High-resolution Study of Gamow-Teller Transitions

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@CNS-SS, '04.Aug.17-20

Nucleus : 3 active interactions out of 4

Strong, Weak, EM

➔Comparison of Analogous Transitions

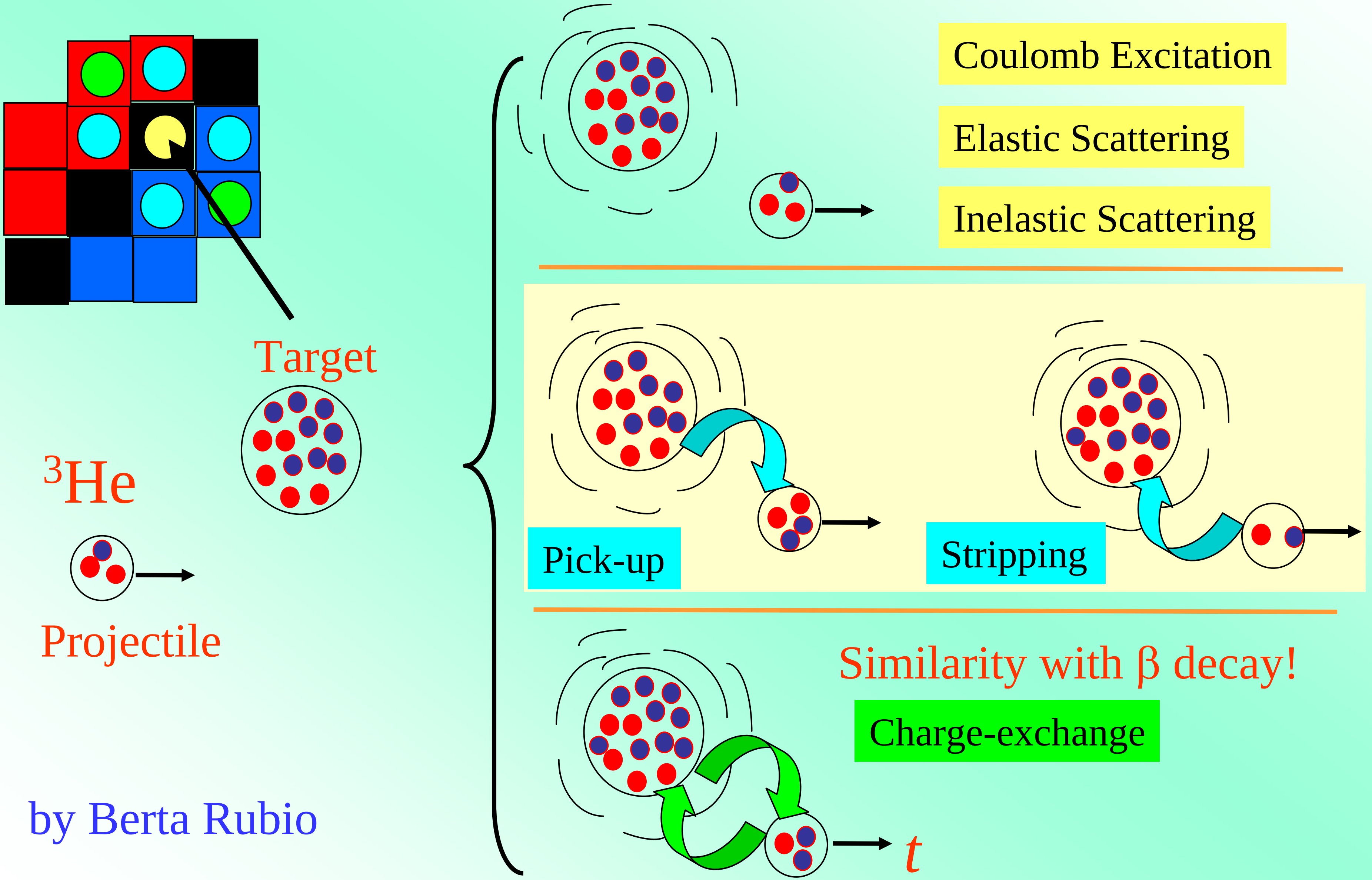
✧High resolution (^{3}He,t) experiment at 0°

ΔE = 30-50 keV

✧β-decay experiment, γ-decay, (e, e') measurements

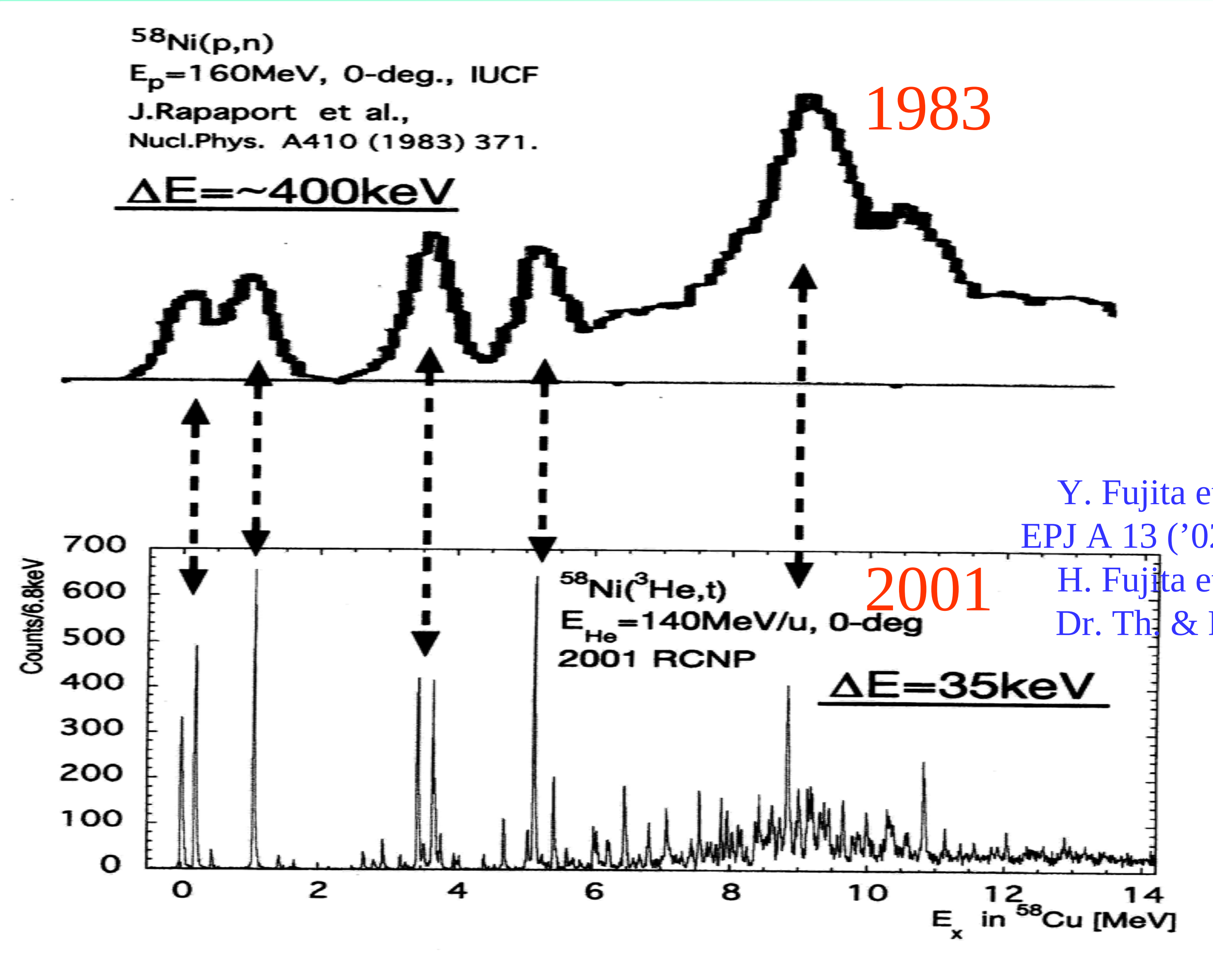
→detailed GT responses up to high excitation energies !

Direct Reactions with Light Projectiles



by Berta Rubio

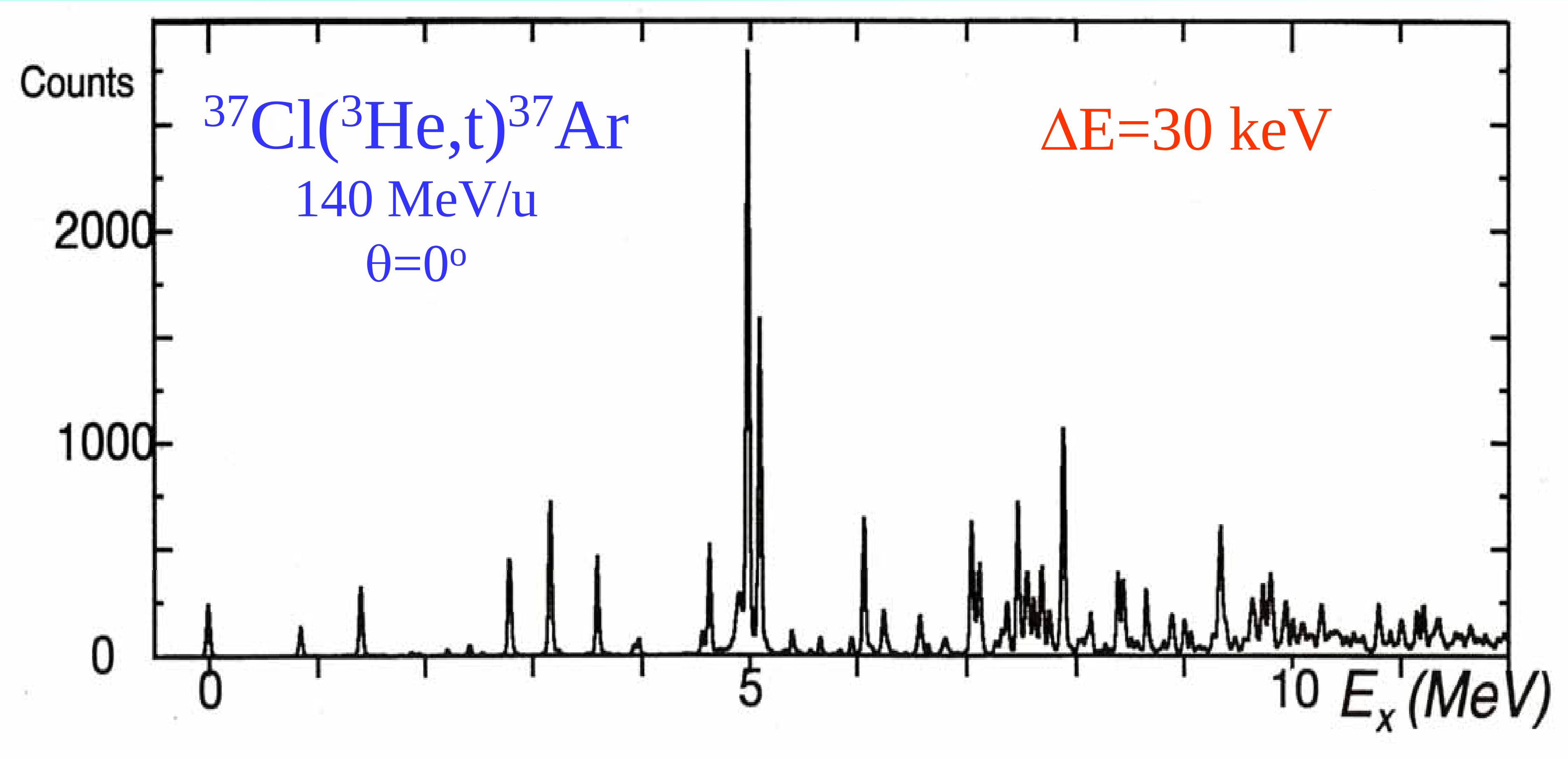
Resolutions Now and Then



Y. Fujita et al.,
EPJ A 13 ('02) 411.
H. Fujita et al.,
Dr. Th. & PRC

$^{37}Cl(^{3}He,t)^{37}Ar$ spectrum

Y.Shimbara et al.



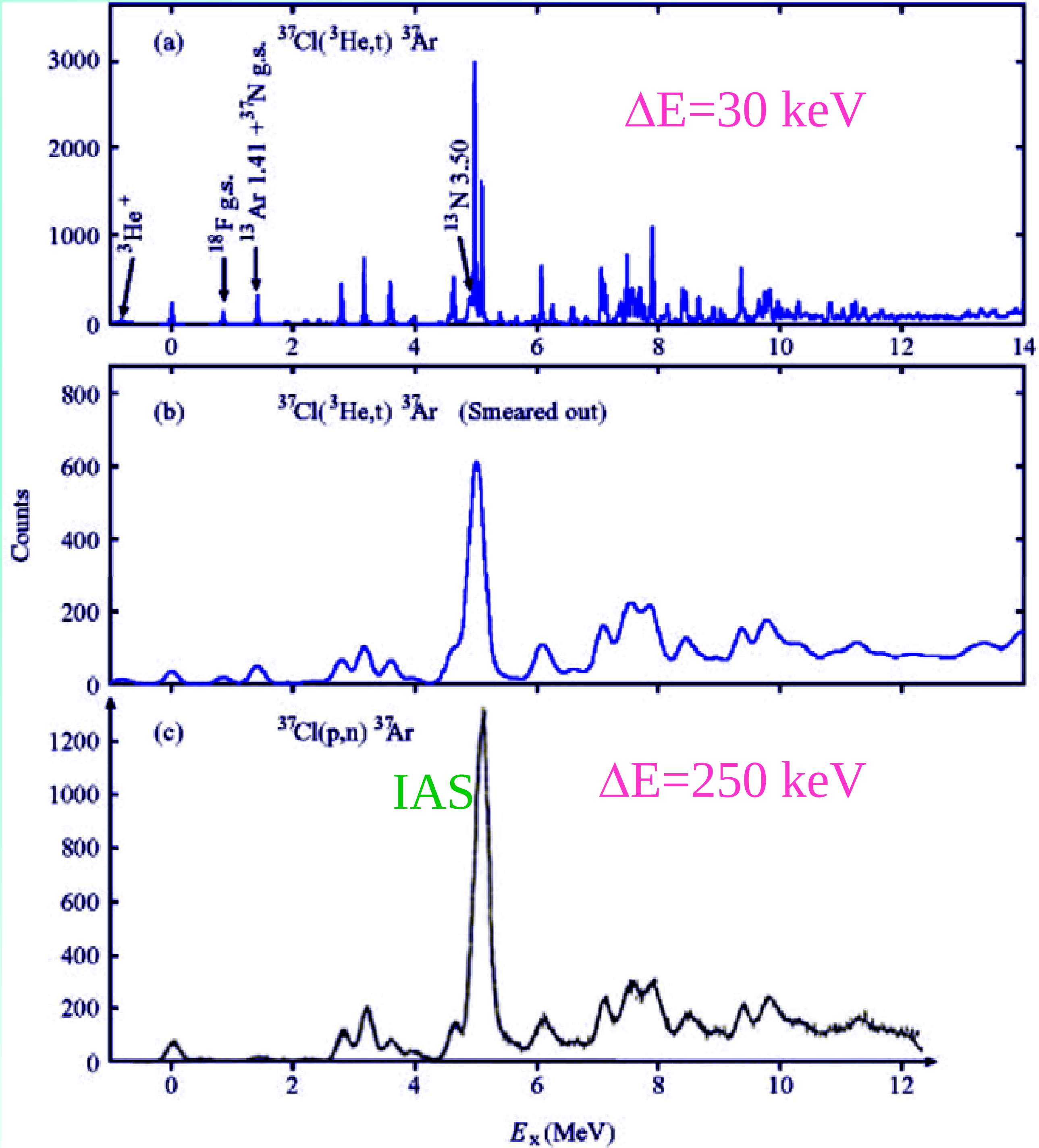
(^{3}He,t) & (p,n) on ^{37}Cl

Original (^{3}He,t)

(^{3}He,t) convoluted with (p,n) resolution

Original (p,n)

Convolution by Y. Shimbara



Key Words

★High Resolution

In Charge Exchange Reactions

--at Intermediate Incident Energies--

(^{3}He,t) reaction : one order better resolution than in a (p,n) reaction

★Active Operators

Similarity of Active Operators

Gamow-Teller operator in β decay (weak interaction)

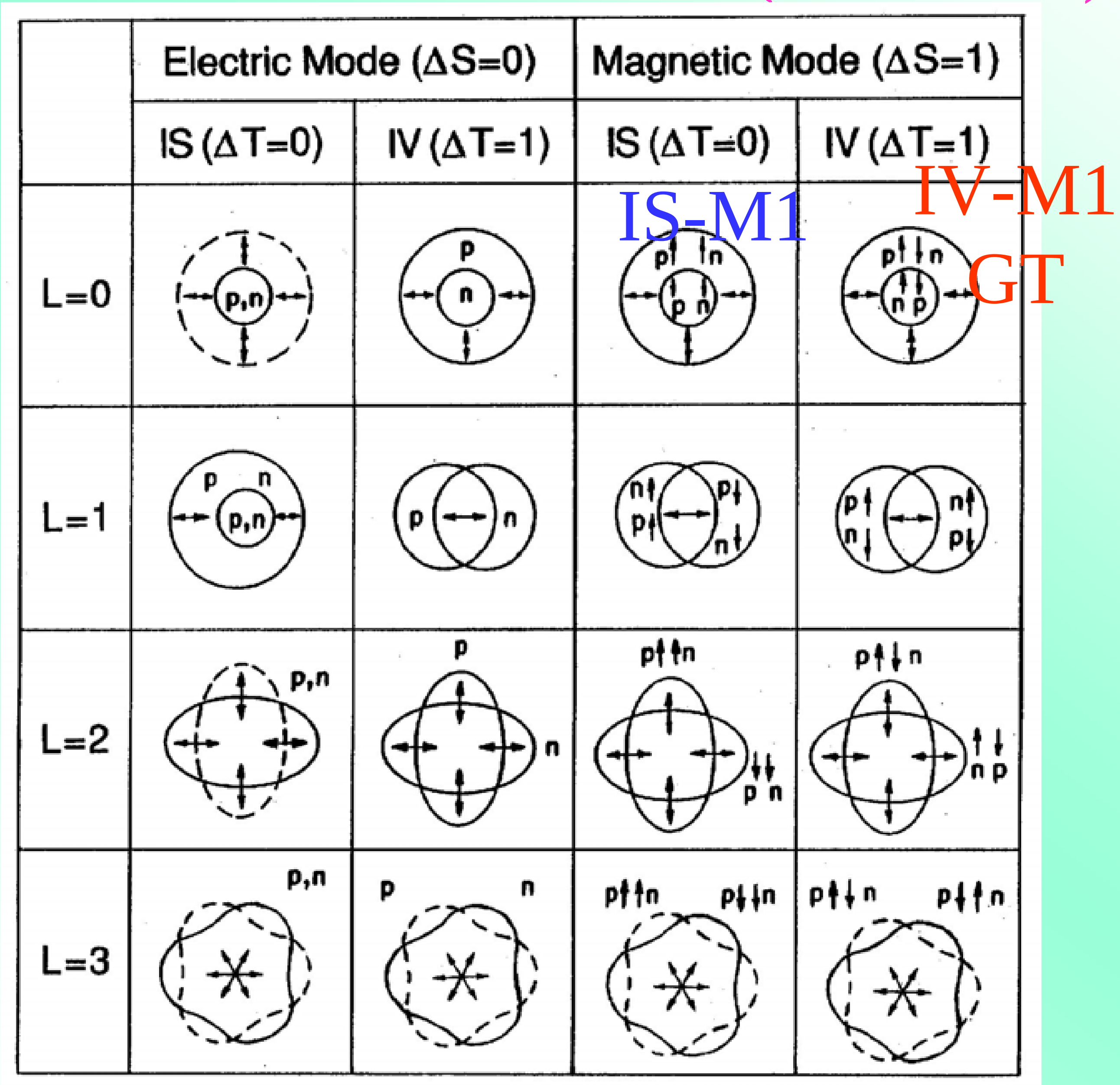
Spin-isospin interaction in reactions (strong interaction)

EM-*M1* interaction in γ decay (electro-magnetic int.)

★Isospin Symmetry

Analog States, Analogous Transitions

Vibration Modes in Nuclei (Schematic)



Vibration Modes in Nuclei (Operators)

Microscopic classification of giant resonances

	$\Delta S = 0$, $\Delta T = 0$	$\Delta S = 0$, $\Delta T = 1$	$\Delta S = 1$, $\Delta T = 0$	$\Delta S = 1$, $\Delta T = 1$
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

An operator is
a hammer
to exite
nuclei !

