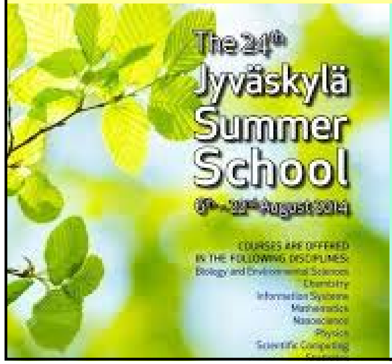
Isovector Nuclear Excitations and Isospin Symmetry



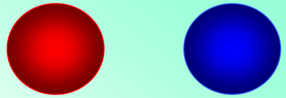
-the 4th lecture-

SS Jyvaskyla
August 06-12, 2014

Yoshitaka Fujita
Osaka University

Nucleon & Coin

back front = Coin



proton neutron = Nucleon

similar mass
nearly the same interaction

T_z=-1/2 T_z= 1/2 isospin T=1/2

***Isovector Excitations & Isospin Symmetry

The ideas of "Isospin" and "Isospin Symmetry" are important in IV excitations that include τ operator.
(e.g., IV-E1(GDR), Gamow Teller)

Symmetry Natures of Strong and EM Interactions

Strong interaction: between

proton-proton	proton-neutron	neutron-neutron
IV int.	IV + IS int.	IV int.

EM interaction: between

proton-proton	proton-neutron	neutron-neutron
Yes	No	No

Isospin symmetry in simple terms

in their structure
Which are the same?

$^{24}_{12}Mg_{12}$ $^{24}_{13}Al_{11}$ $^{24}_{14}Si_{10}$

Hint:
strong (nuclear) interaction is responsible for the main part of nuclear structure !

$^{25}_{12}Mg_{13}$ $^{25}_{13}Al_{12}$ $^{25}_{14}Si_{11}$

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

**Fermi & Gamow-Teller Excitations

**Simplest nuclear excitations that include τ operator.

**Especially, GT includes both τ and σ that are unique in nuclei.

Isospin in simple terms

in their structure
Which are the same?

Mirror Nuclei have the same structure in terms of Strong int. !

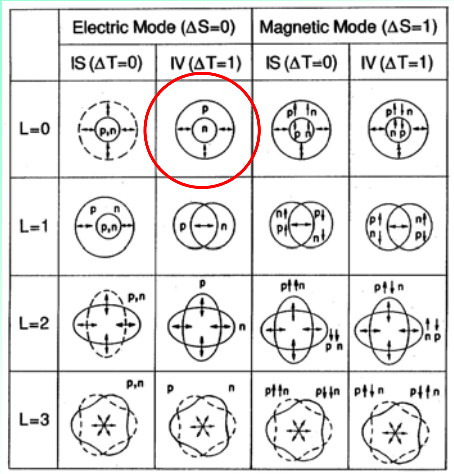
$^{24}_{12}Mg_{12}$ $^{24}_{13}Al_{11}$ $^{24}_{14}Si_{10}$

Hint:
Strong (Nuclear) interaction is responsible for the main part of Nuclear structure !

$^{25}_{12}Mg_{13}$ $^{25}_{13}Al_{12}$ $^{25}_{14}Si_{11}$

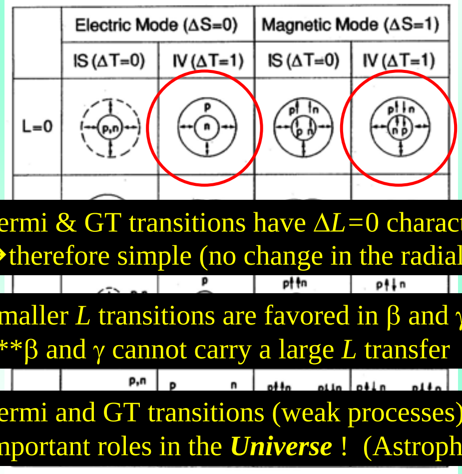
$^{26}_{12}Mg_{14}$ $^{26}_{13}Al_{13}$ $^{26}_{14}Si_{12}$

