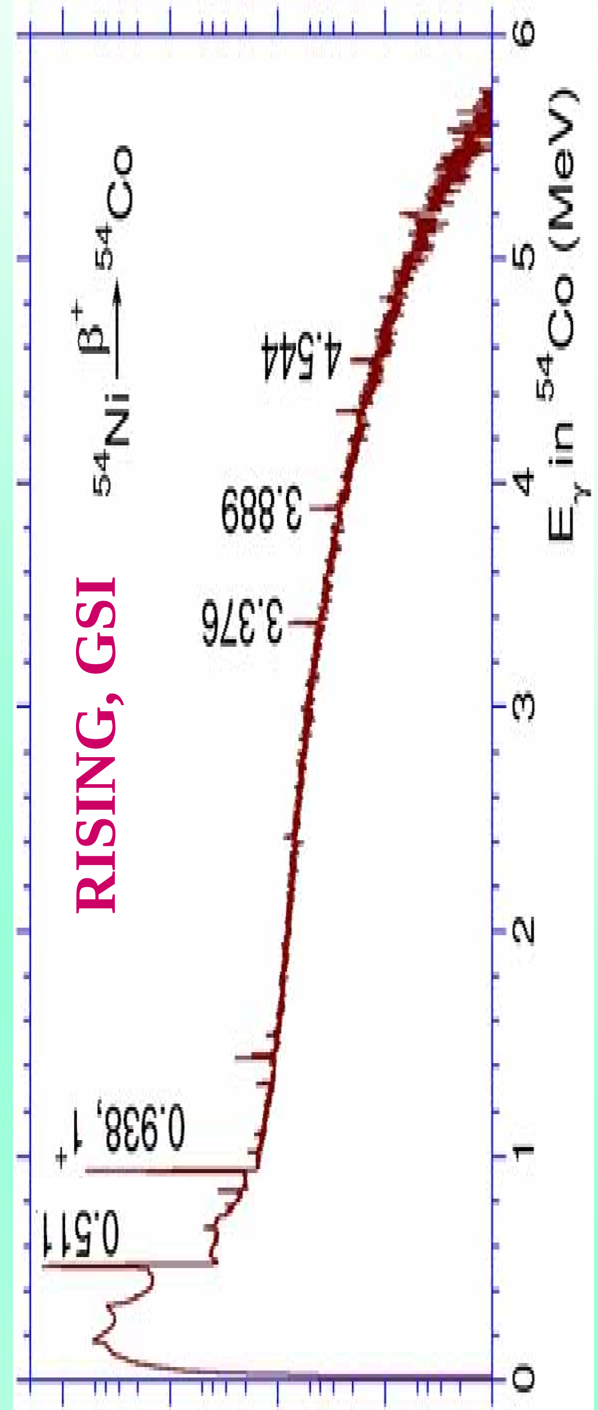

T. Adachi, PhD thesis
(a) 54Fe(3He,t)54Co
E=140 MeV/nucleon
RCNP, Osaka
Counts
g.s.(IAS)
0.937, 1+
3.373
3.888
4.542
4.820
5.910
Ex in 54Co (MeV)
(b) 54Ni β+ → 54Co
RISING, GSI
Counts
0.511
0.938, 1+
3.376
3.889
4.544
Observed for the first time!
Eγ in 54Co (MeV)
F. Molinar, PhD work