Supernova SN1987A

Crucial Weak Processes during the Collapse

K.L &G.M-P Rev.Mod.Phys.75('04)819

(***A***,***Z***)=nuclei of Fe Ni region

mainly by στ

can be studied by (^{3}He,t)

$$p + e^- \rightleftarrows n + \nu_e,$$
$$n + e^+ \rightleftarrows p + \bar{\nu}_e,$$
$$(A,Z) + e^- \rightleftarrows (A,Z-1) + \nu_e,$$
$$(A,Z) + e^+ \rightleftarrows (A,Z+1) + \bar{\nu}_e,$$
$$\nu + N \rightleftarrows \nu + N,$$
$$N + N \rightleftarrows N + N + \nu + \bar{\nu},$$
$$\nu + (A,Z) \rightleftarrows \nu + (A,Z),$$
$$\nu + e^{\pm} \rightleftarrows \nu + e^{\pm},$$
$$\nu + (A,Z) \rightleftarrows \nu + (A,Z)^*,$$
$$e^+ + e^- \rightleftarrows \nu + \bar{\nu},$$
$$(A,Z)^* \rightleftarrows (A,Z) + \nu + \bar{\nu}.$$

B(GT) derivation

★β decay :fundamental, but E_X range :limited "Q-window limitation"

★(p, n) reaction at intermediate energies (E = 100-500 MeV)

"proportionality" : B(GT) and $\sigma(0^o)$

$$\sigma(0^o) = K N_{\sigma\tau} \mid J_{\sigma\tau}(0^o) \mid^2 B(\mathrm{GT})$$

⇒Breakthrough against "Q-window limitation"

but resolution : rather poor (ΔE = 200-400 keV)

★(^{3}He, t) reaction at intermediate energies (E = 130-150 MeV/u)

"high resolution" (ΔE < 50 keV)

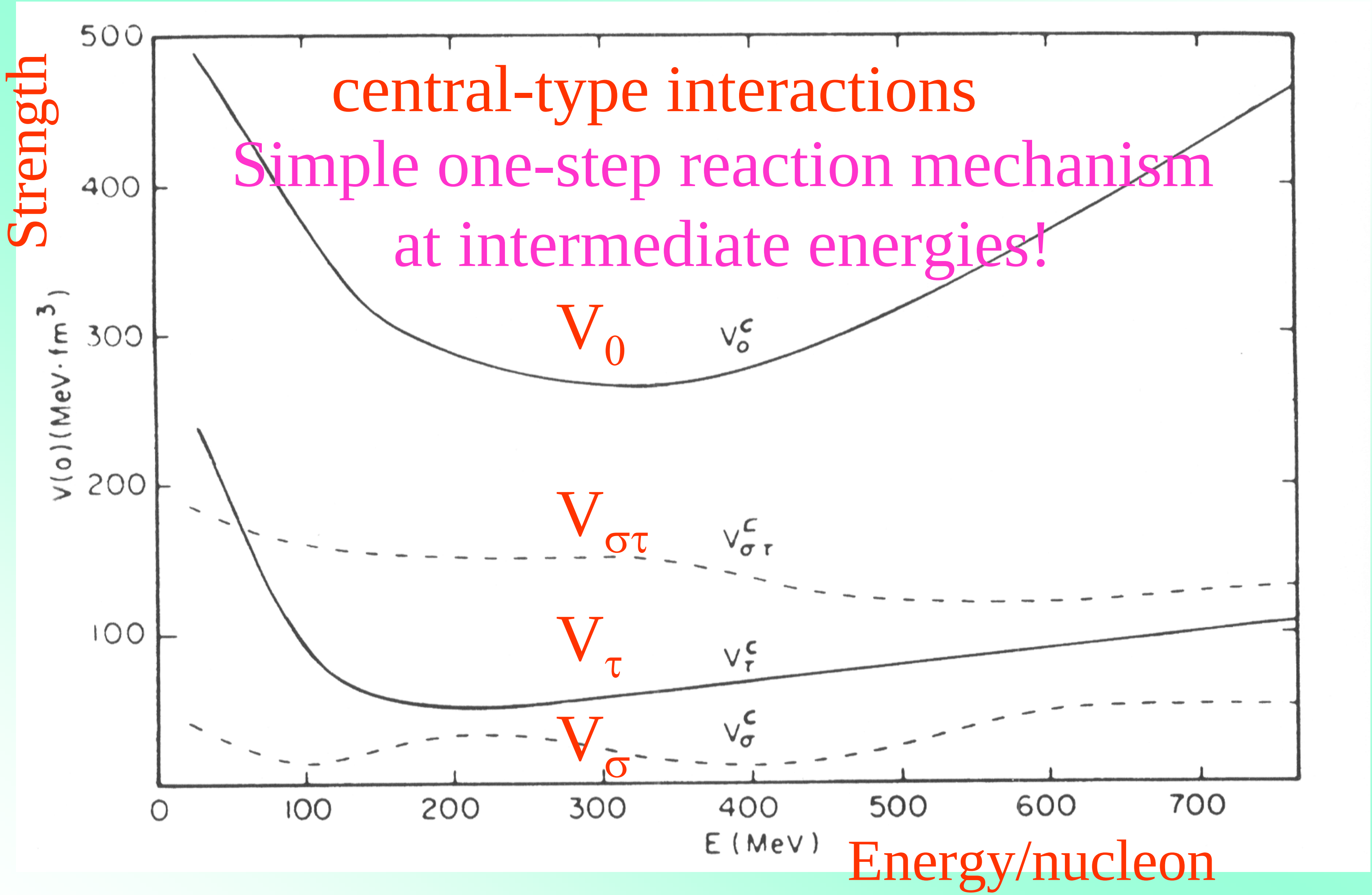
☆magnetic spectromerter, matching techniques

"proportionality" : good (B(GT) > 0.03)

⇒Breakthrough against "Energy resolution limitation"

⇒Reliable B(GT) values for individual transitions

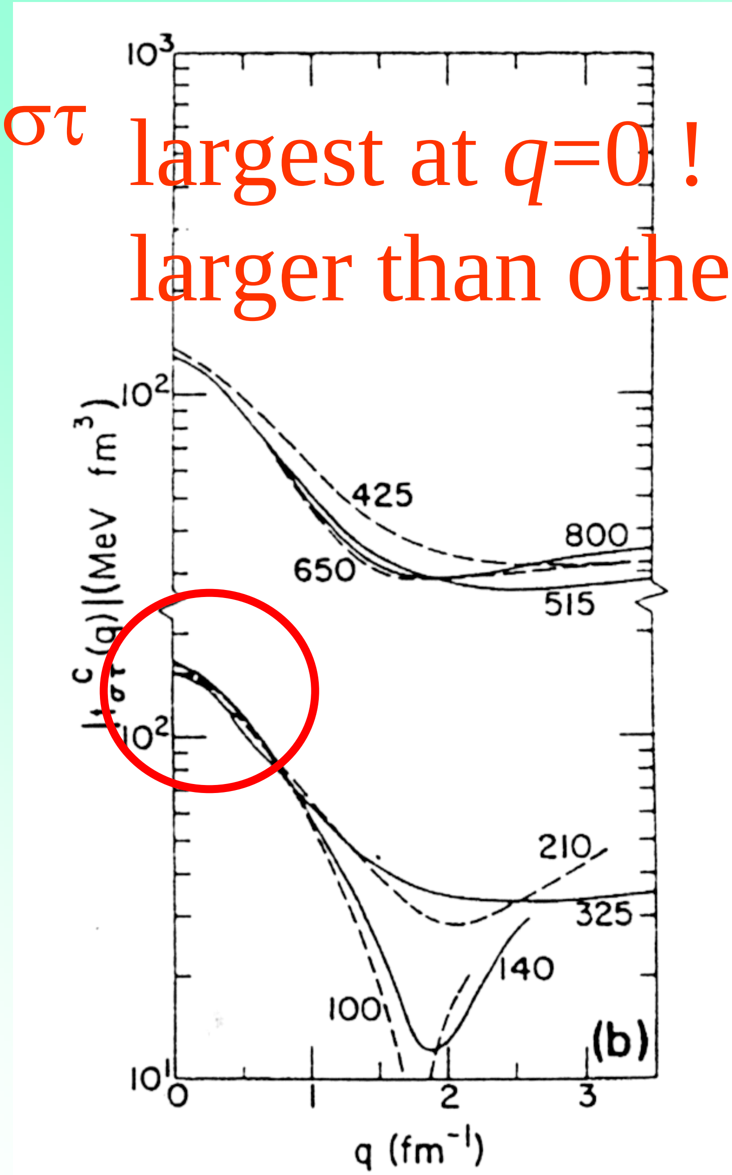
Nucleon-Nucleon Int. : E_{in} dependence at q =0



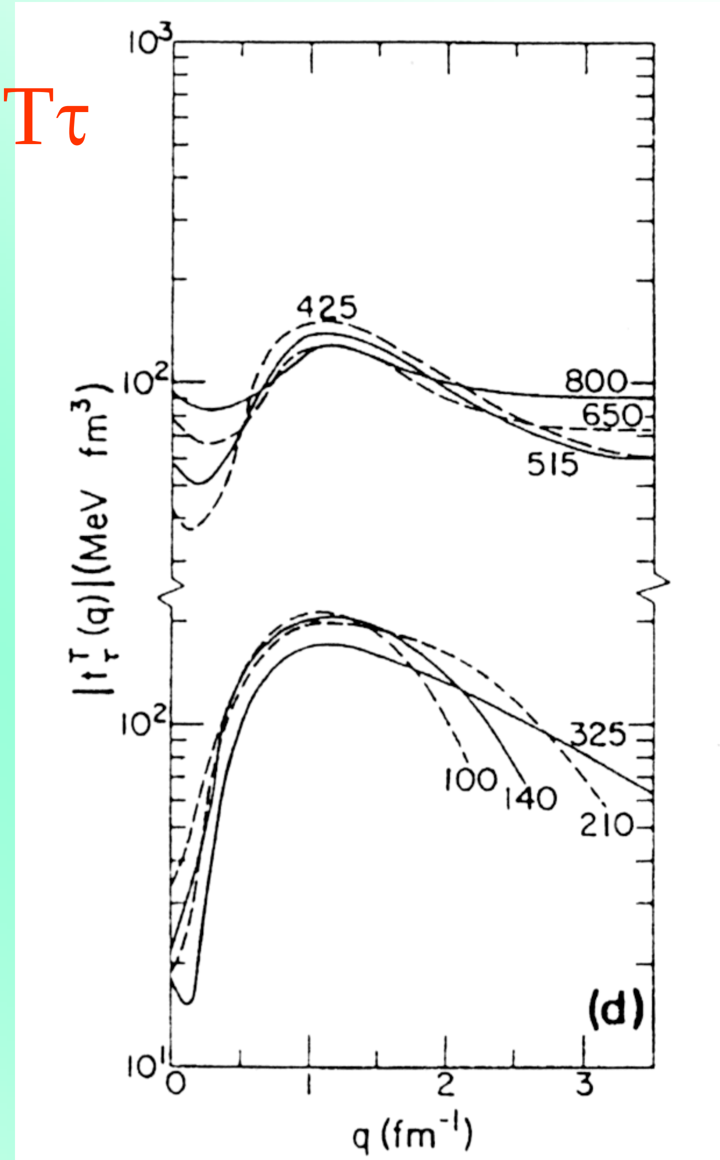
N.-N. Int. : στ & Tensor-τ *q*-dependence

στ largest at *q*=0 !

larger than others !

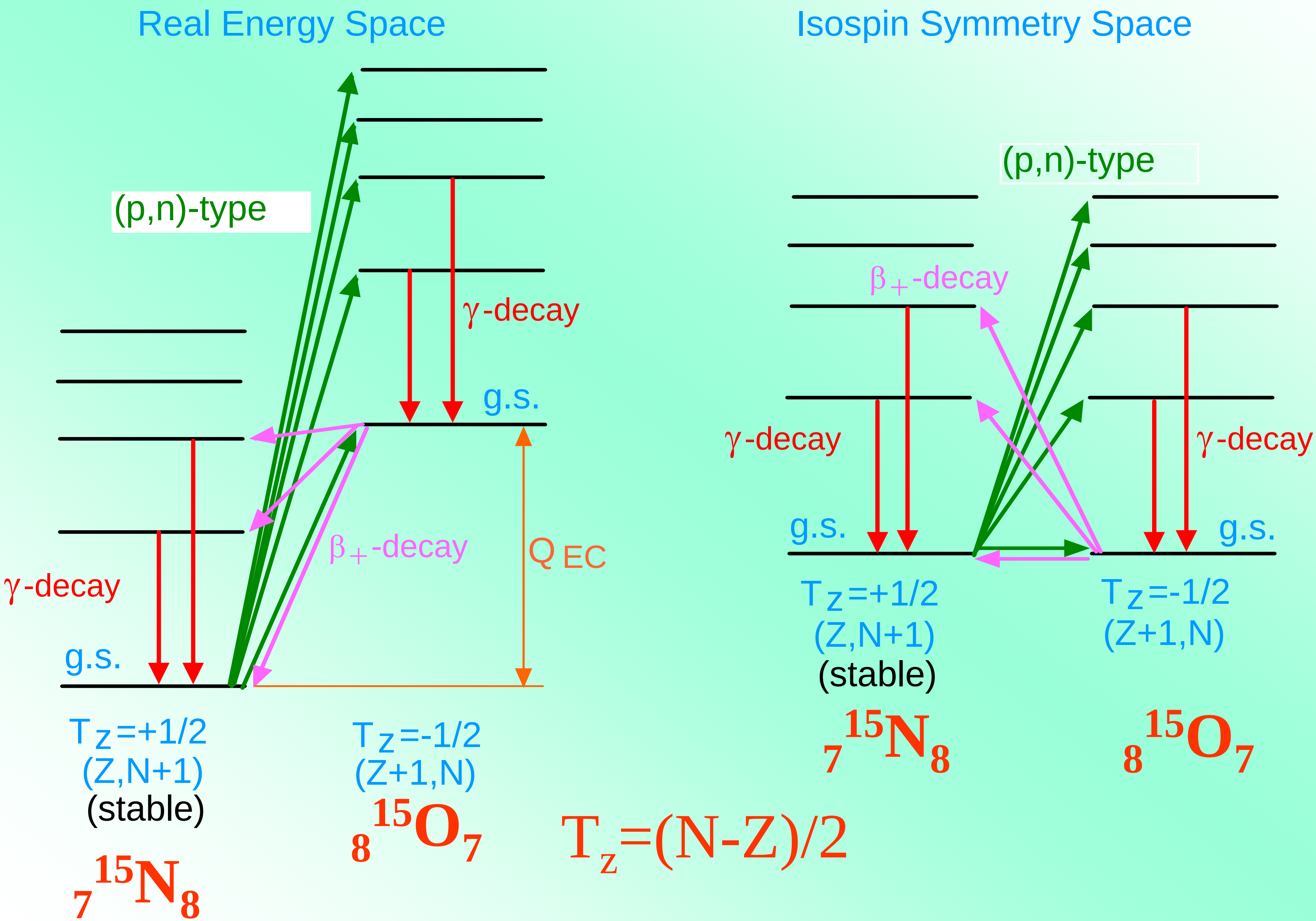


Tτ



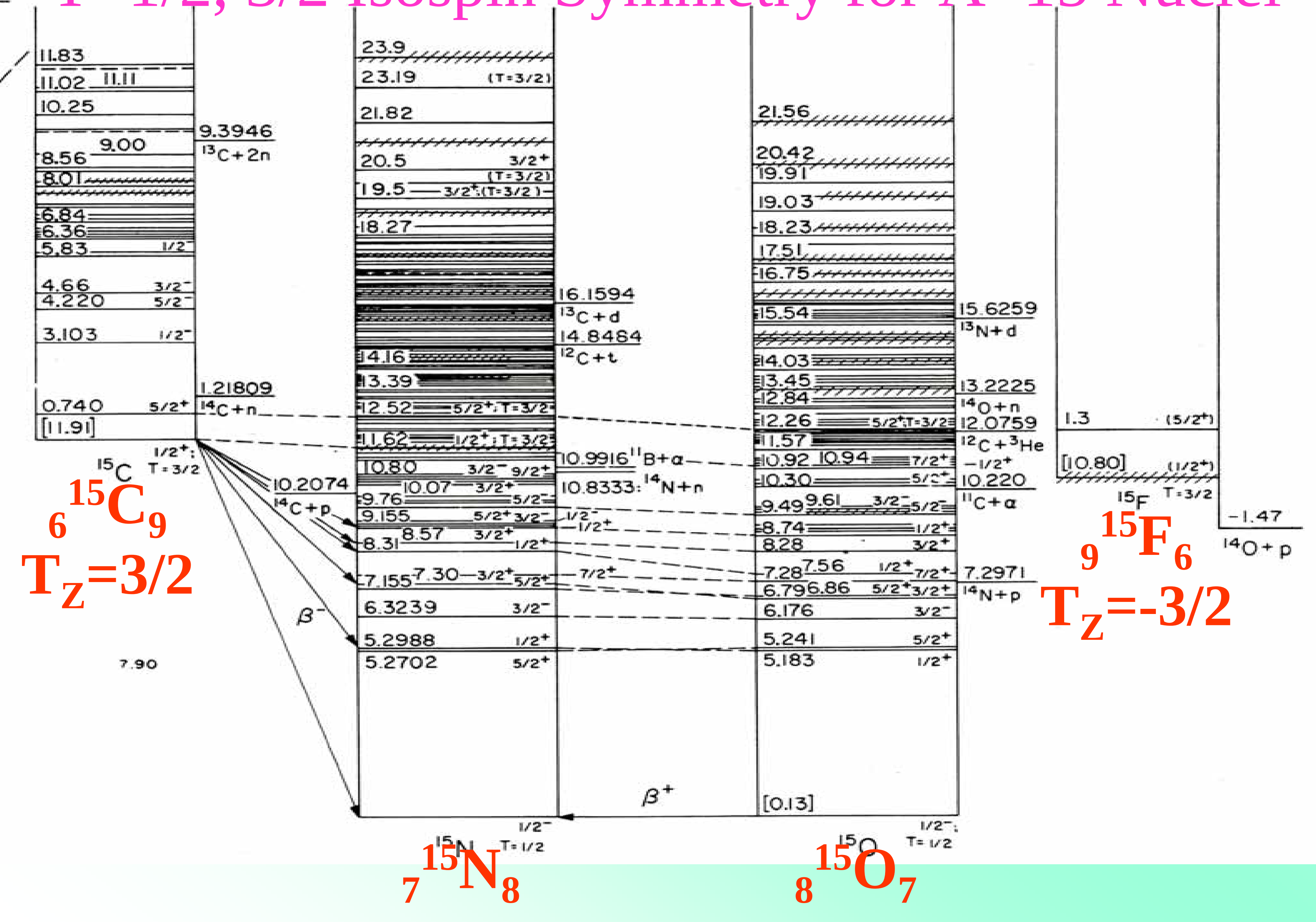
Love & Franey PRC 24 ('81) 1073

Analogous Structures and Transitions in T=1/2 System

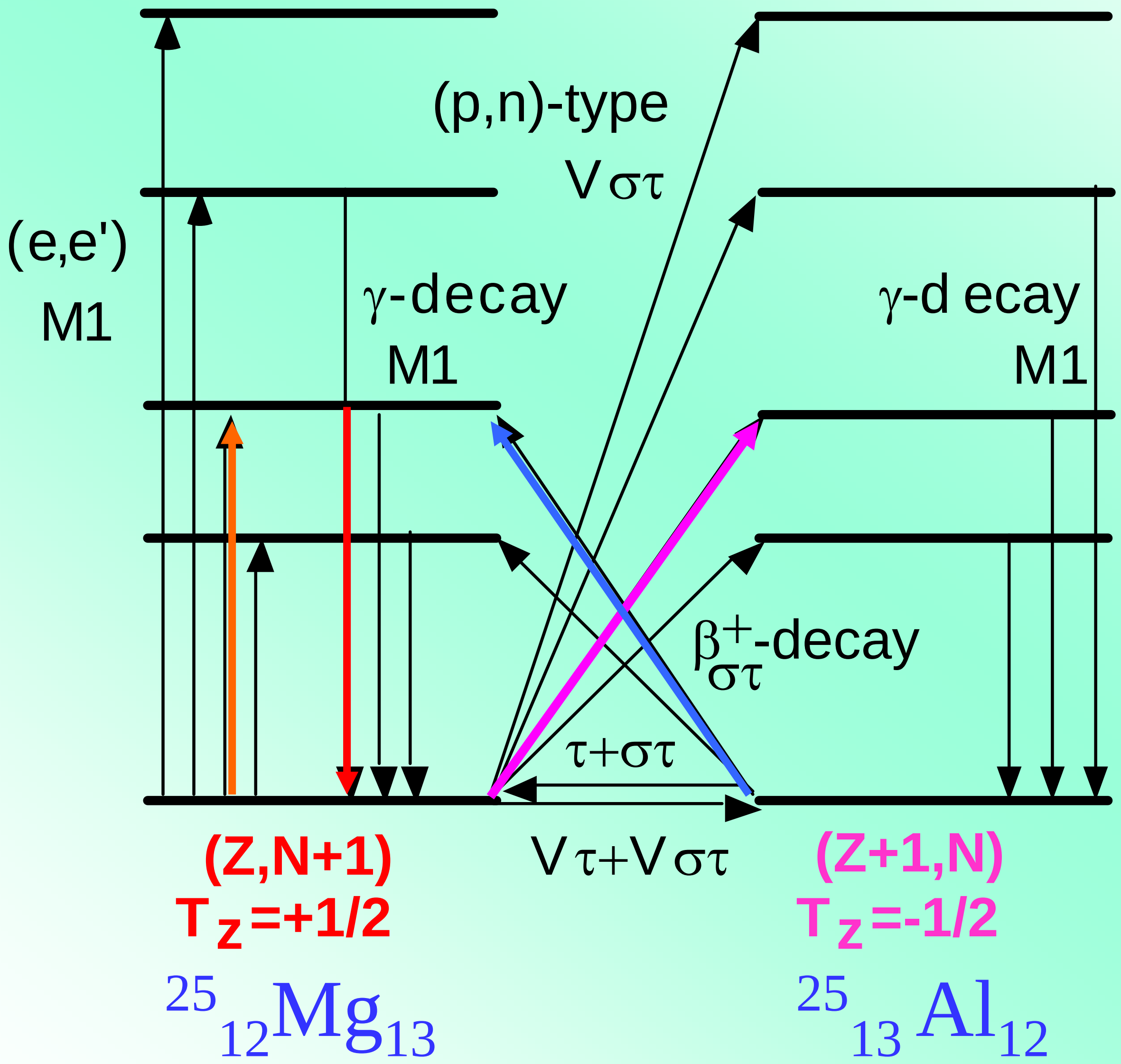


$T_z=(N-Z)/2$

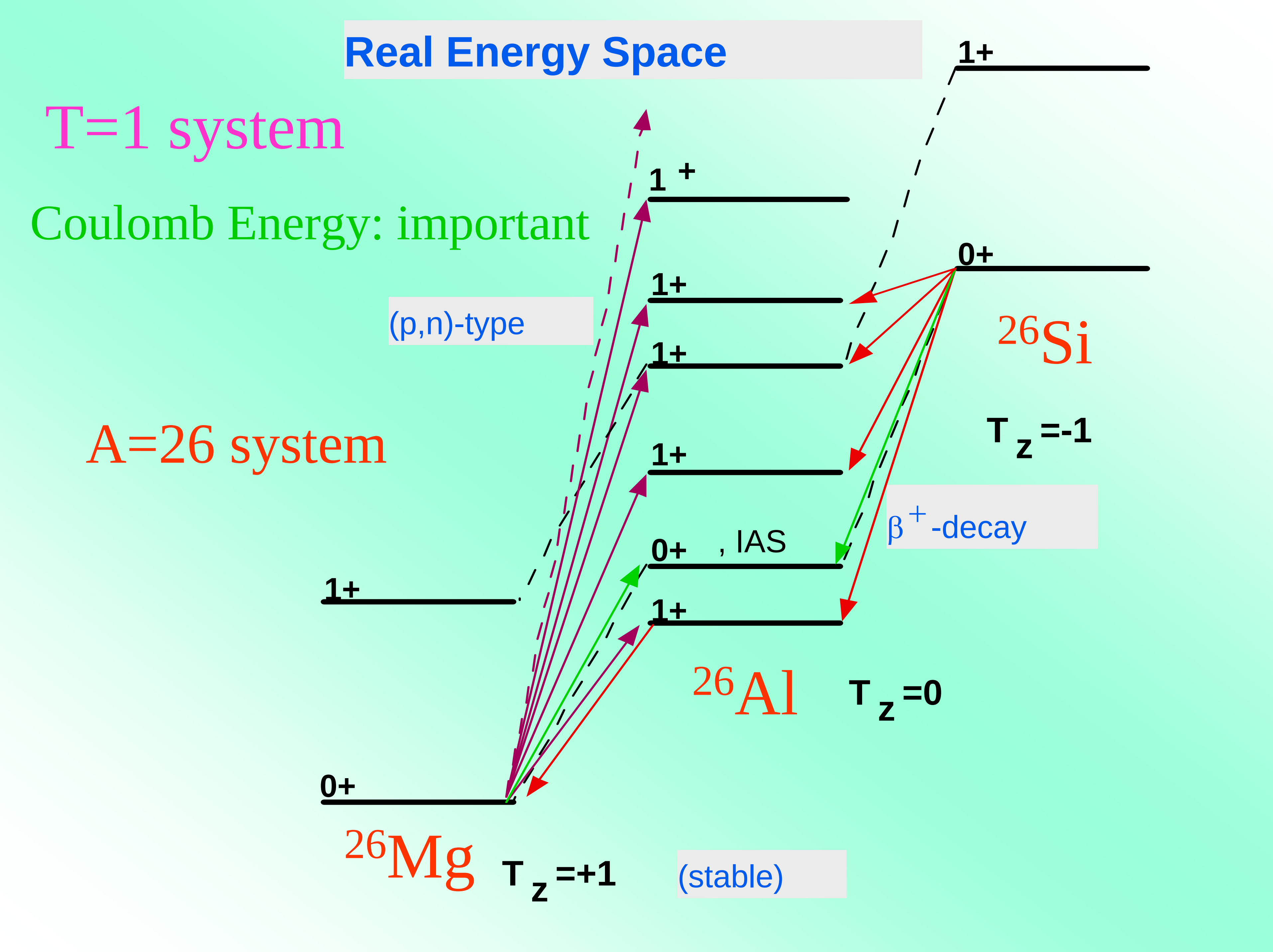
T=1/2, 3/2 Isospin Symmetry for A=15 Nuclei