Vibration Modes in Nuclei (Schematic)



Fermi mode
(τ)

Vibration Modes in Nuclei (Schematic)



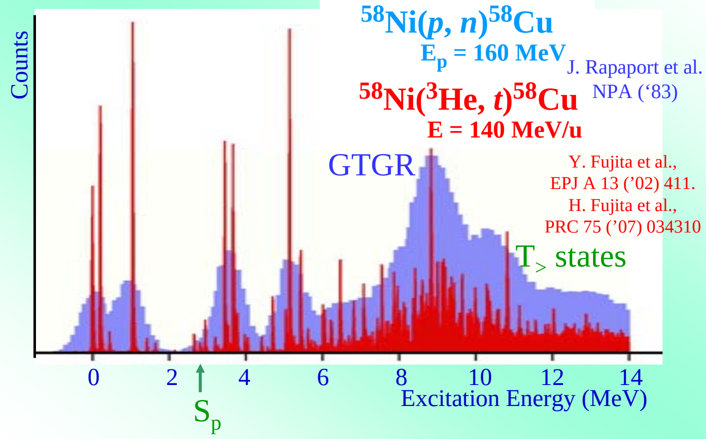
Gamow-Teller mode ($\sigma\tau$)

Fermi & GT transitions have $\Delta L=0$ character
→therefore simple (no change in the radial w.f.)

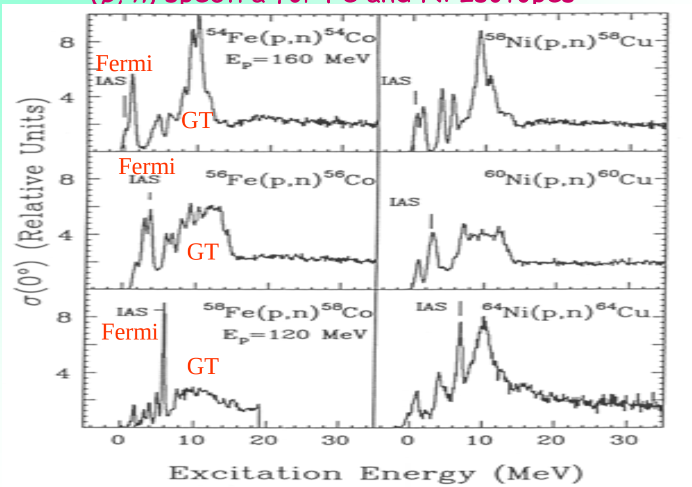
Smaller L transitions are favored in β and γ decays
***β and γ cannot carry a large L transfer

Fermi and GT transitions (weak processes) play important roles in the ***Universe*** ! (Astrophysics)

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



(p, n) spectra for Fe and Ni Isotopes



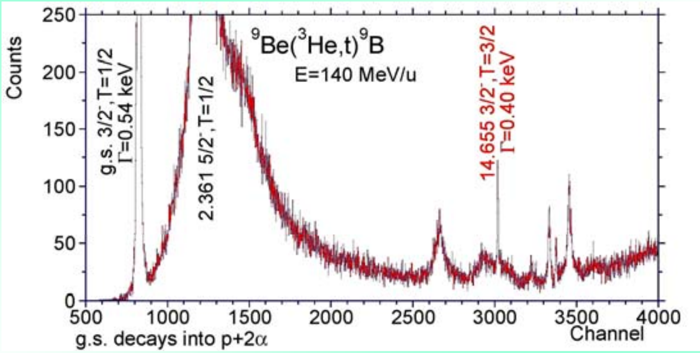
**Properties of GT transitions

Caused by the $\sigma\tau$ 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. (ex. $j_> = f_{7/2}$ and $j_< = f_{5/2}$)
3) τ operatpr: isospin quantum number T plays an important role. (isospin selection rule)

→GT transitions in each nucleus are UNIQUE !
(reflecting nuclear structure of each nucleus)