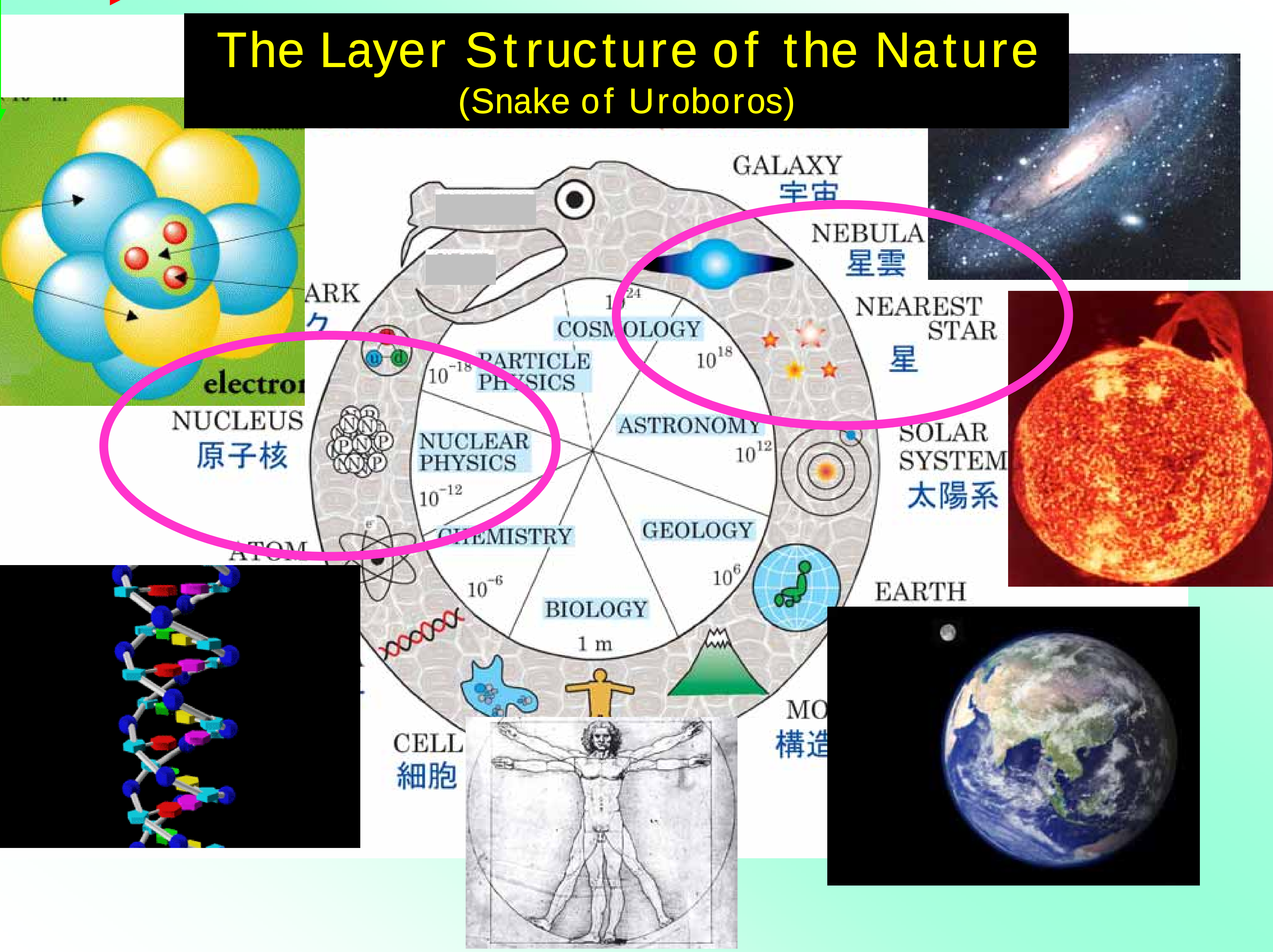


Comparison

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

*B(GT) values using $T_{1/2}$=115 ms (Louvain)




The Layer Structure of the Nature
(Snake of Uroboros)
GALAXY
宇宙
NEBULA
星雲
NEAREST STAR
星
SOLAR SYSTEM
太陽系
EARTH
NUCLEUS
原子核
ATOM
CELL
細胞
electron
COSMOLOGY
PARTICLE PHYSICS
NUCLEAR PHYSICS
CHEMISTRY
BIOLOGY
GEOLOGY
ASTRONOMY
10^{24}
10^{18}
10^{12}
10^{6}
1 m
10^{-6}
10^{-12}
10^{-18}

Summary

* Weak response of Nuclei was studied by using Strong Int.

  --Charge Exchange Reaction--

* Isospin Symmetry was introduced.
* High resolution of the (^{3}He,t) reaction

  allowed the comparison of analogous transitions

* Absolute *B*(GT) strengths were derived.
* High resolution (p, p’) and/or (^{3}He,^{3}He’)

  allows the study of B(E1) strengths.

Extended Collaboration is very important!