T=1/2 Mirror Nuclei : Structures & Transitions

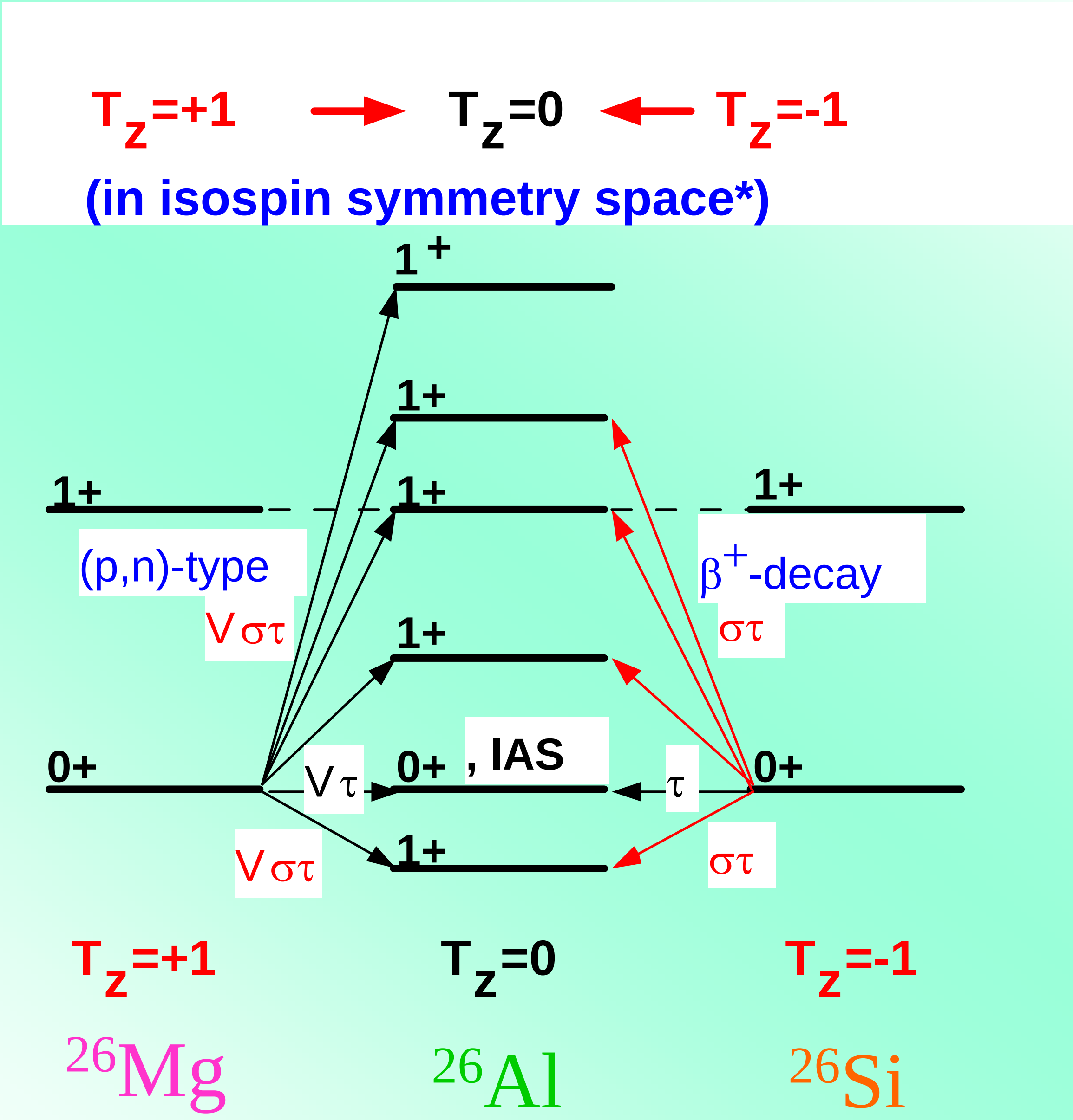


Analogous
Transitions
in β decay
in CE reaction
in γ-decay
in IE reaction

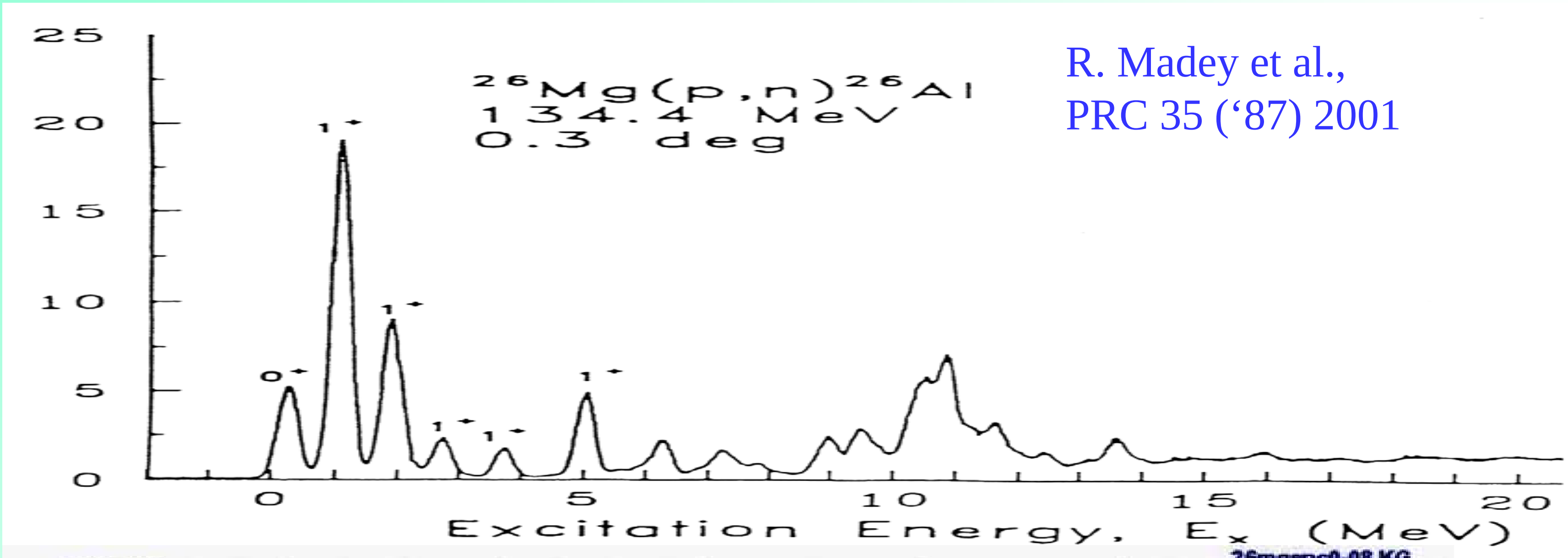


Real Energy Space
T=1 system
Coulomb Energy: important
A=26 system
(p,n)-type
1+
1 +
0+
1+
1+
1+
0+ , IAS
1+
1+
0+
26Si
Tz =-1
β + -decay
26Al
Tz =0
26Mg
Tz =+1
(stable)

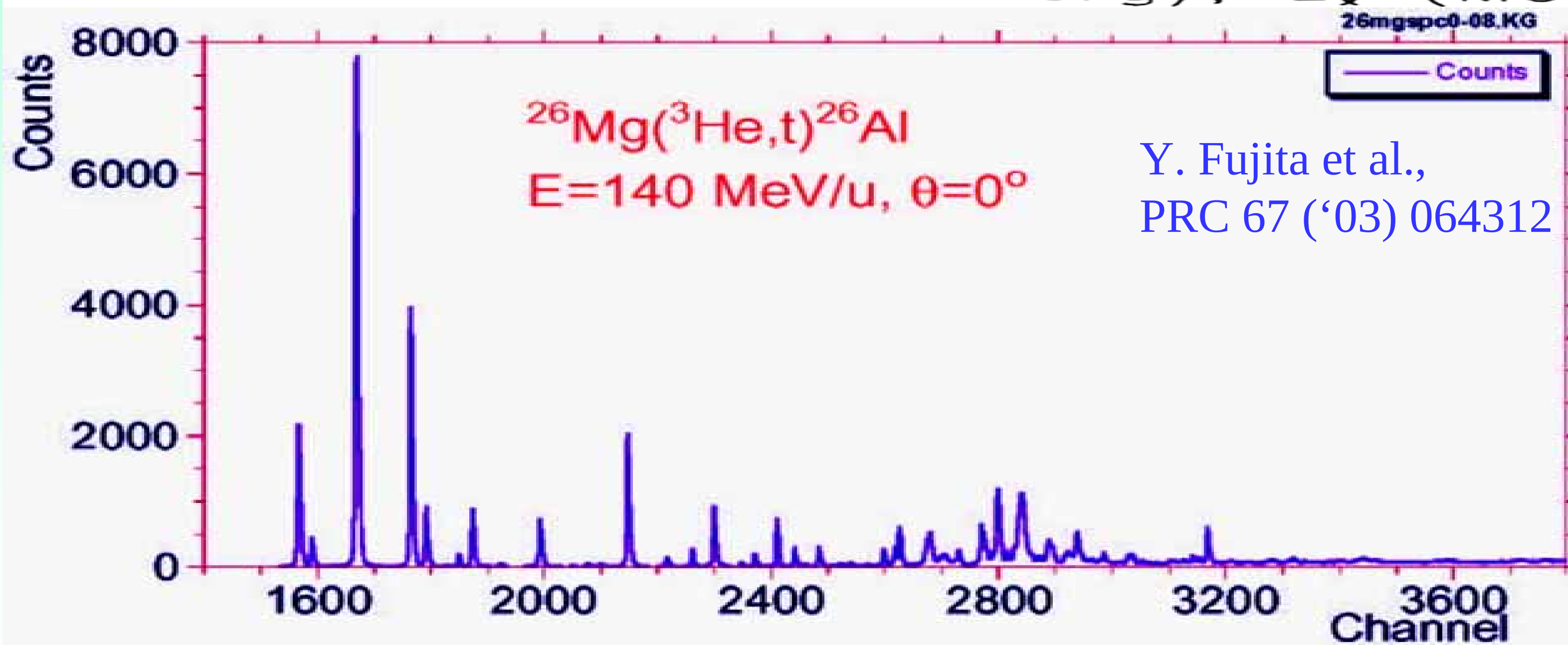
T=1 symmetry : Structures & Transitions



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

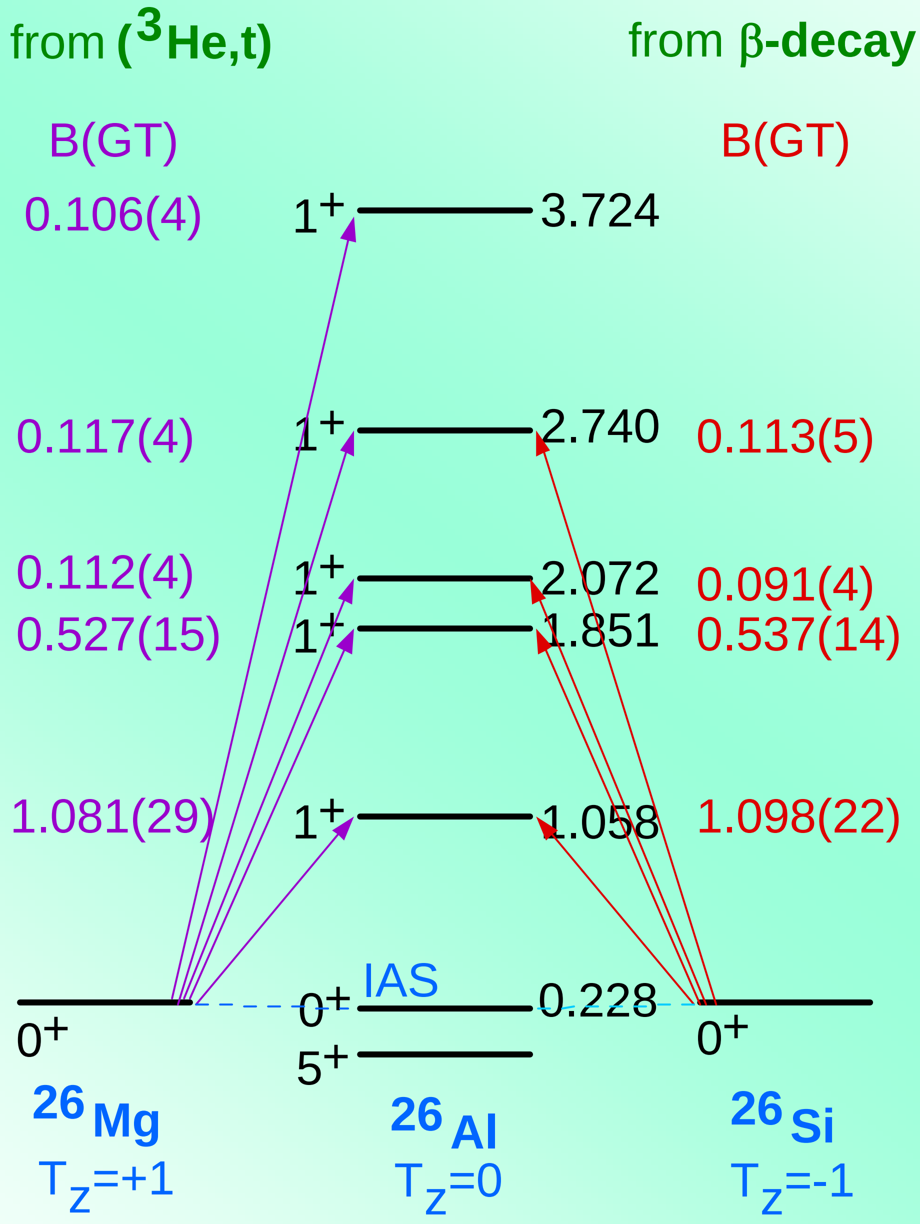


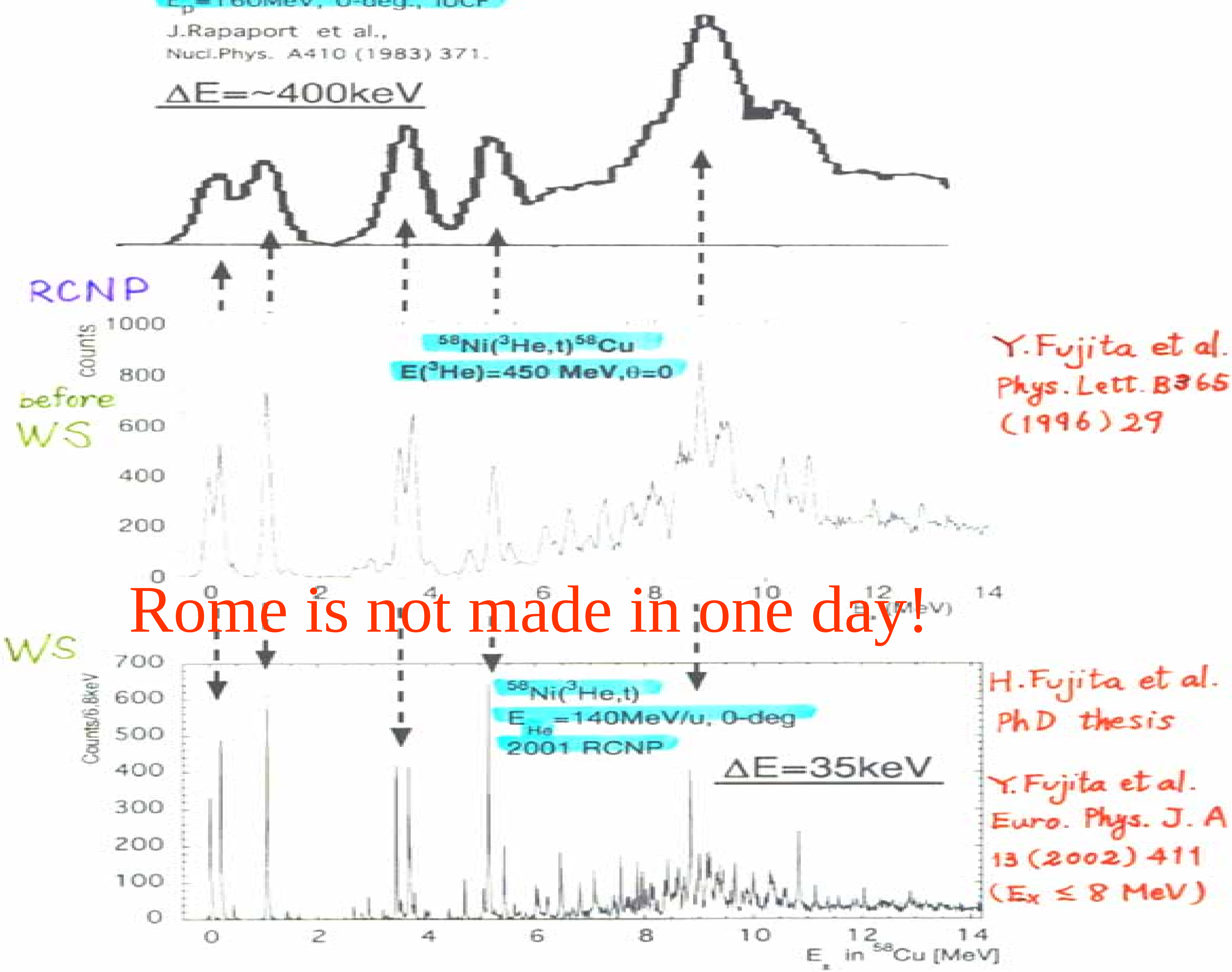
R. Madey et al.,
PRC 35 ('87) 2001



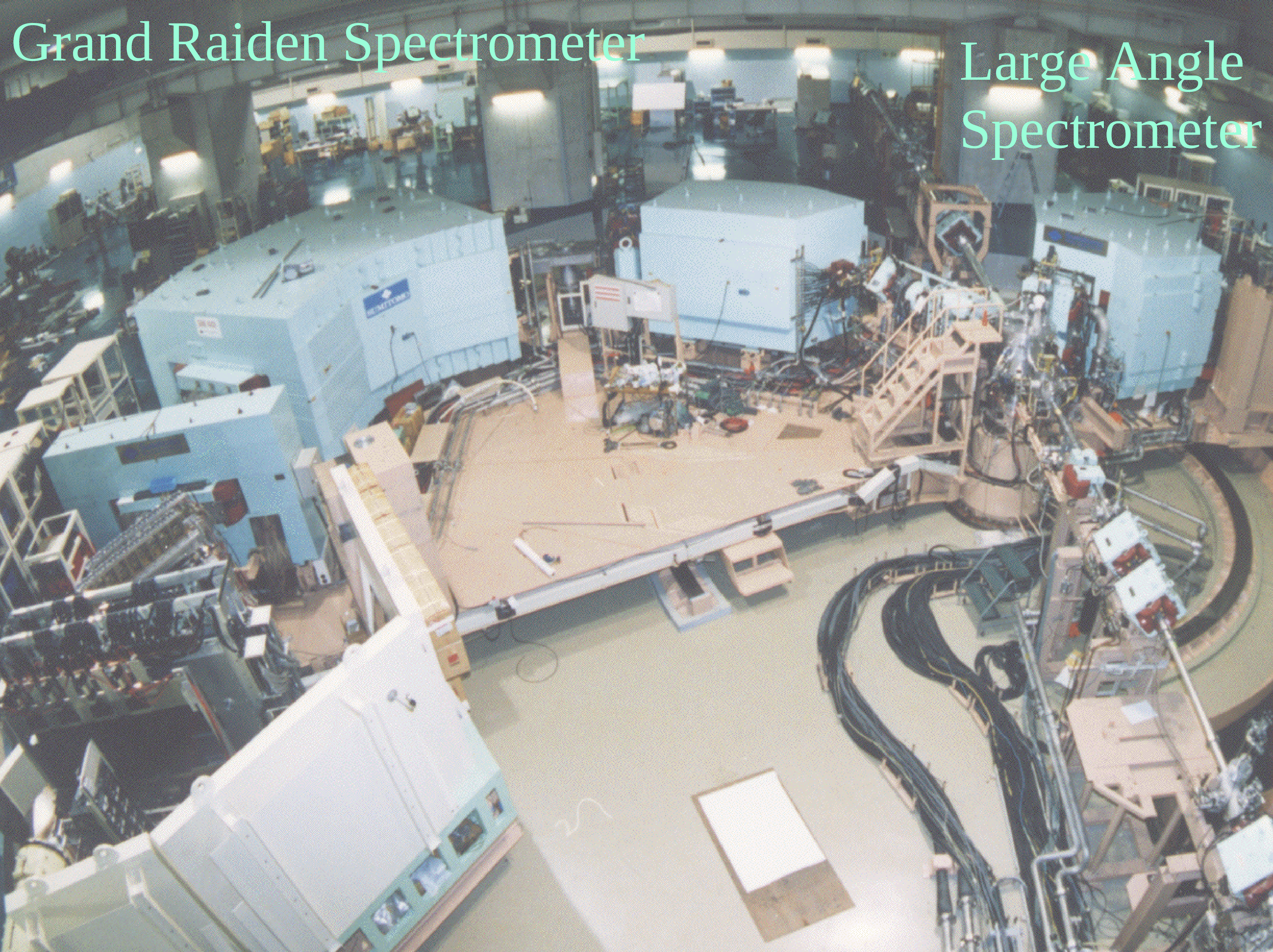
Y. Fujita et al.,
PRC 67 ('03) 064312

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





Rome is not made in one day!