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



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

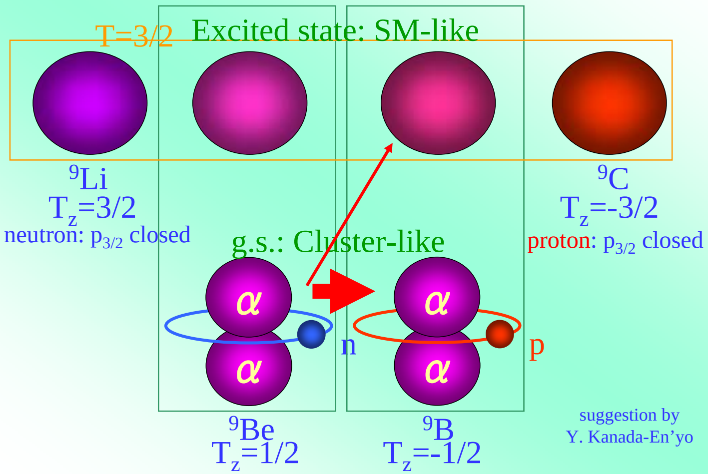
Strength ratio of g.s. & 14.7 MeV $3/2^-$ states: 140:1

***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.

Shell Structure and Cluster Structure



suggestion by Y. Kanada-En'yo

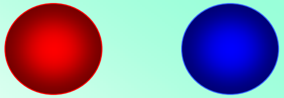
T=1/2 Isospin Symmetry

Koelner Dom in Germany (157m high)

Nucleon & Coin

back face

= Coin



proton neutron

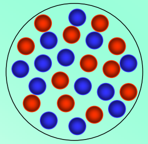
similar mass

nearly the same interaction

= Nucleon

T_z=-1/2 T_z= 1/2 isospin T=1/2

Isospin of a Nucleus



$^{A}_{N}Z$

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

*z-component: conserved

The size of a vector should be larger than its z-component!

T = or > $|T_z|$

ex. ^{27}Al (Z=13, N=14) : T_z=+1/2, T=1/2, 3/2, …

^{27}Si (Z=14, N=13) : T_z= -1/2, T=1/2, 3/2, …

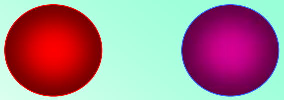
**only Z and N numbers are reversed !

Isospin Analogous Structure is expected !

Nucleus & Coin

back front

= Coin

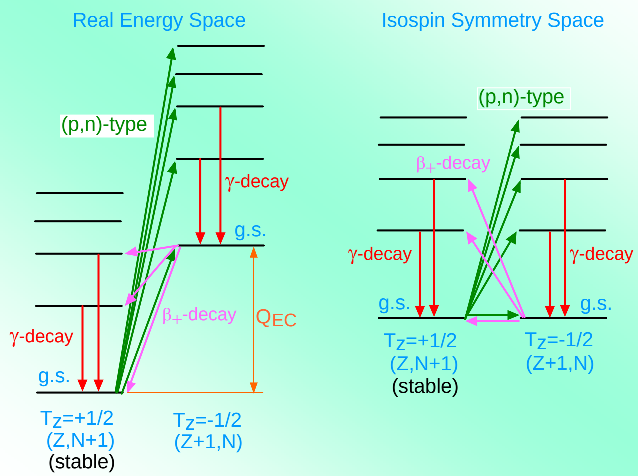


= Nuclei

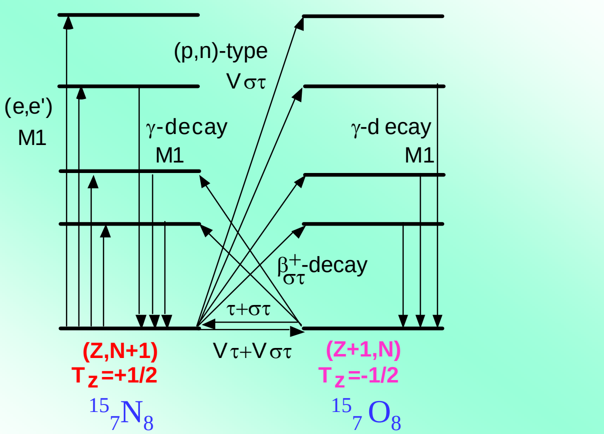
$^{27}_{13}Al_{14}$ $^{27}_{14}Si_{13}$ $T_z = (1/2)N + (-1/2)Z$