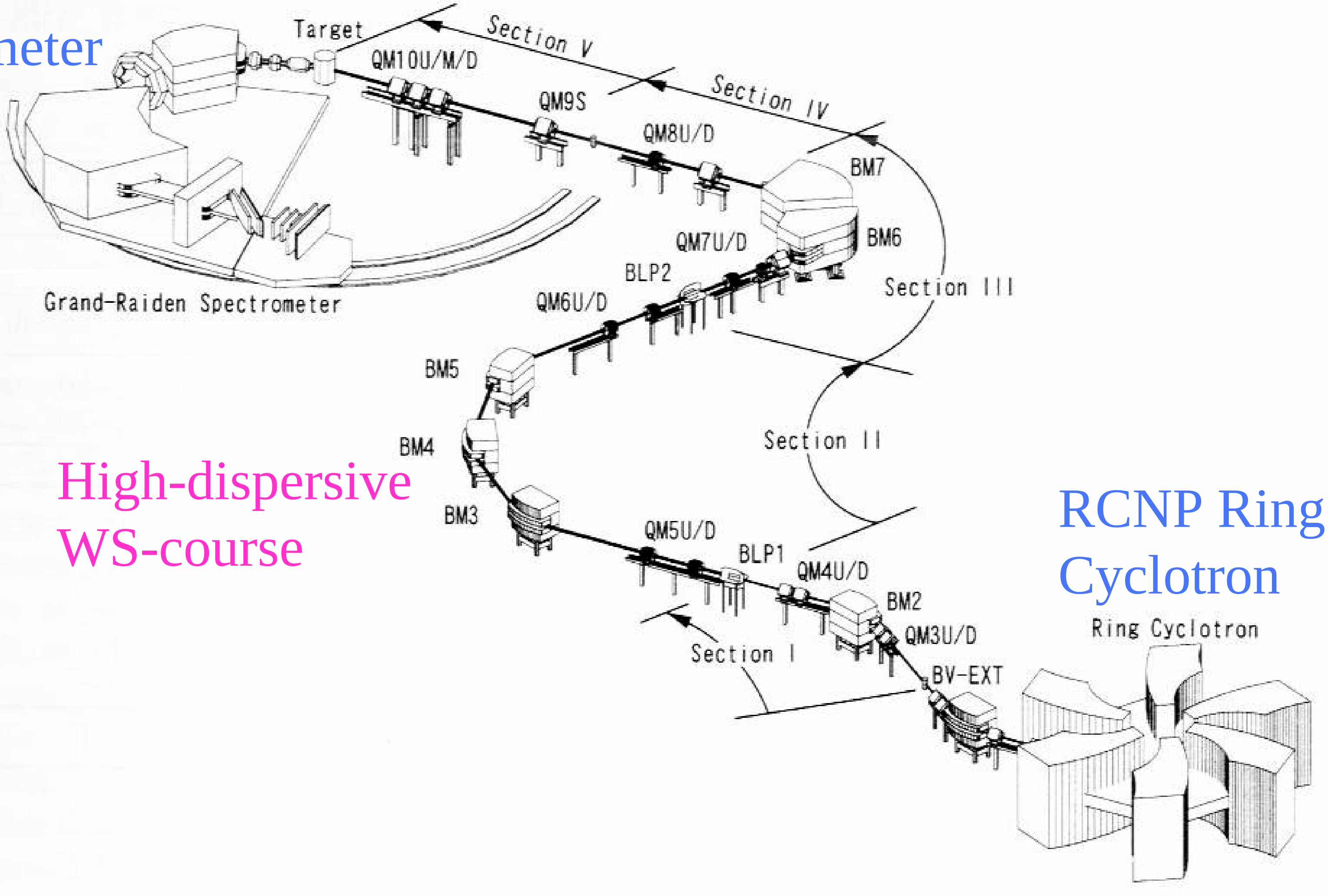

Grand Raiden Spectrometer
Large Angle Spectrometer

RCNP Ring Cyclotron

Beam line WS-course

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

Grand-Raiden Spectrometer



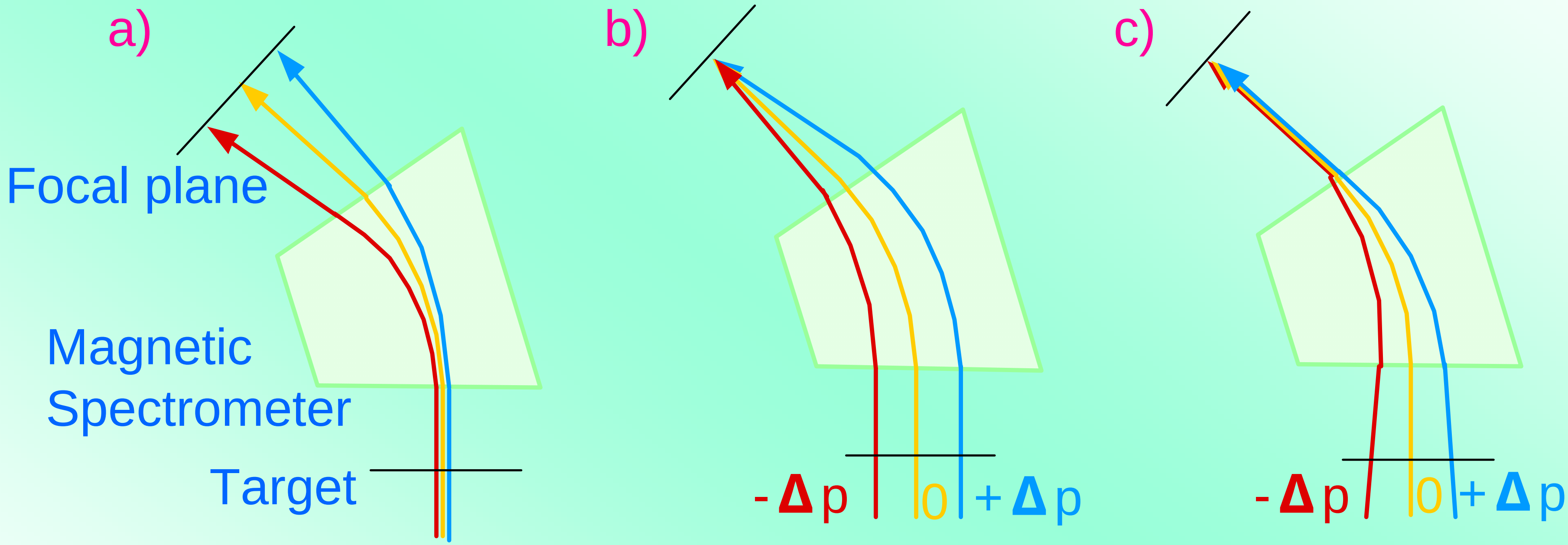
High-dispersive WS-course

RCNP Ring Cyclotron

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

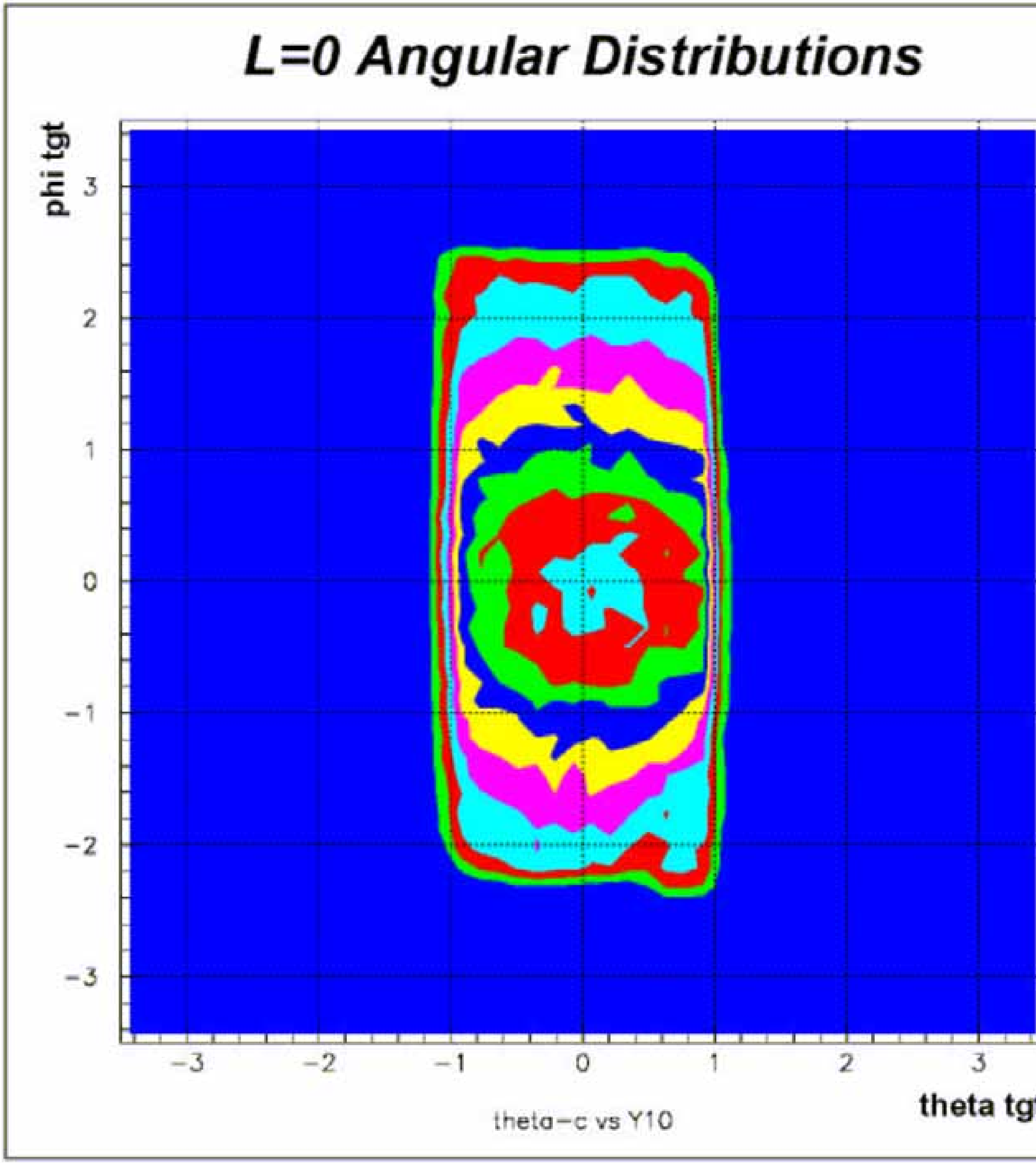
$\Delta\theta_{sc} > 15$mrad

Angular dispersion matching

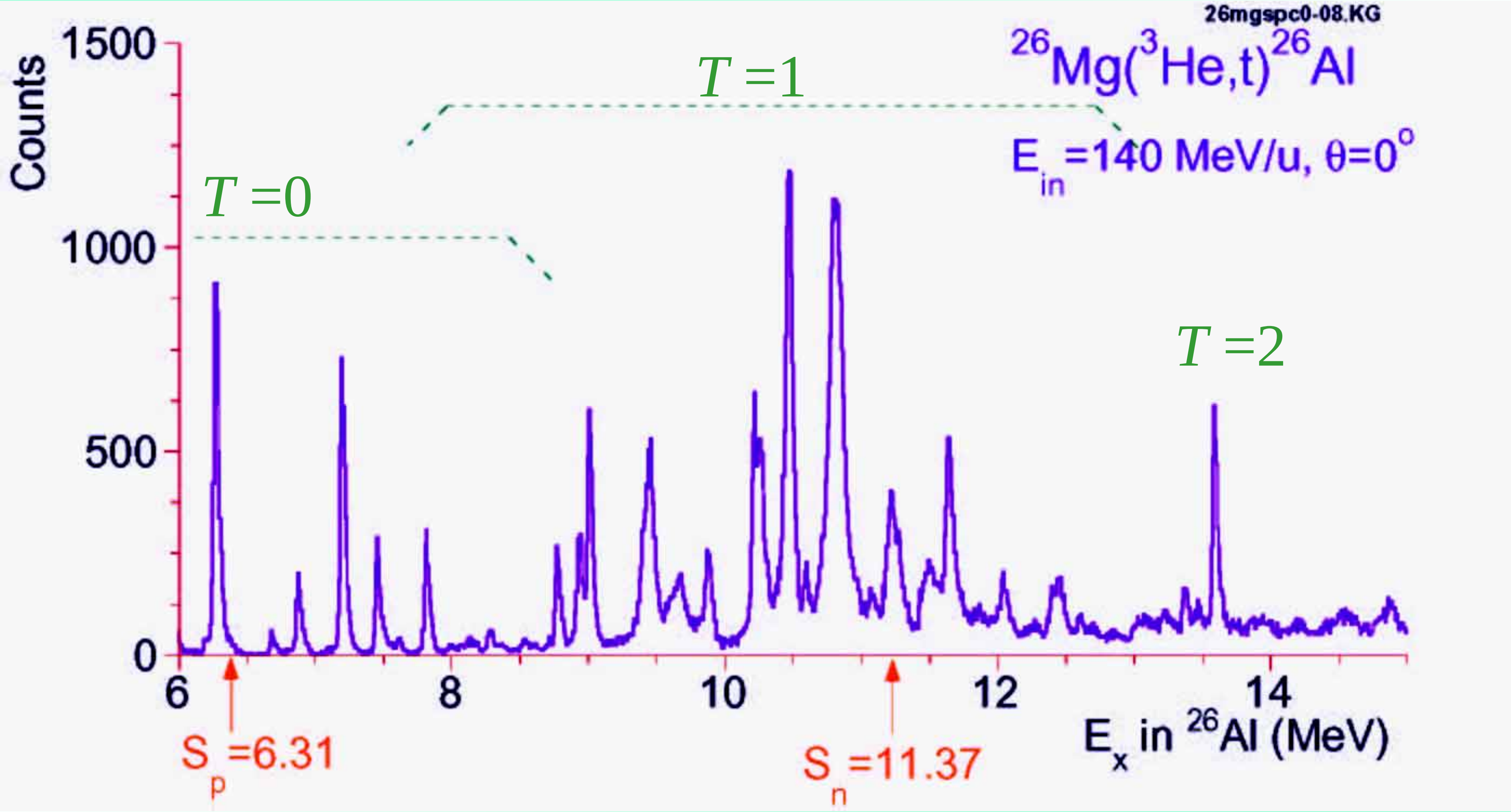
$\Delta\theta_{sc} \sim 5$mrad

Contour Map within the Acceptance

Concentric L=0 angular distribution around 0º



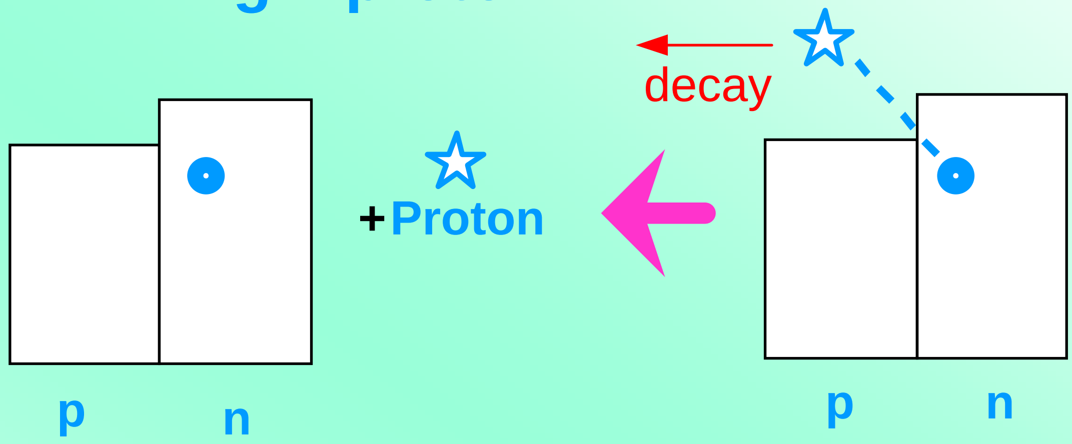
Higher-E_x region in ^{26}Al : *T*=1 & *T*=2 states



With of a state: observed !   ΔE Δt ~ h

Importance of Isospin : in *p*-decay of ^{26}Al

^{25}Mg + proton **^{26}Al**



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

T : 1/2 + 1/2 = 0 or 1

3/2 + 1/2 = 1 or 2

#S_p (p-sep. energy) in ^{26}Al : 6.31 MeV

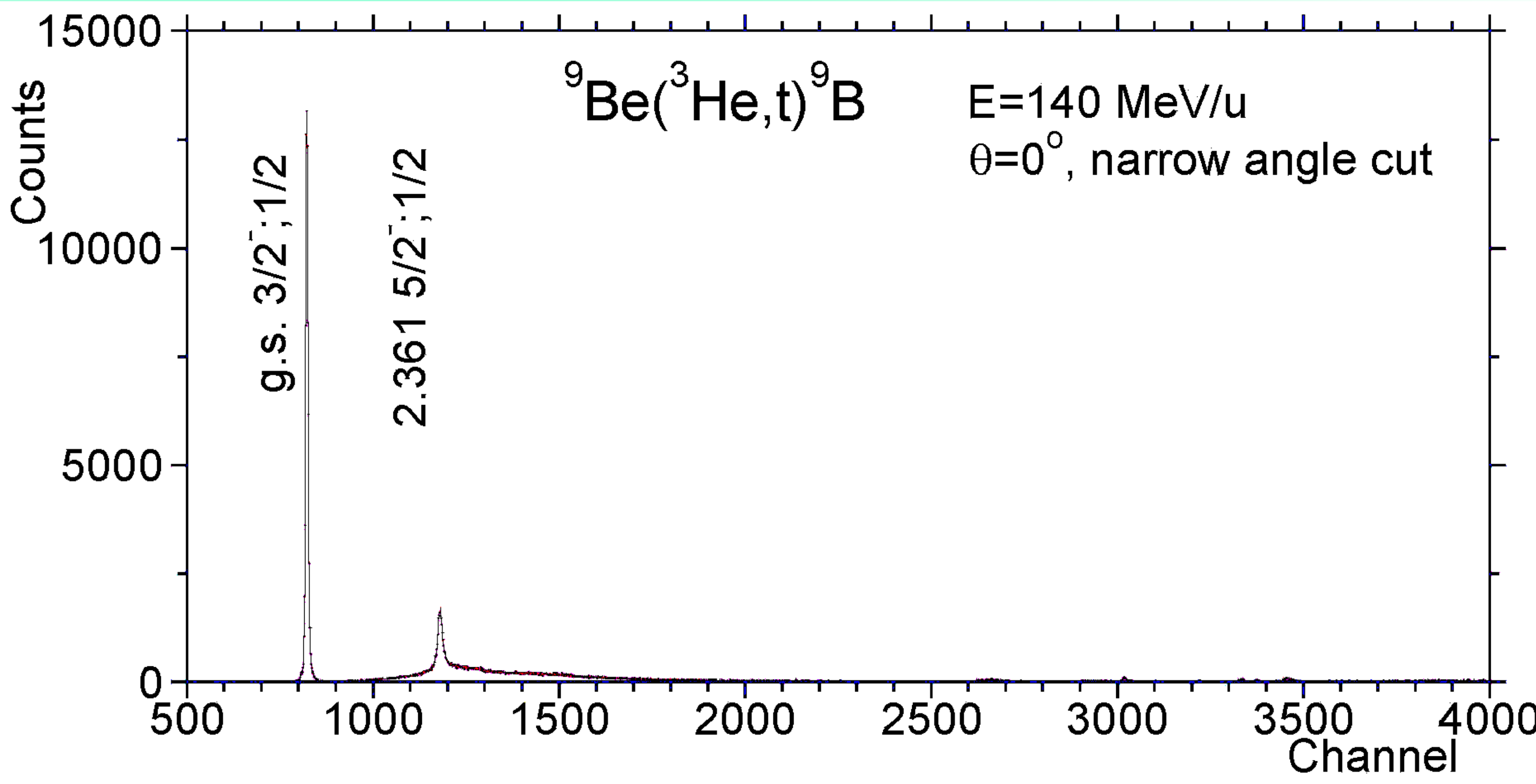
#T=3/2 state in ^{25}Mg : E_x > 7.79 MeV

→ effective S_p in ^{26}Al

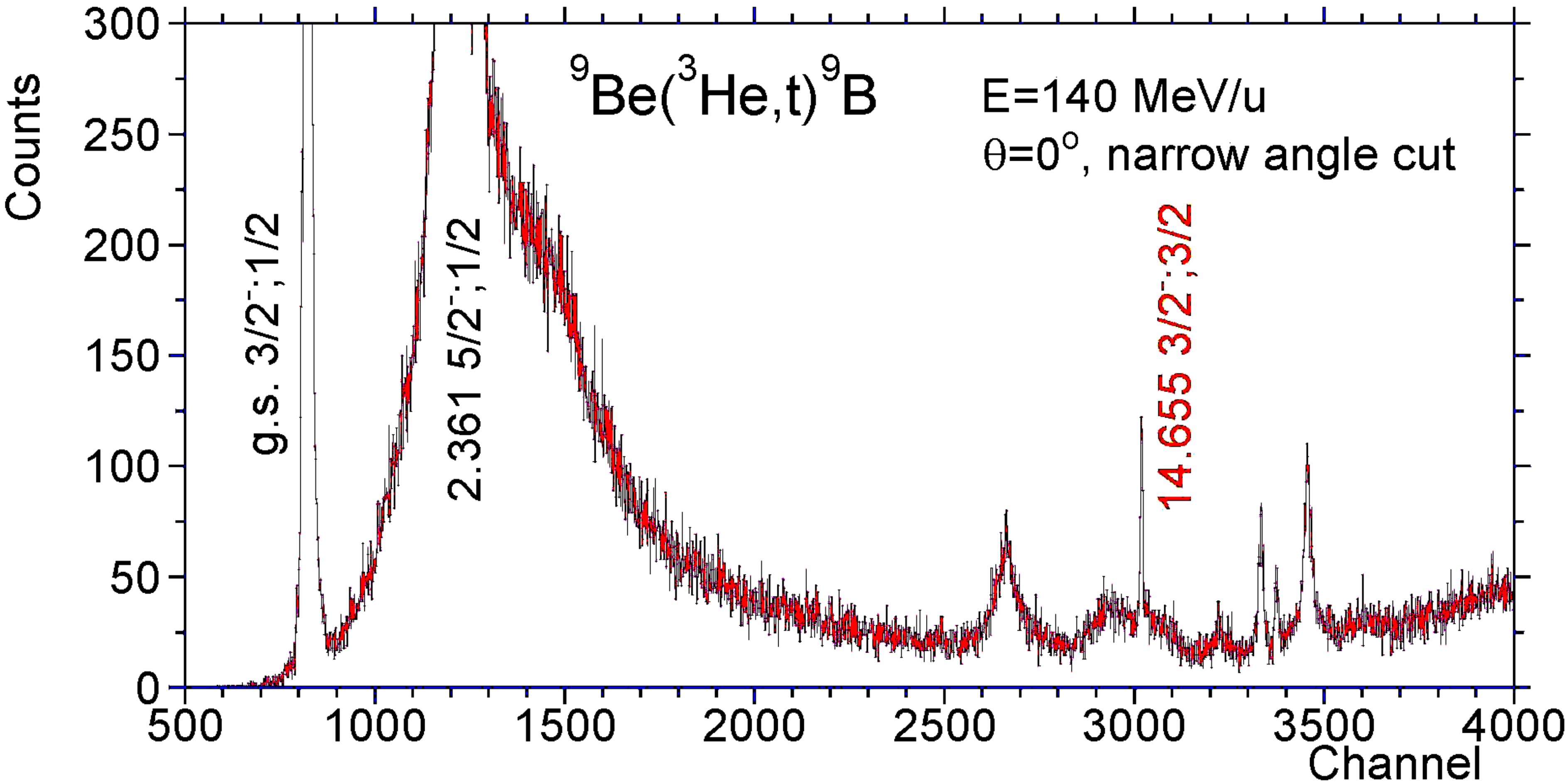
for T = 0, 1 states : E_x = 6.31 MeV

for T = 2 states : E_x = 14.1 MeV

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

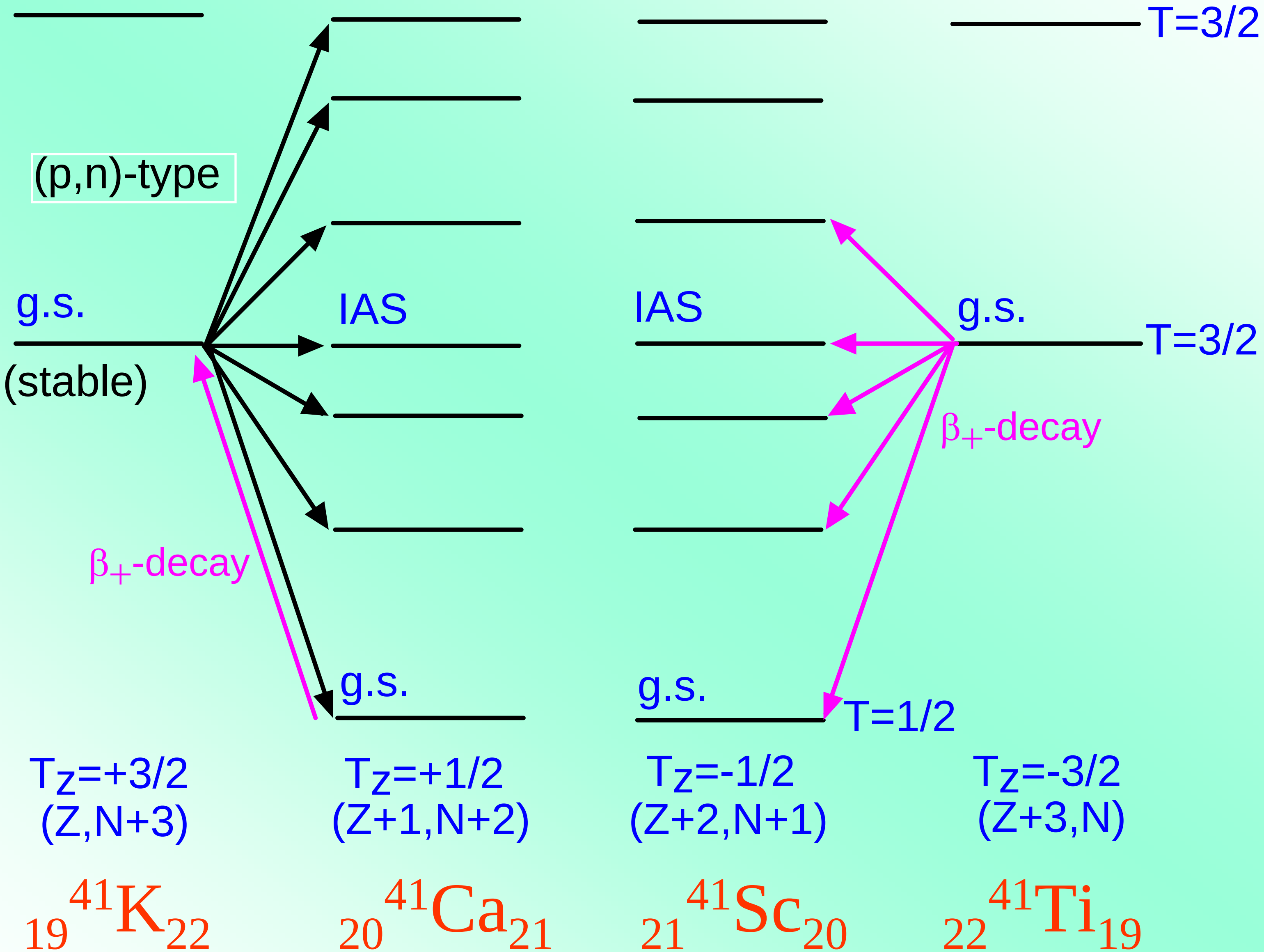


$^{9}Be(^{3}He,t)^{9}B$ spectrum (II) x50

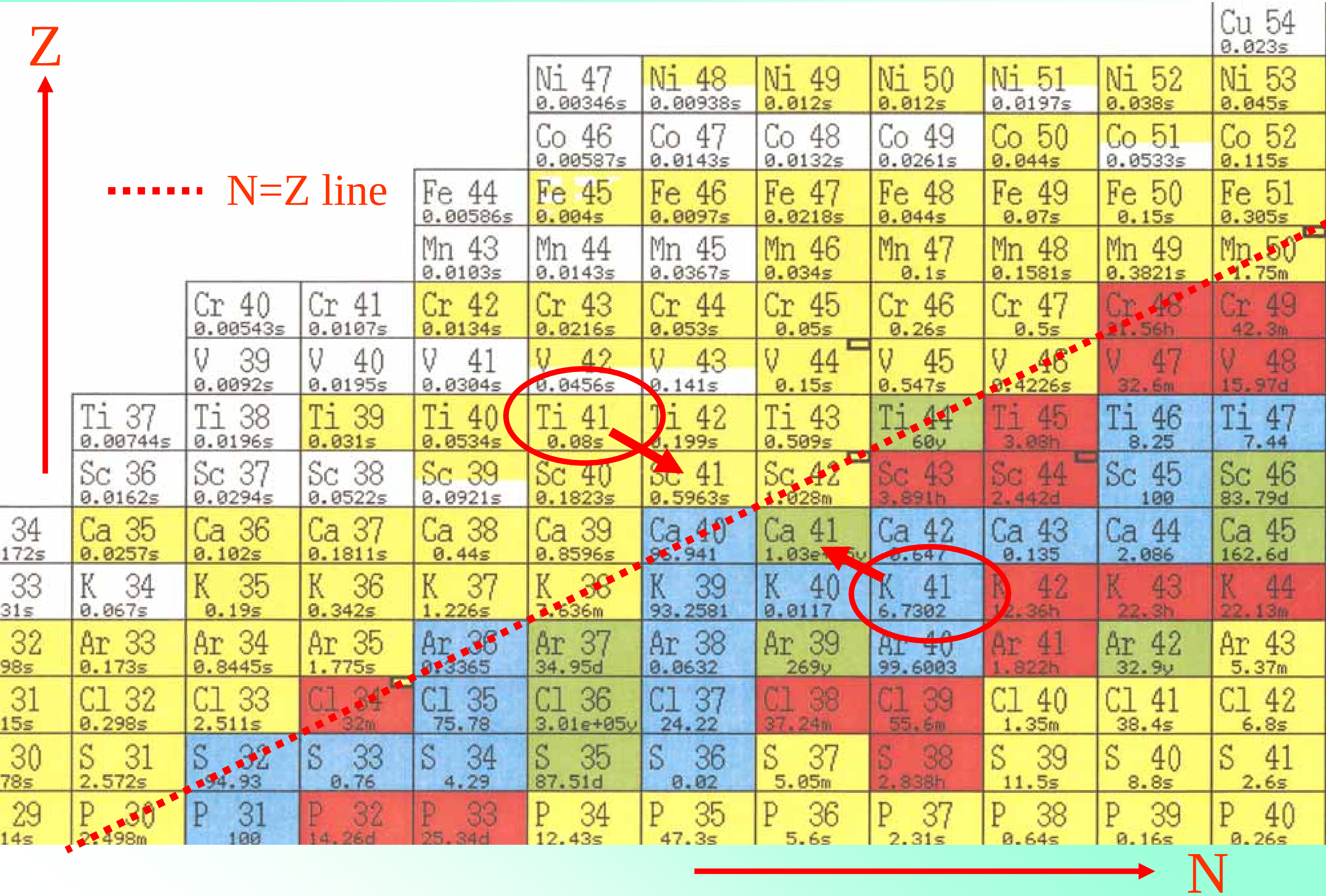


Isospin selection rule allows no particle decay of $T_{>}$ state

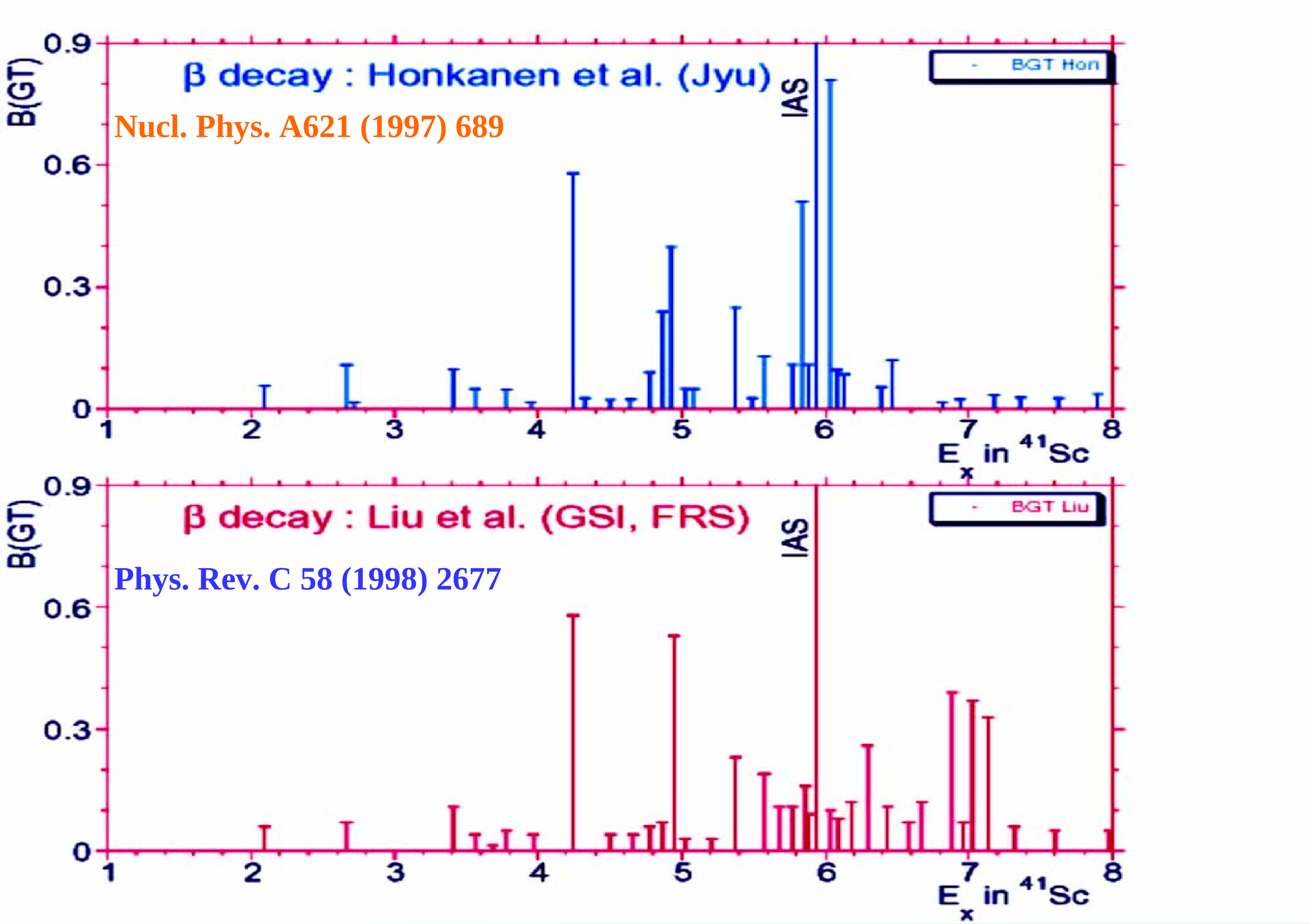
T=3/2 system: structures & transitions



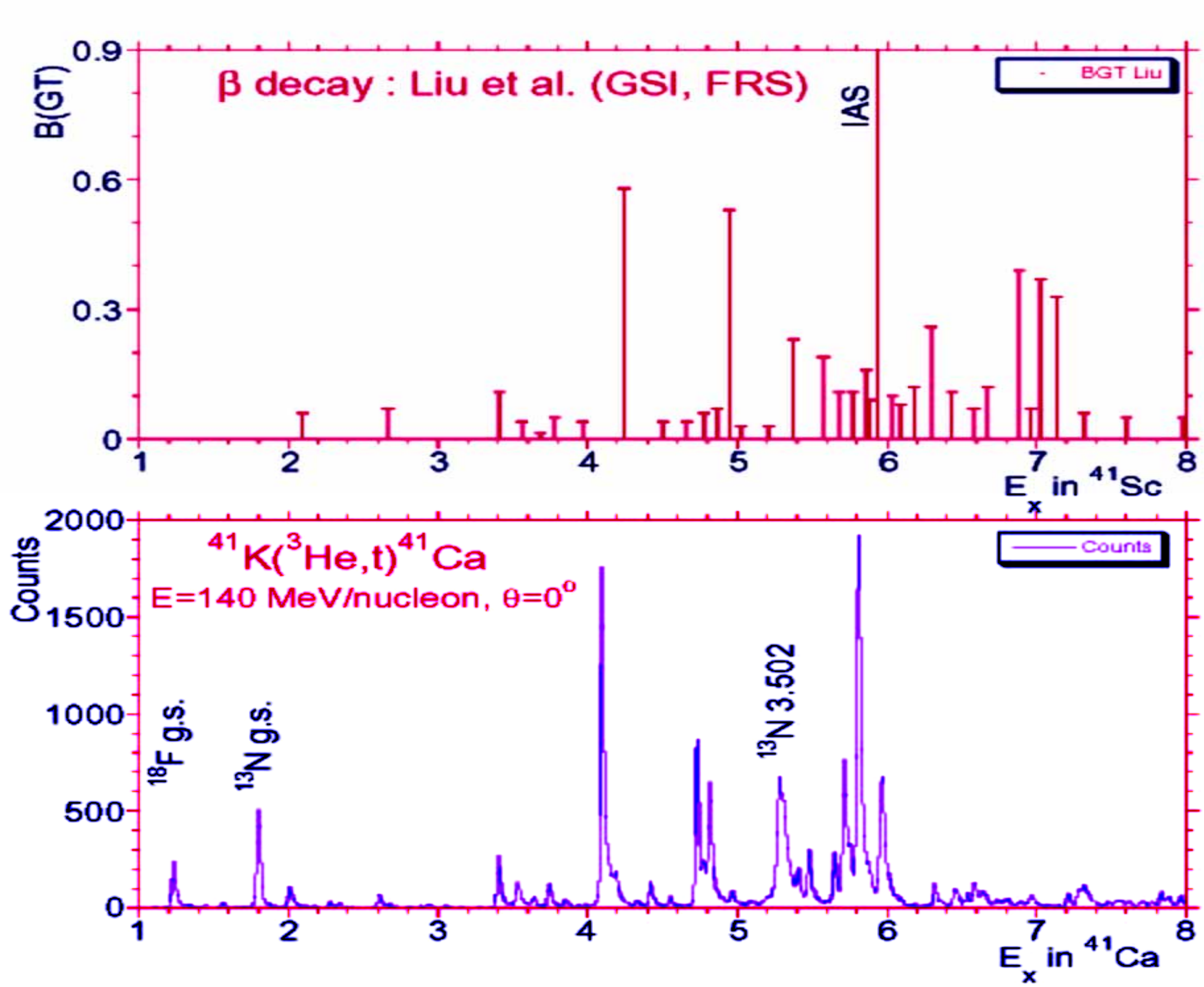
Nuclear Chart



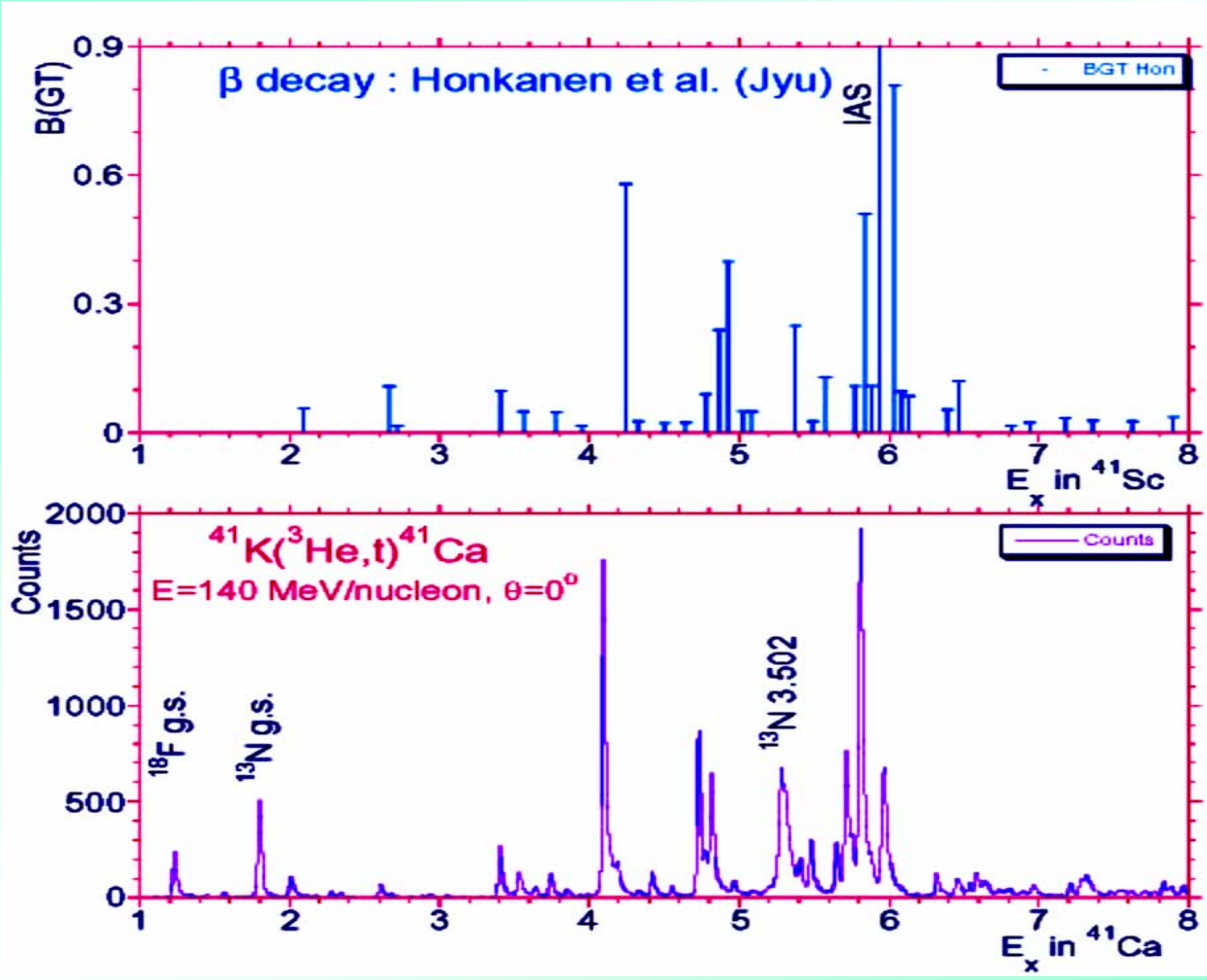
Comparison of two β-decay results



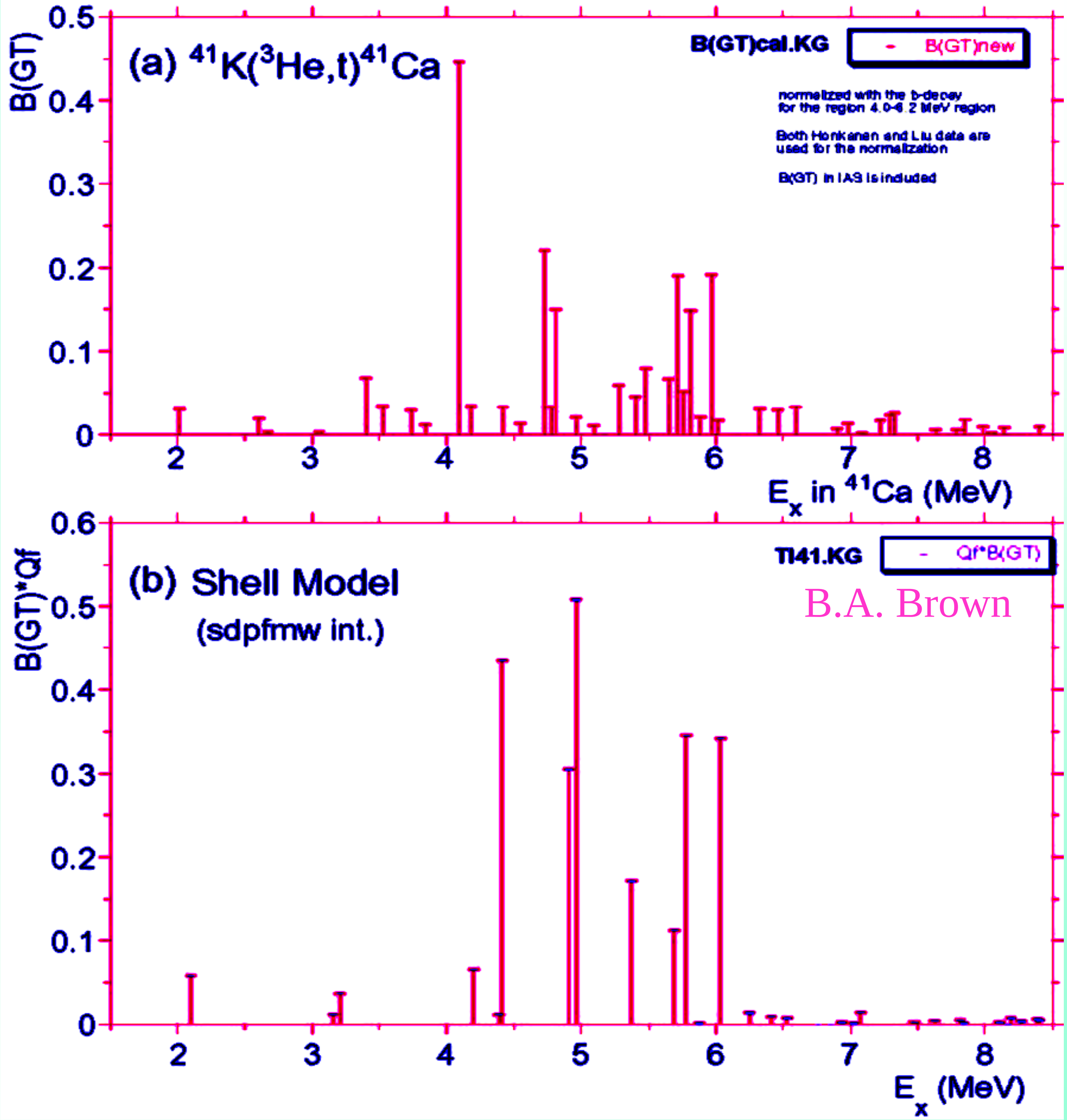
Comparison with $^{41}K(^{3}He,t)^{41}Ca$ (I)