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

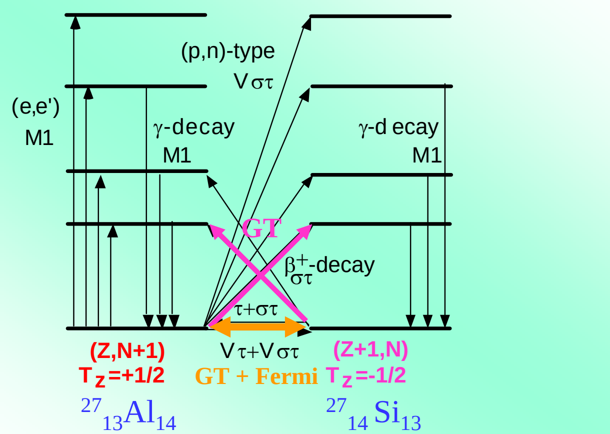
Analogous Structures, Transitions in T=1/2 System



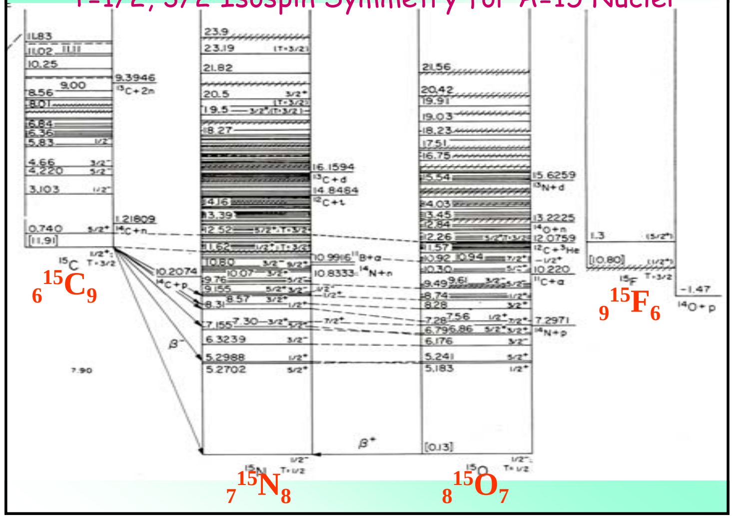
T = 1/2 Mirror Nuclei : Structures



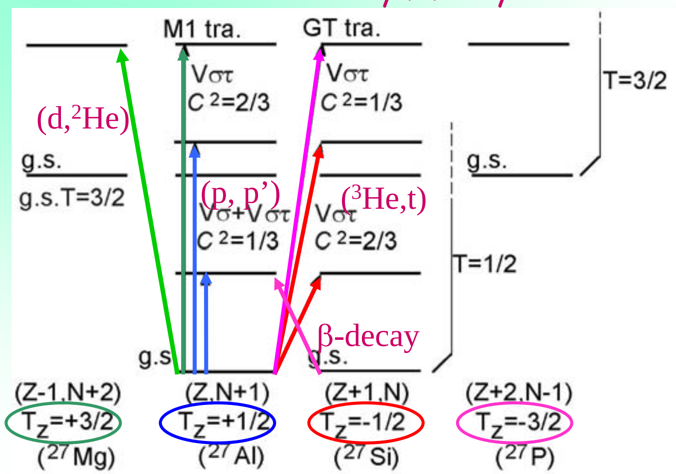
T=1/2 Mirror Nuclei : Structures & Transitions