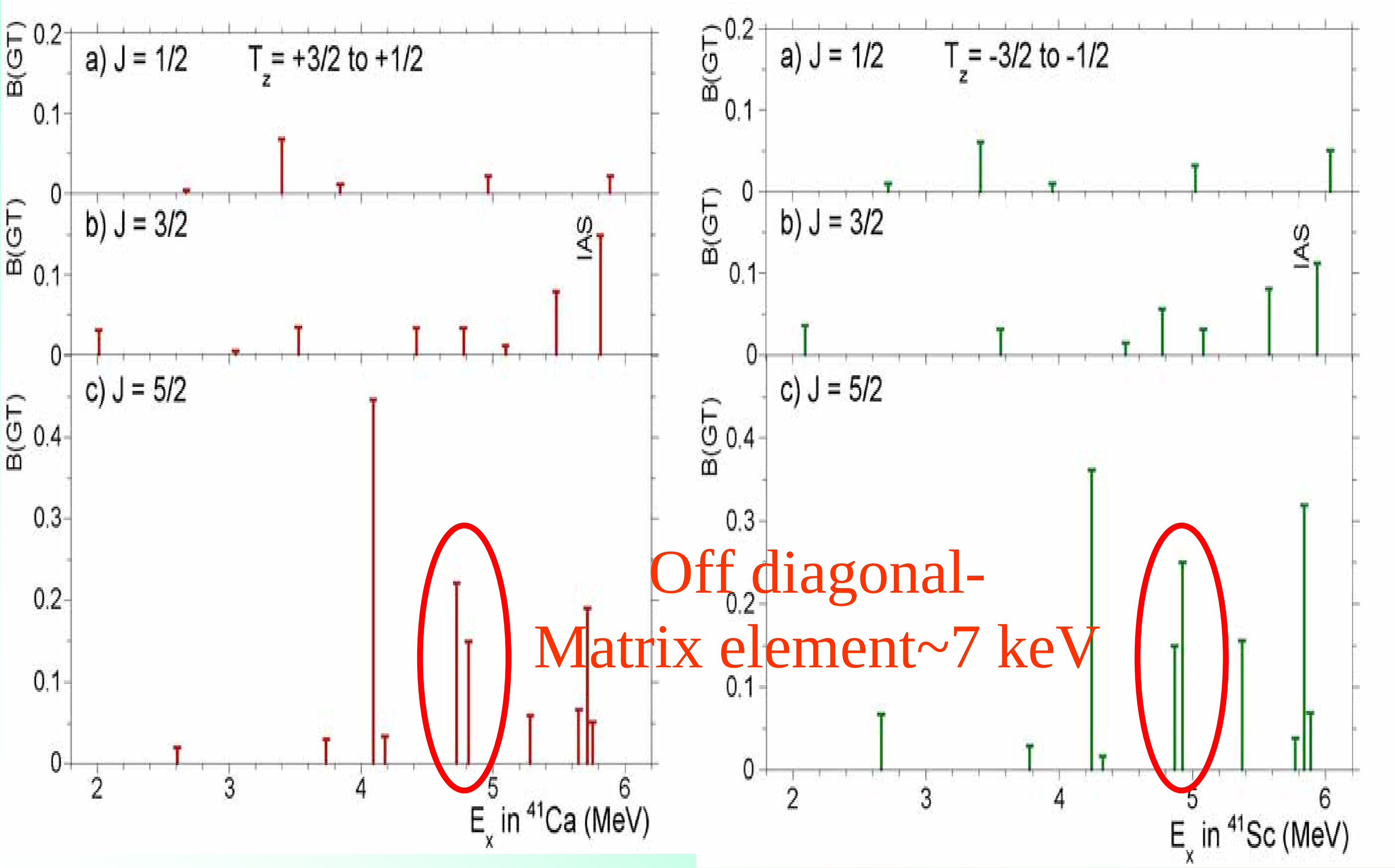
Comparison with ^{41}K(^{3}He,t)^{41}Ca (II)



Comparison: $^{41}K(^{3}He,t)^{41}Ca$ & Shell Model



Reversed Strength in T_z=+-1/2



(*p*, *n*) spectra for A>90 Nuclei

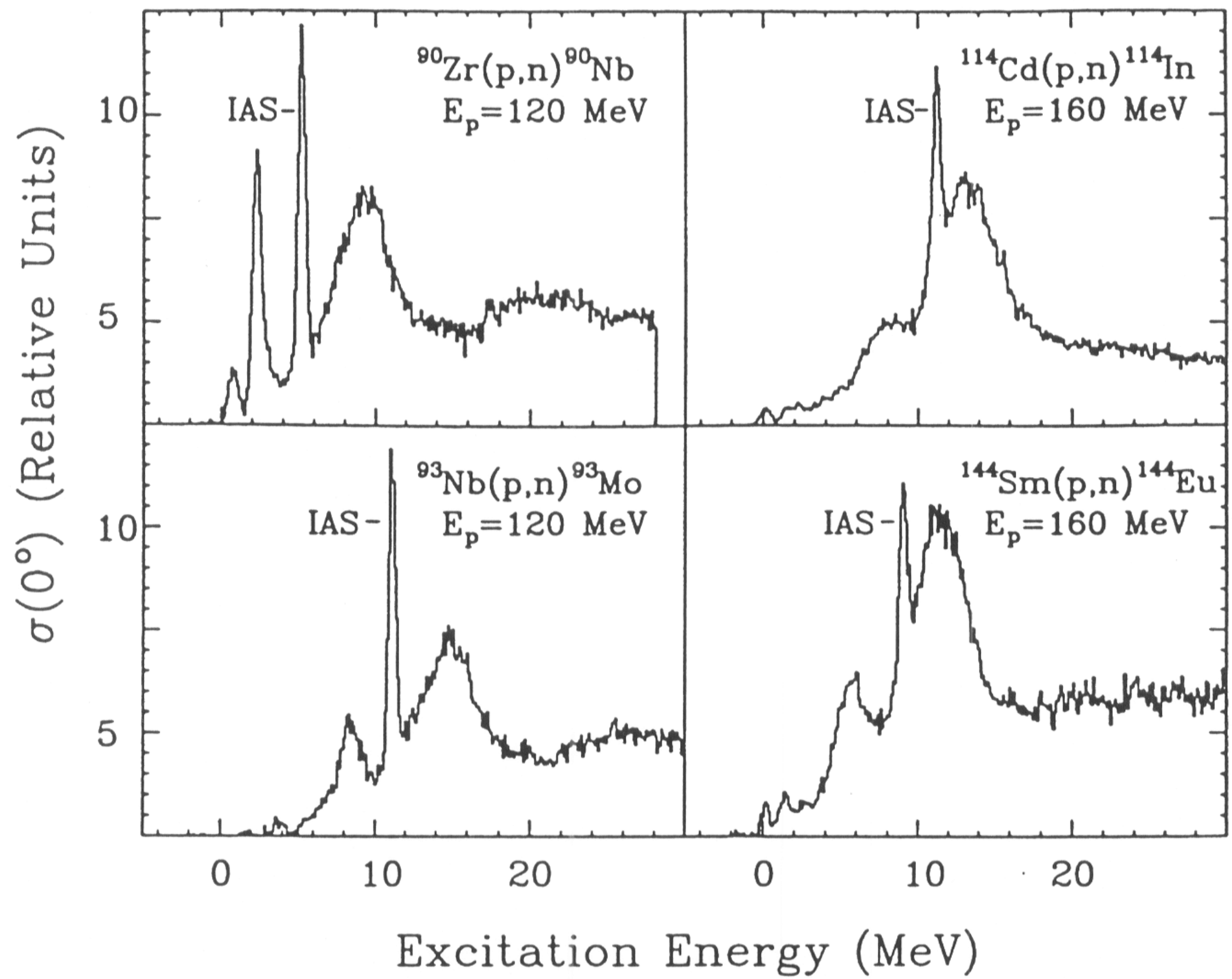
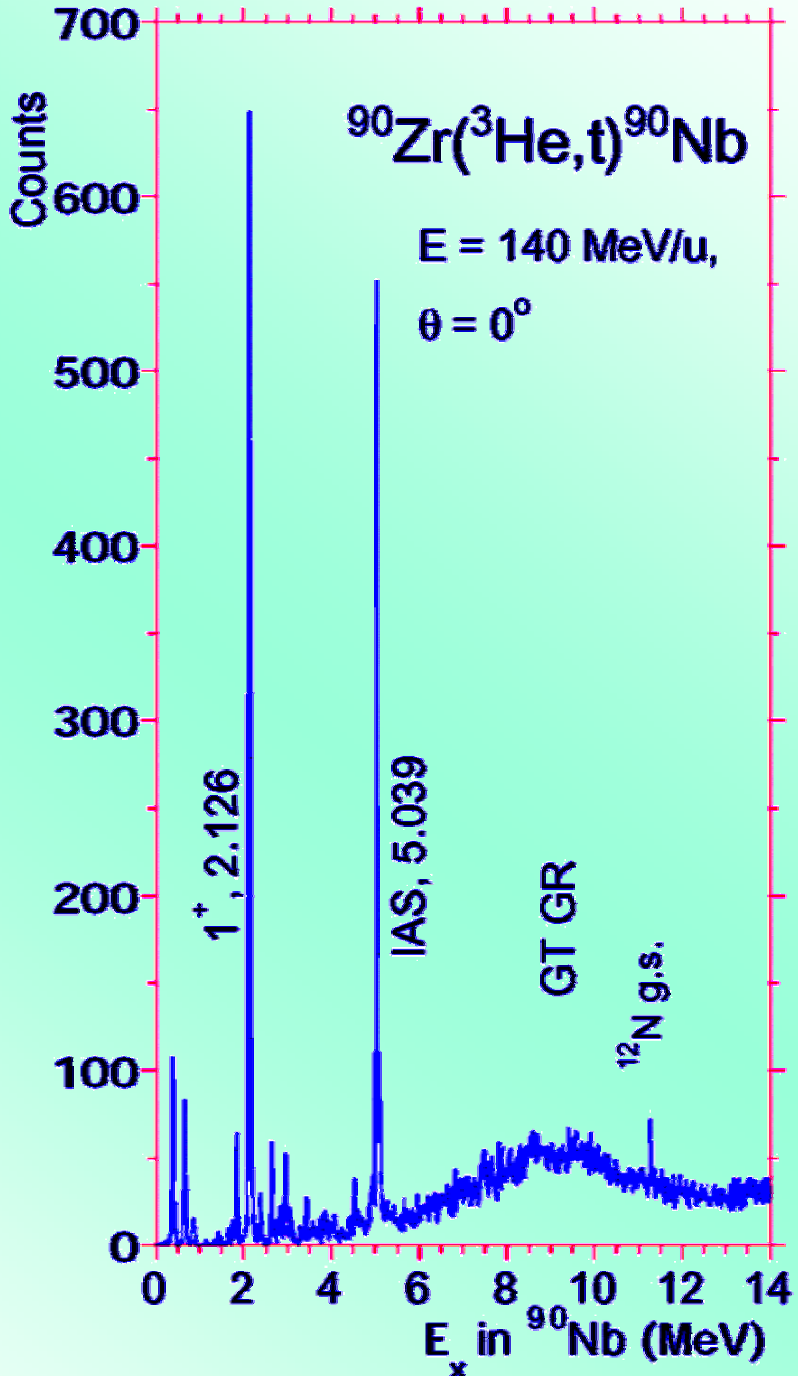
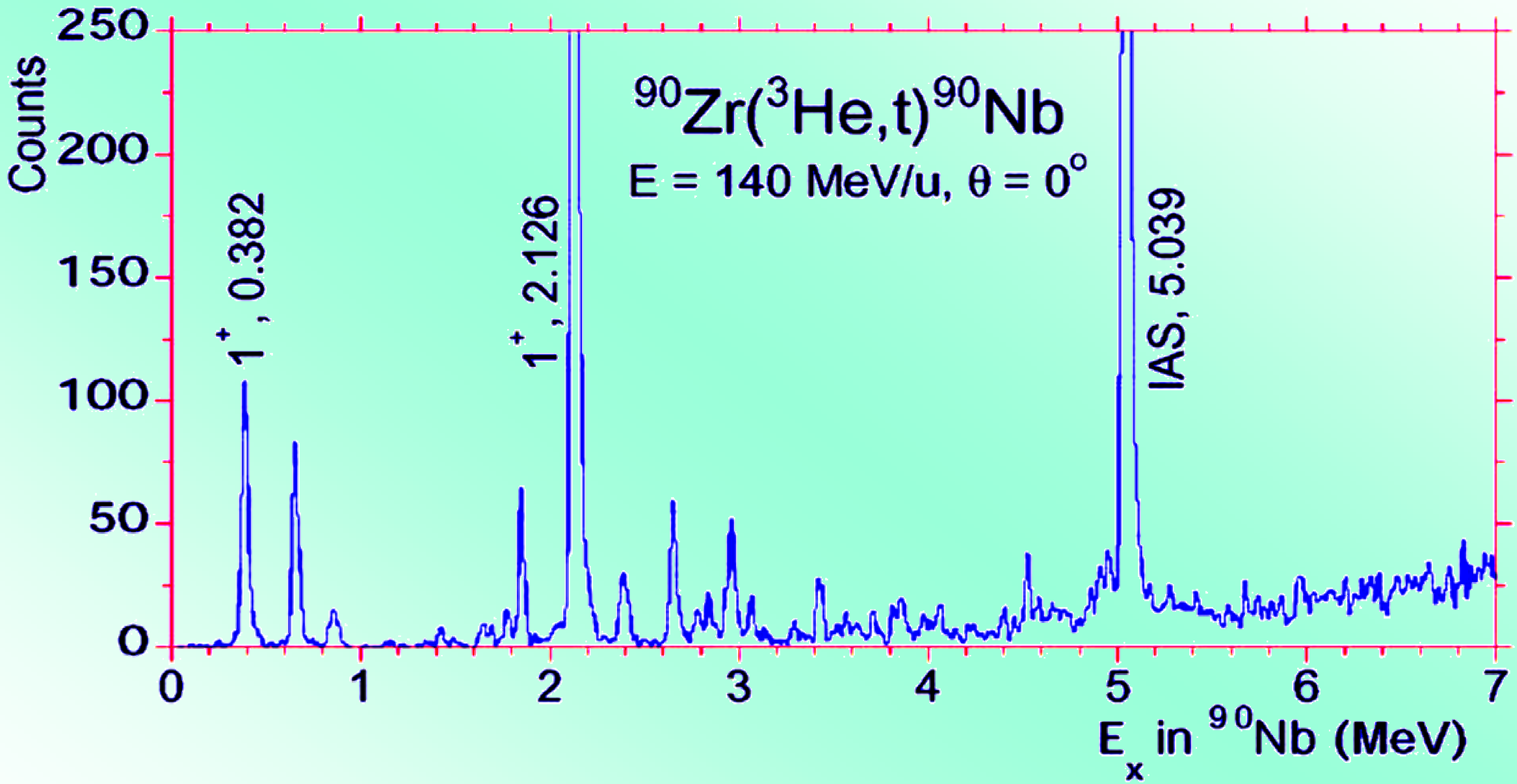


Figure 10 Zero-degree (*p*,*n*) spectra for medium *A*-mass nuclei at the indicated incident energies.

Discrete States and GT GR in ^{90}Nb (II)

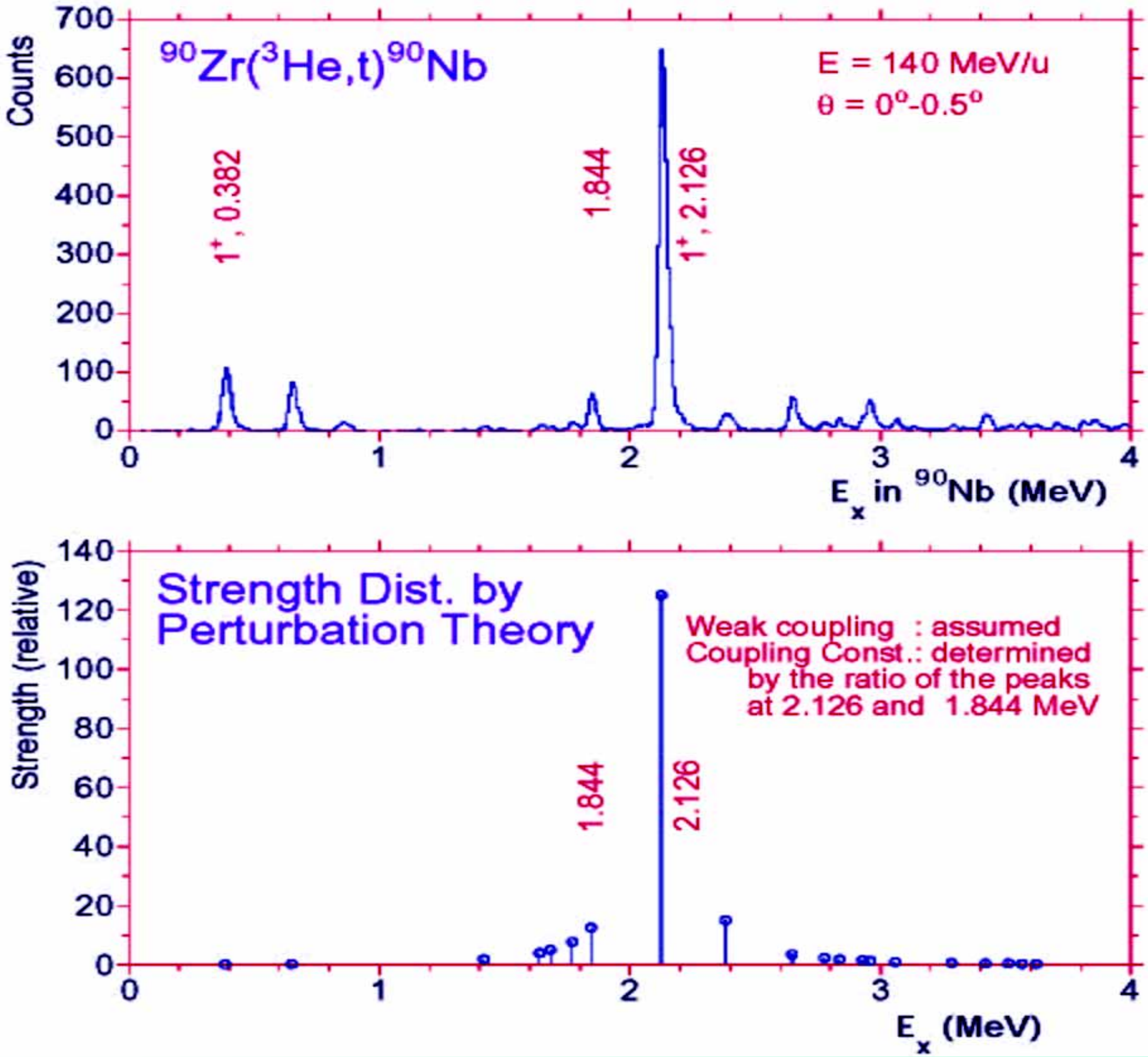


Fragmented low-lying states in ^{90}Nb



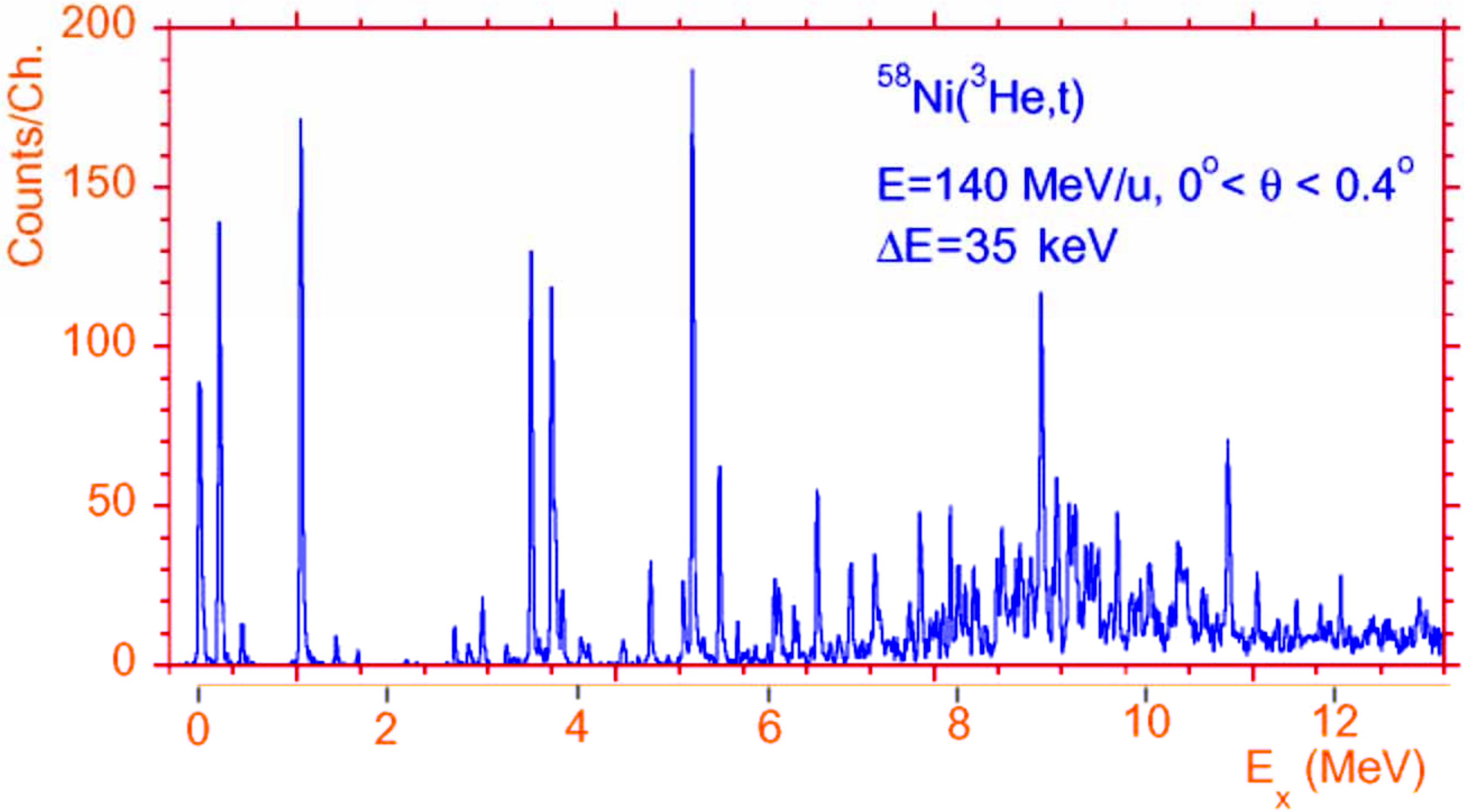
Sp=5.08 MeV

Strengths: Exp. & Perturbation Th.