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



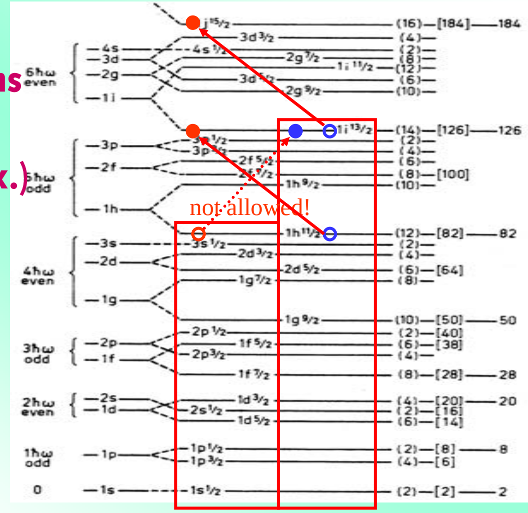
T=1/2 & 3/2 Symmetry



**Transitions Starting from
T= 0 Nuclei

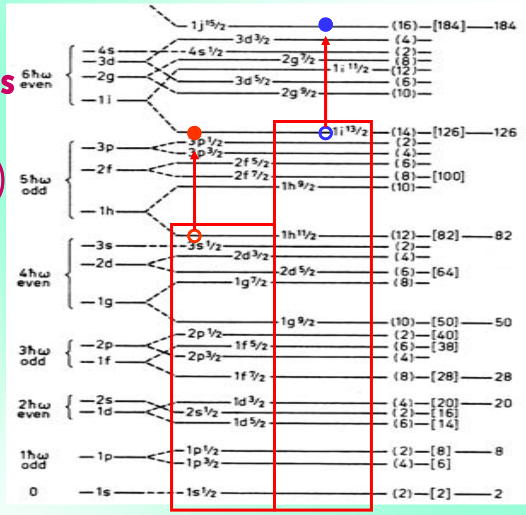
1p-1h Excitations in ^{208}Bi (charge ex.)

Z=83, N=125

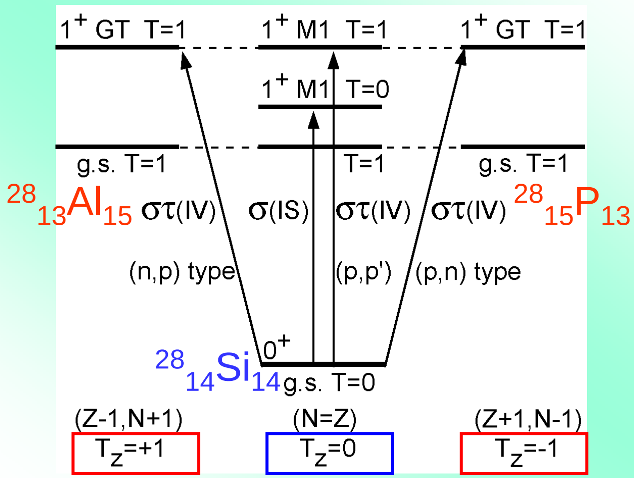


1p-1h Excitations in ^{208}Pb (inelastic)