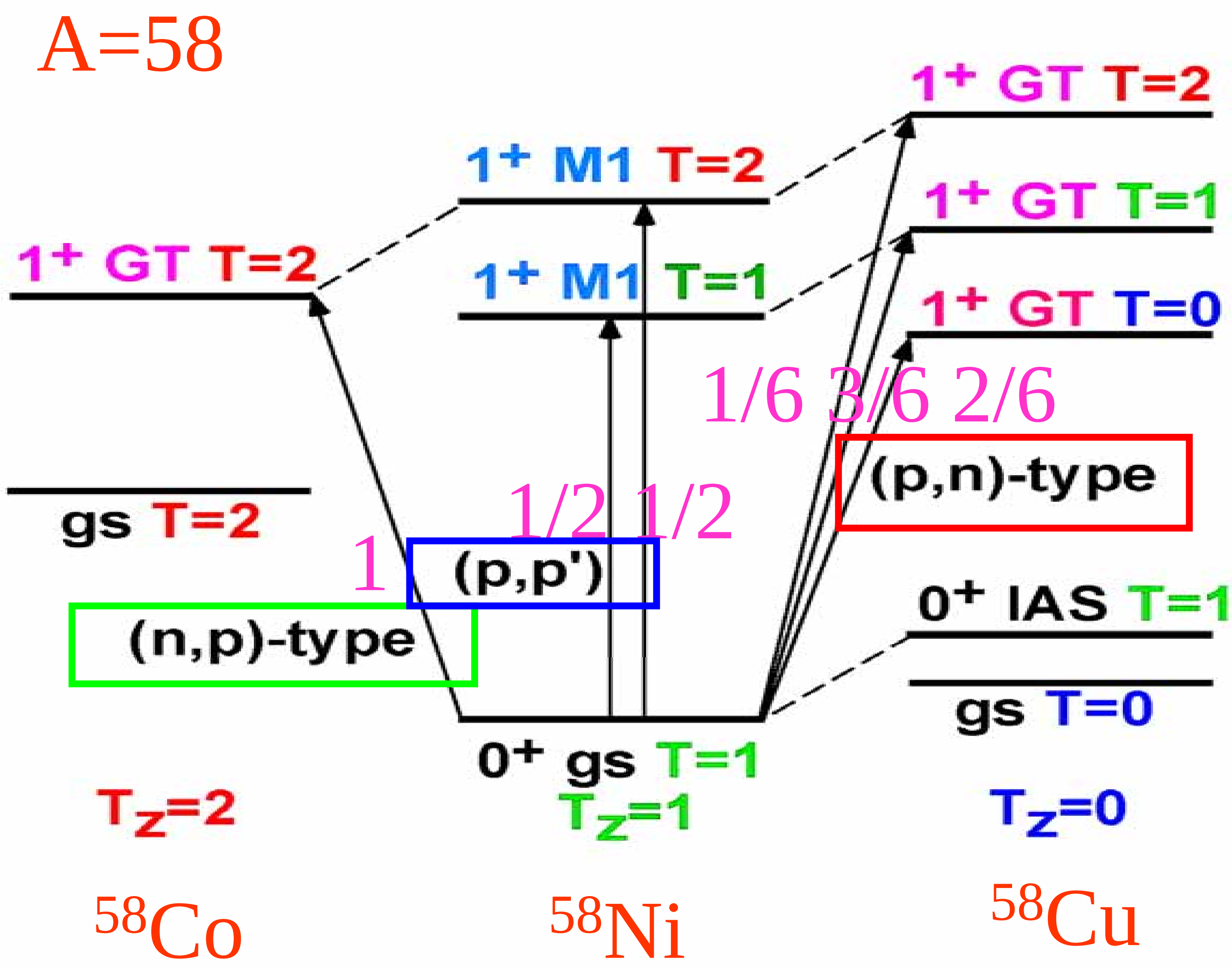


High resolution (^{3}He,t) spectrum

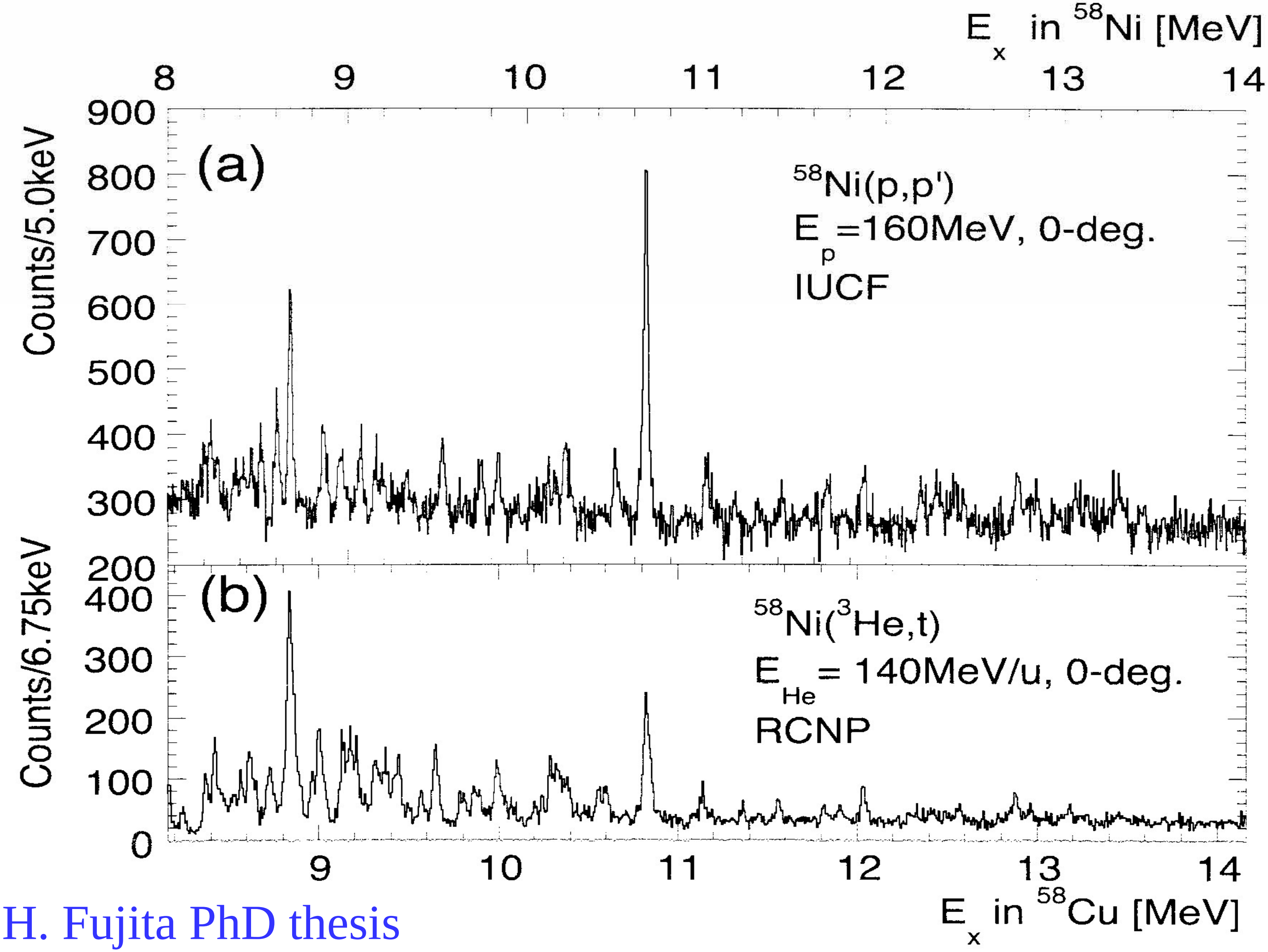
H. Fujita PhD thesis



Isospin symmetry structure & στ operator

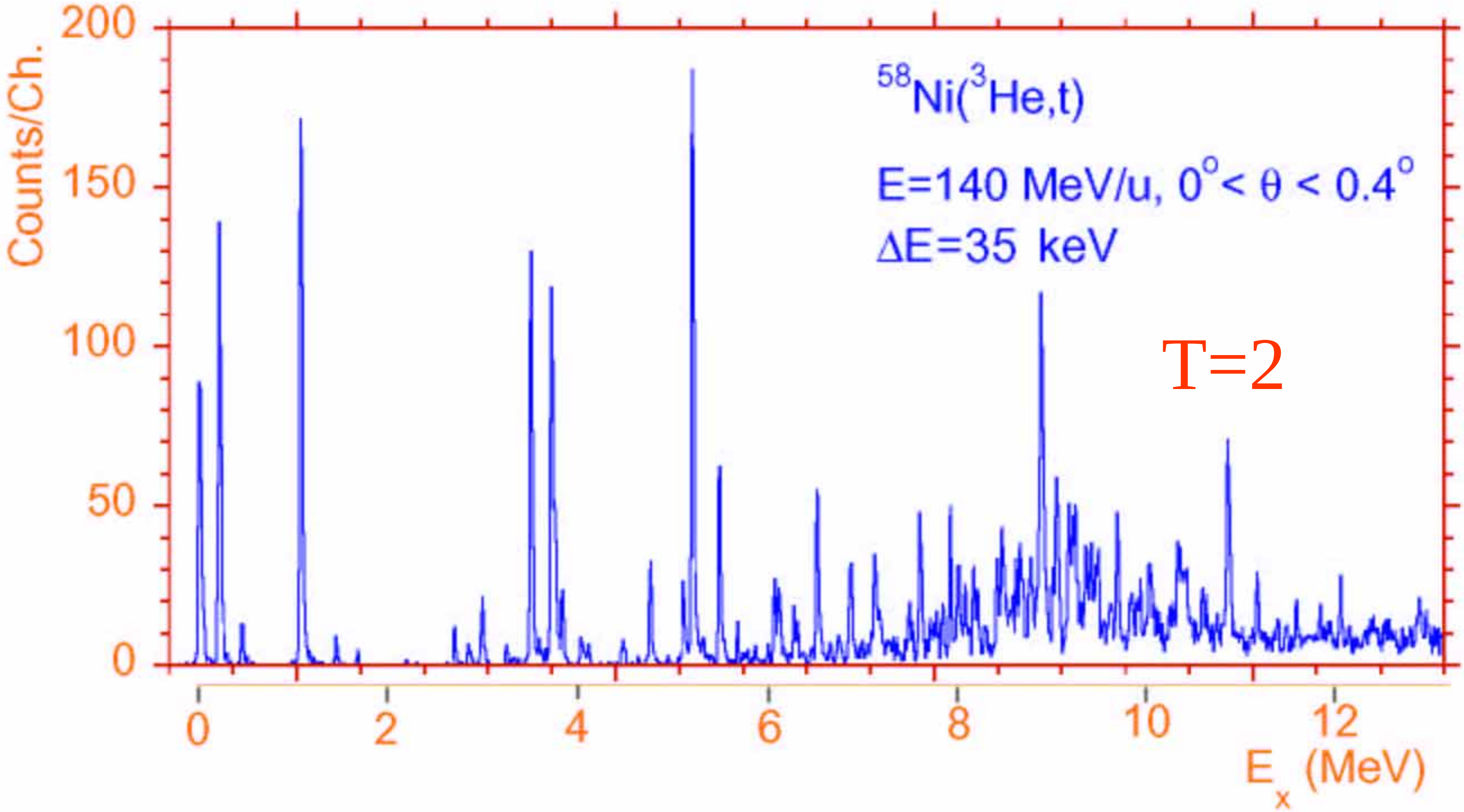


Comparison: ^{58}Ni(^{3}He,t)^{58}Cu & ^{58}Ni(p,p')

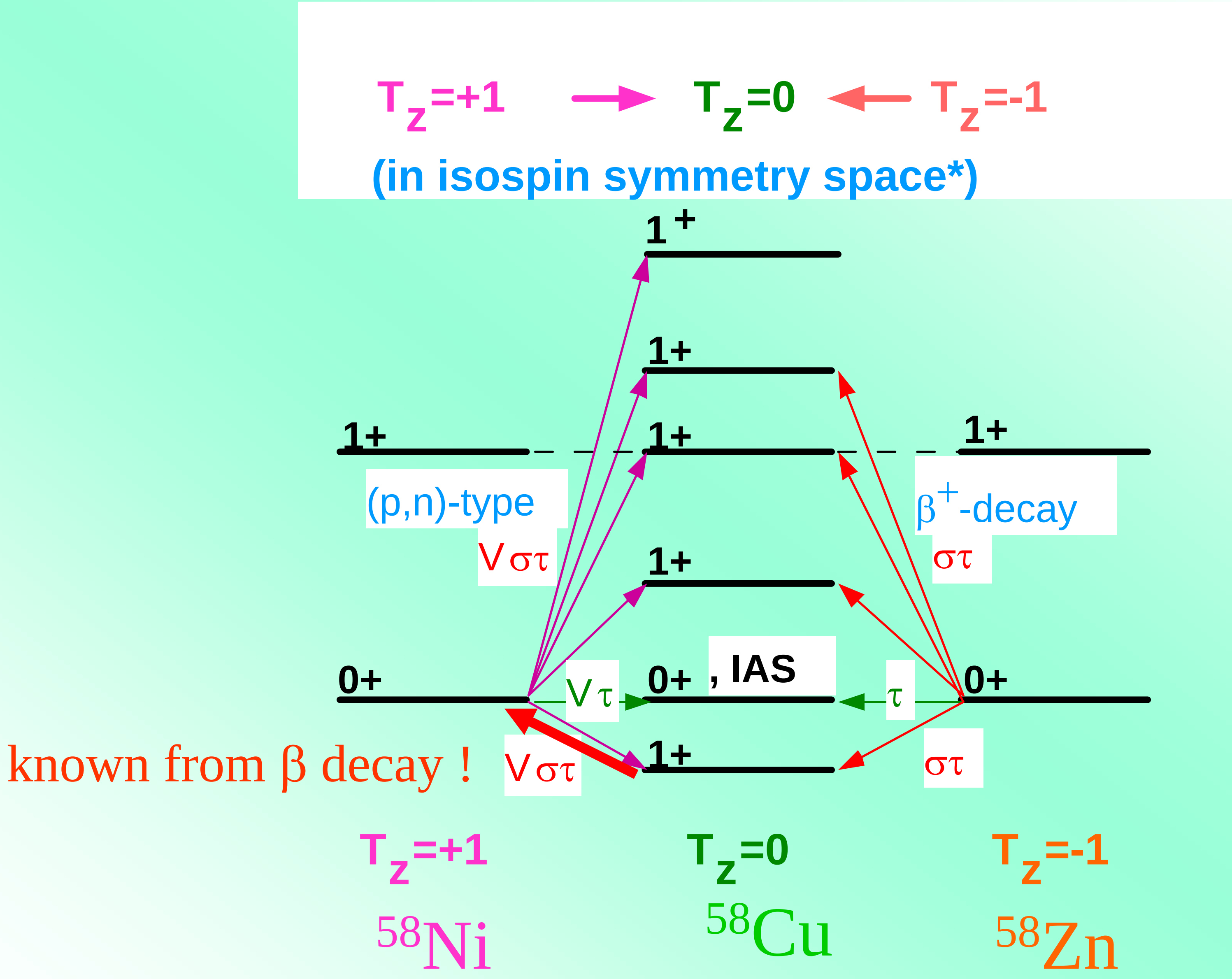


H. Fujita PhD thesis

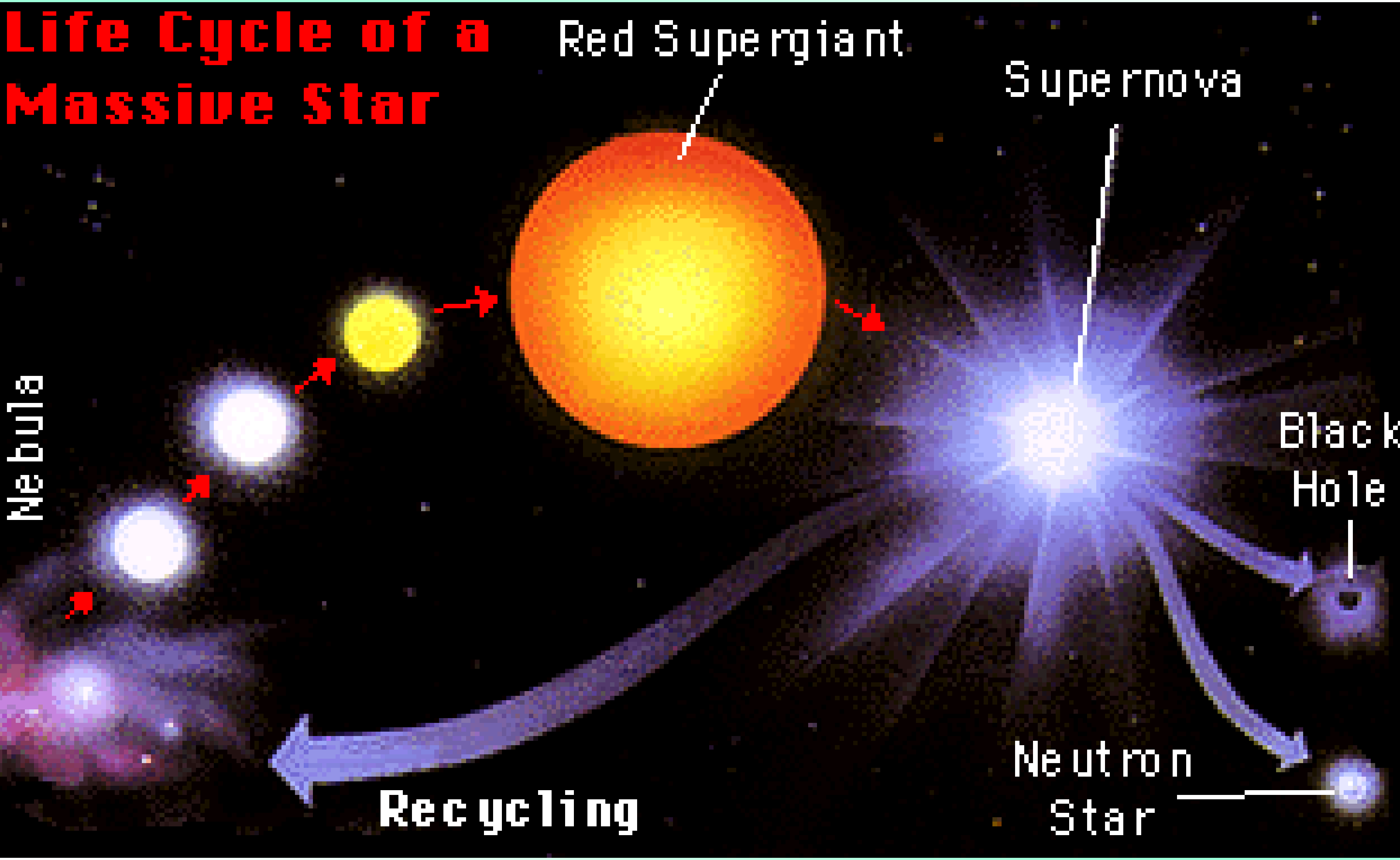
High resolution $^{58}Ni(^3He,t)^{58}Cu$ spectrum



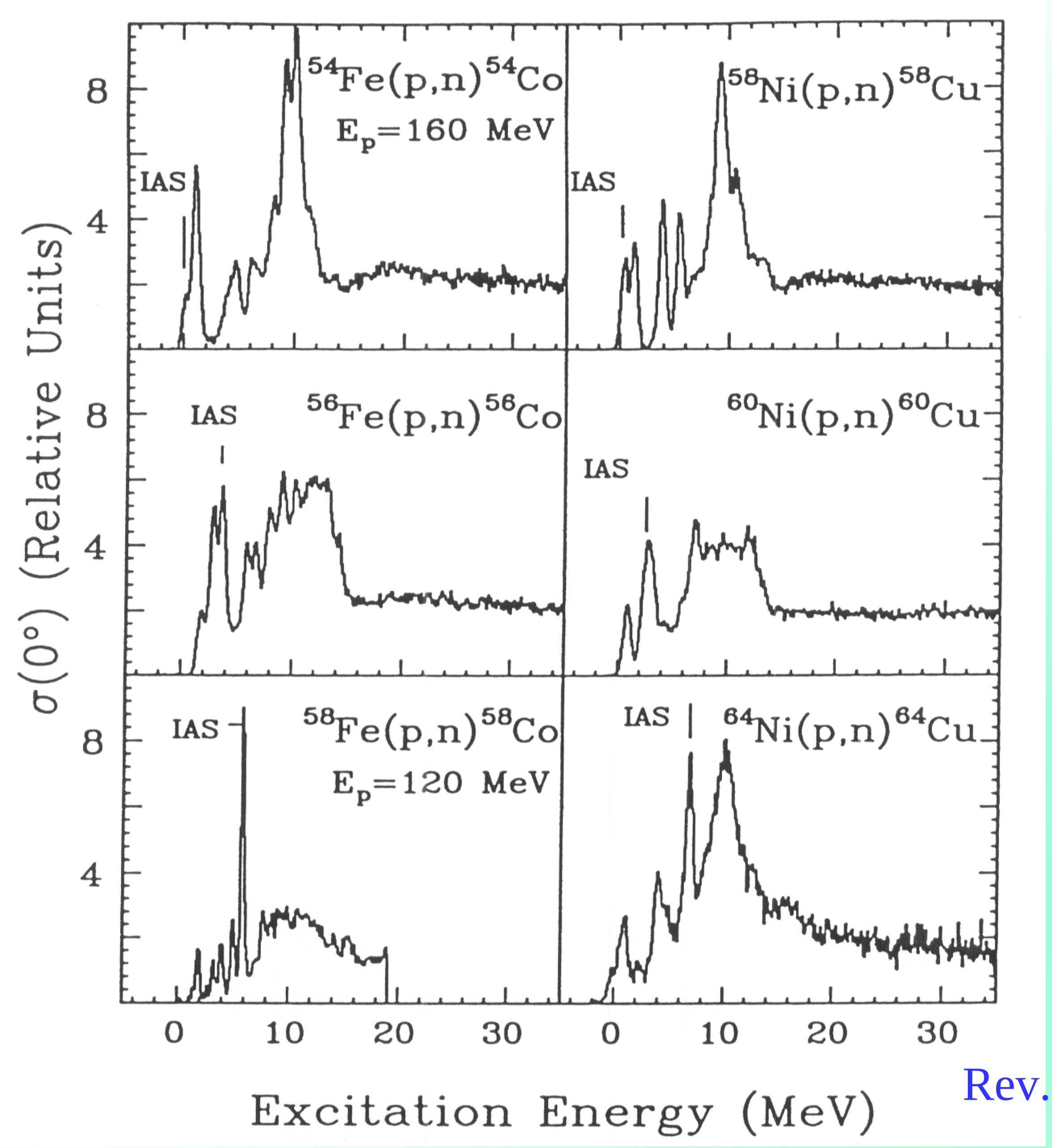
A=58, *T*=1 symmetry : Structures & Transitions



Supernova Cycle



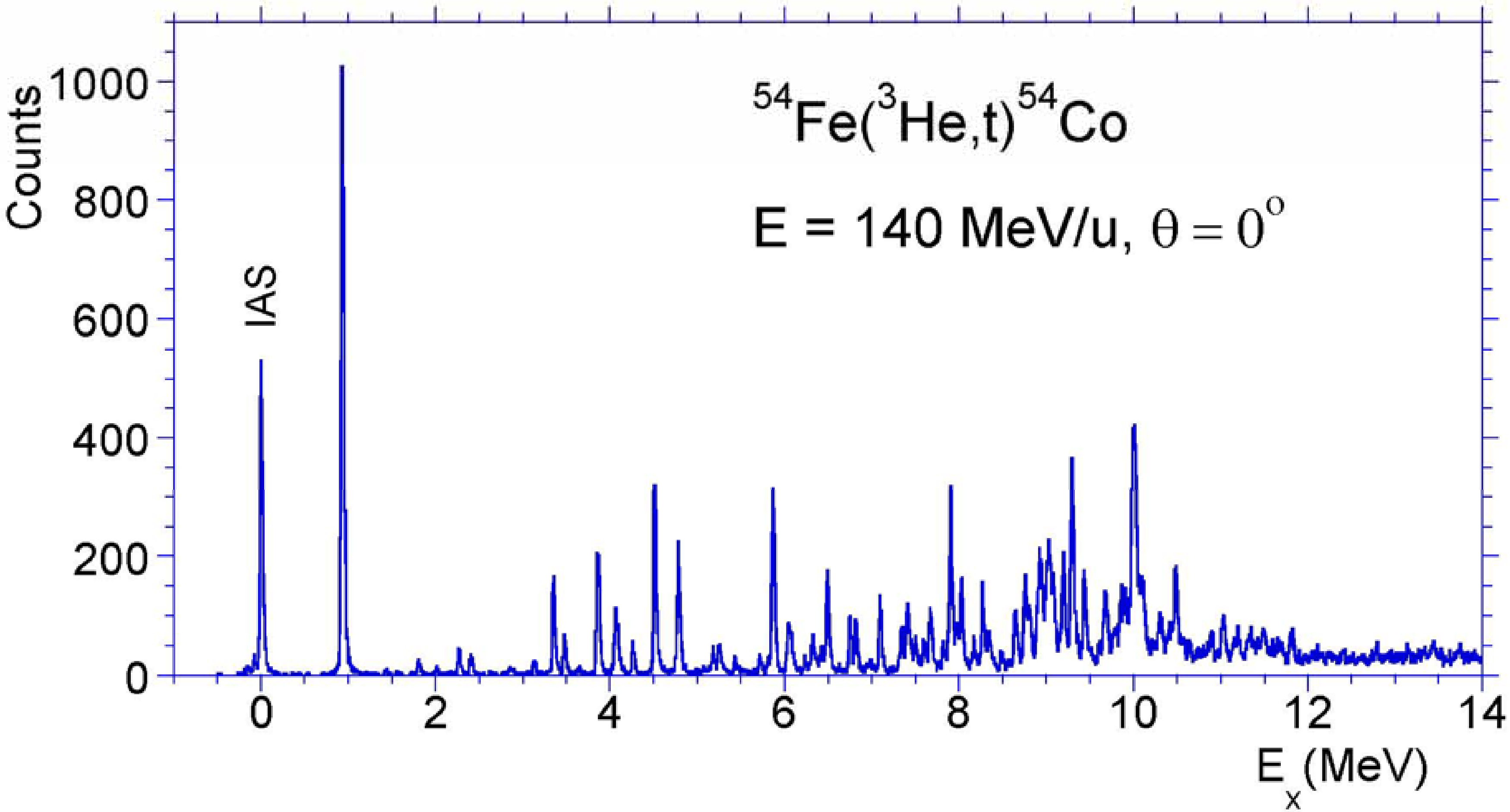
(p, n) spectra for Fe and Ni Isotopes



Rapaport
&
Sugarbaker
Rev. Mod. Phys. ('94)

High resolution $^{54}Fe(^{3}He,t)$ spectrum

T. Adachi et al.



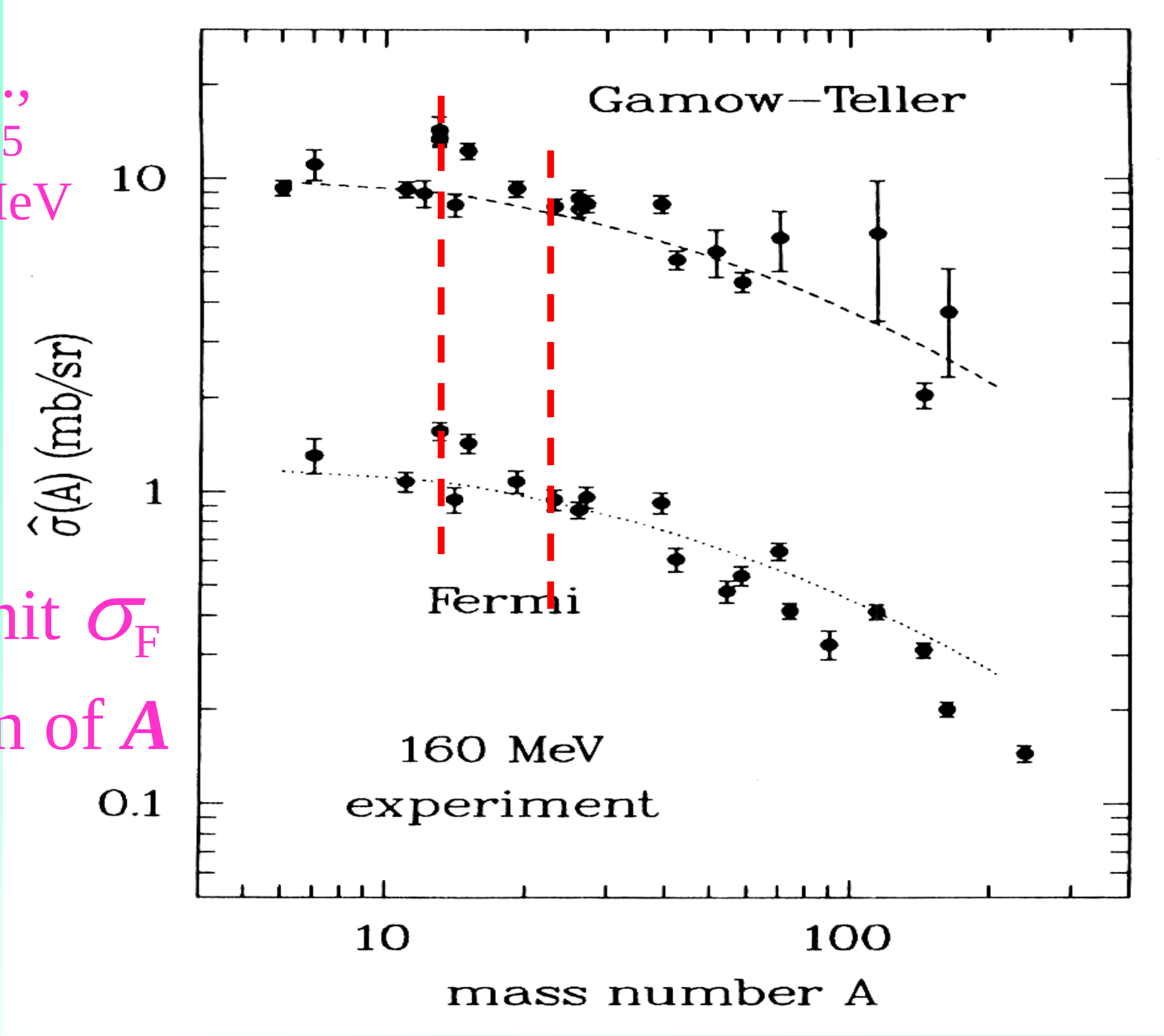
Target nuclei under study : T_0=1 ^{46}Ti, ^{50}Cr, ^{54}Fe, ^{58}Ni

T_0=2 ^{48}Ti, ^{52}Cr, ^{56}Fe, ^{60}Ni

T_0=3 ^{50}Ti, ^{62}Ni

GT & Fermi : unit cross sections in (*p*,*n*)

Taddeucci *et al.*,
N.P. A469 (1987) 125
survey at E_p=160 MeV



R^2=unit σ_{GT}/unit σ_F
smooth function of ***A***

Unit σ and R^2

$$\sigma_{GT}(0^o) = KN_{\sigma\tau}\,|J_{\sigma\tau}(0^o)|^2\, B(\mathrm{GT})$$

$$\sigma_F(0^o) = KN_{\tau}\,|J_{\tau}(0^o)|^2\, B(\mathrm{F})$$

define

R^2 = unit $\sigma_{GT}(0^o)$/ unit $\sigma_F(0^o)$,

where

unit $\sigma_{GT}(0^o) = \sigma_{GT}(0^o)/B(\mathrm{GT})$

unit $\sigma_F(0^o) = \sigma_F(0^o)/B(\mathrm{F})$ $= N\text{-}Z$

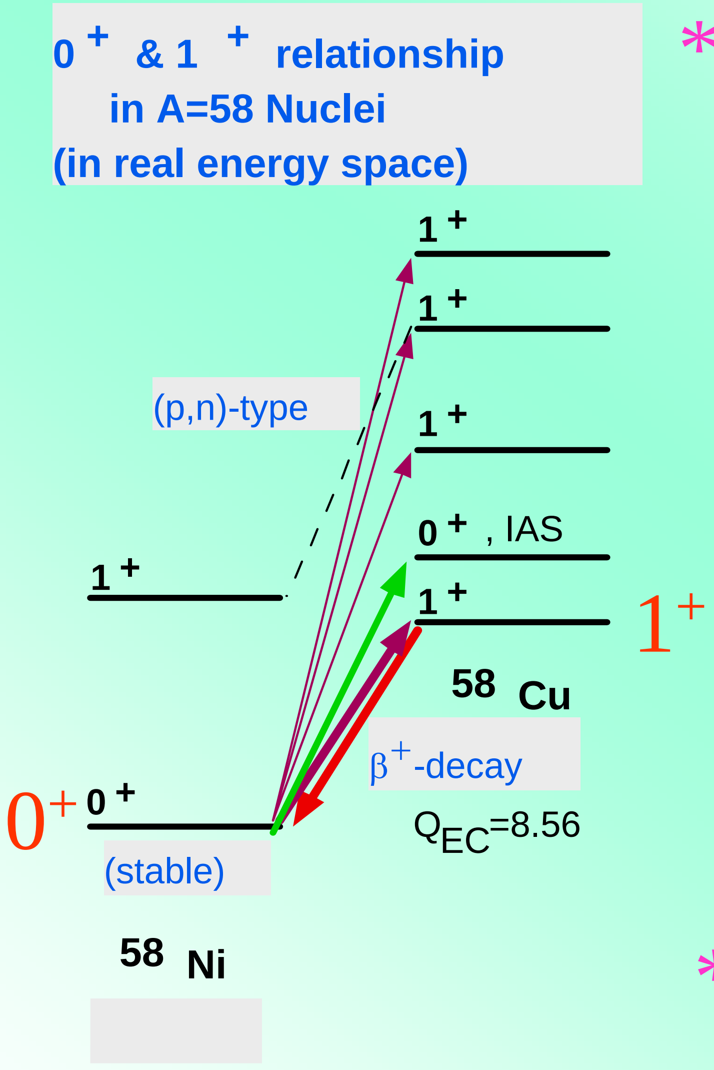
trick

Fermi strength concentrates in the IAS

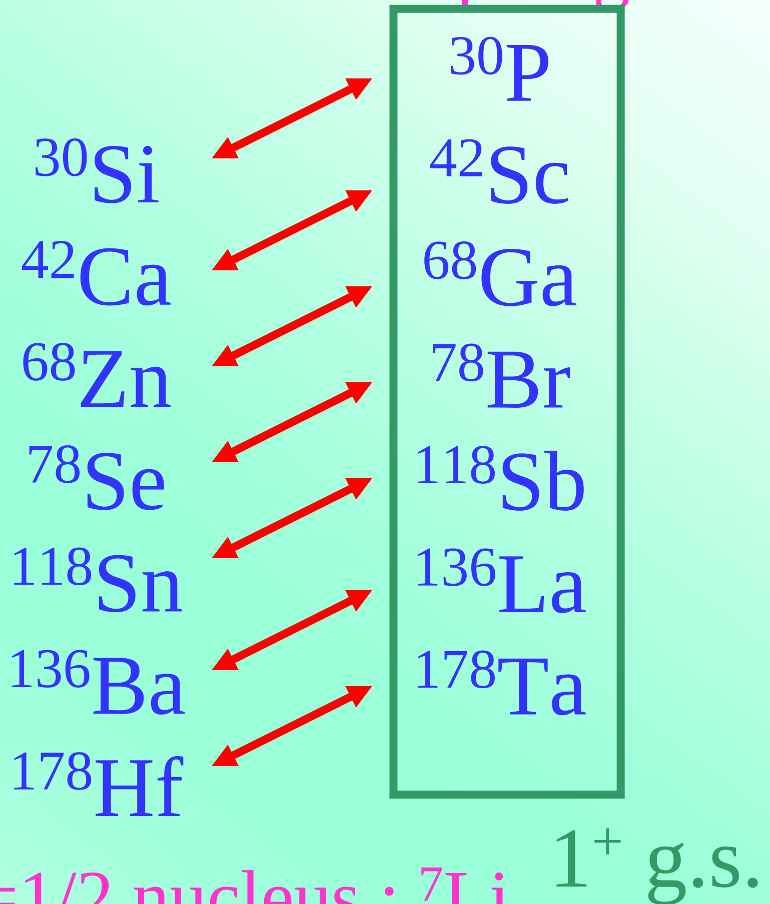
$B(\mathrm{F}) = N - Z$

Systematics of R^2 value ?

Connection between Charge Exchange & β decay



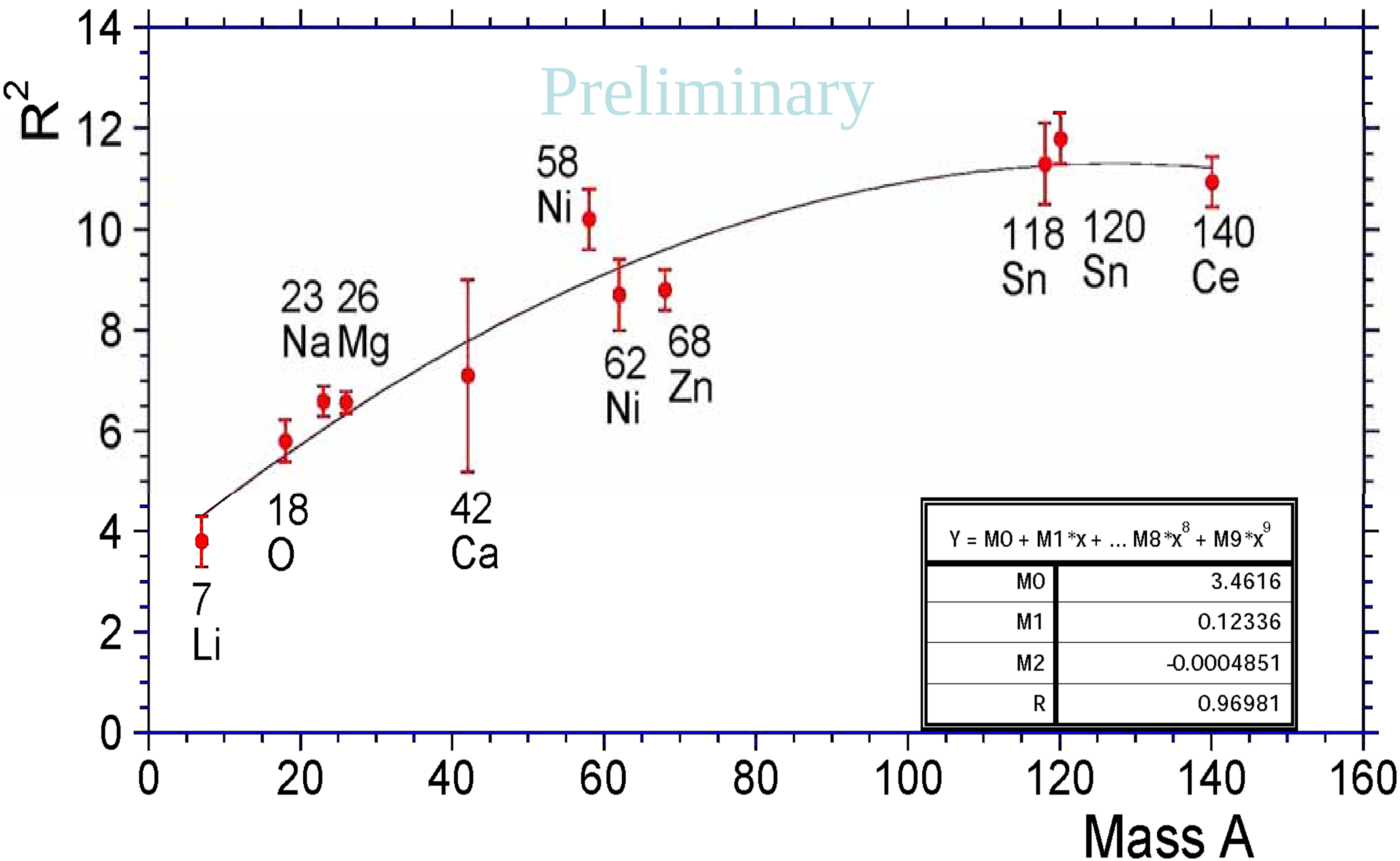
* 0^+ & 1^+ relationship of g.s.



* T_z=1/2 nucleus : ^{7}Li

^{7}Li ⟷ ^{7}Be

R^2 (= unit σ_{GT}/unit σ_F)



Perspective

Accelerator : underway for improvement

smaller beam emitance,
better beam energy resolution

As a Result:

smaller beam size

→ samller backbround

→ good chance for (p, p') at 0^{o}

→ *M1* and *E1* response

better energy resolution

→ even better spectrum resolution

→ smaller beam spot size

→ angular distribution measurement

High-Resolution Collaborations

TU Darmstadt (Germany) : (e, e’), (^{3}He, t), (p, p’)
Gent (Belgium) : (^{3}He, t), (d, ^{2}He), (γ, γ’)
GSI, Darmstadt (Germany) : inverse kinematics
ISOLDE, CERN (Switzerland) : β decay
iThemba LABS. (South Africa) : (p, p’), (^{3}He, t)
Jyvaskyla (Finland) : β decay
Koeln (Germany) : γ decay, (^{3}He, t)
KVI, Groningen (The Netherlands) : (d, ^{2}He)
LTH, Lund (Sweden)
Valencia (Spain) : β decay
Michigan State University (USA) : (t, ^{3}He)
Muenster (Germany) : (d, ^{2}He)
Rossendorf (Germany) : (γ, γ’)

Summary Words

★High Resolution

In Charge Exchange and Inelastic Reactions

--at Intermediate Incident Energies--

(^{3}He,t) reaction : one order better resolution than in a (p,n) reaction

(p, p') reaction : spectrum as low as E_x=5 MeV

★Active Operators, Isospin Symmetry

Similarity of Active Operators for Analog Transitions

Gamow-Teller operator in β decay (weak interaction)

Spin-isospin interaction in reactions (strong interaction)

★Spin-Isospin Responses

In Various Nuclei with High Resolution