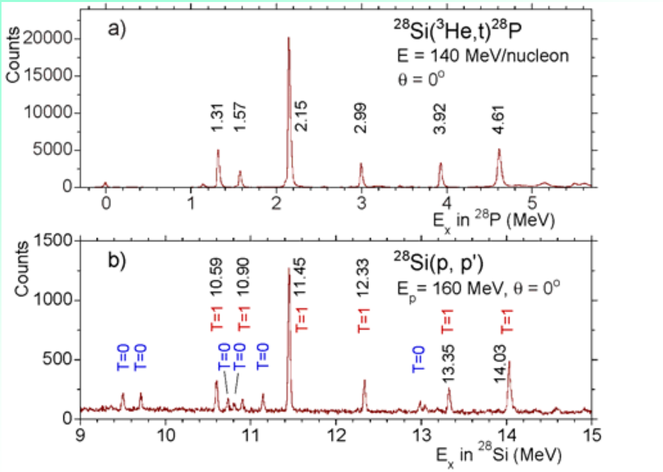
Z=82,N=126



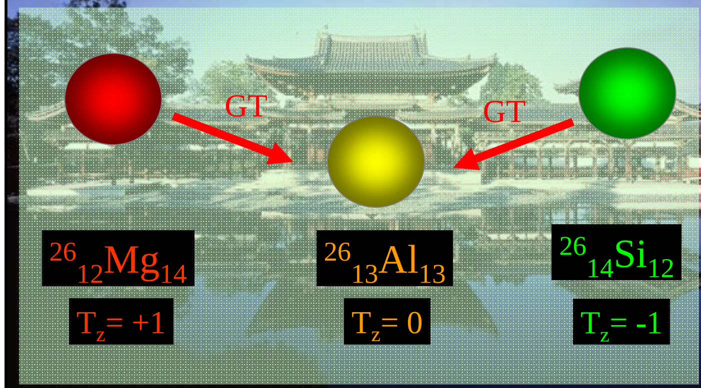
Isospin Symmetry in *T*=0 and 1 Nuclei



Spectra ^{28}Si(p, p') and ^{28}Si(3He,t)^{28}P



T=1 Isospin Symmetry



**Higher T Symmetry

Nuclei & Coin

back front

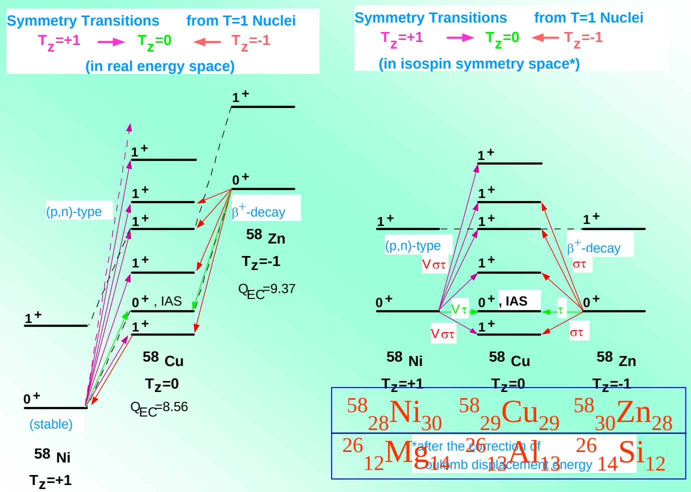
Coin

$^{26}_{12}Mg_{14}$ $^{26}_{13}Al_{13}$ $^{26}_{14}Si_{16}$

Nuclei

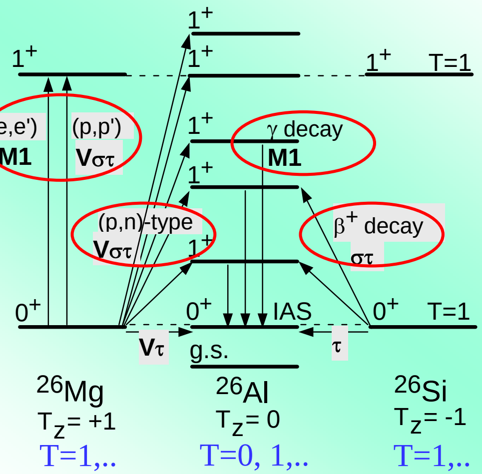
T_z= 1 T_z= 0 T_z= -1 isospin T=1 triplet

Transitions in real & isospin space (T=1)



***Derivation of B(GT) strength

Analogous Transitions in A=26 Nuclei



Case 1 : γ-decay & β-decay

*both have very simple mechanism.
(people even don't think of "mechanism !")

*Operators are relatively simple!
Weak : Gamow-Teller, Fermi
EM : E1, E2,… M1, M2,…

matrix element & $t_{1/2}$
($1 / t_{1/2}$) = Coup.Const. x PhaseSpaceFac.
x $|\langle \mathbf{f} \,|\, \mathbf{\mathit{Op}} \,|\, \mathbf{i} \rangle|^2$

*if *Op* is specified, w.f.(=structures) are studied !
(*Op* specification is not always easy!)
* highly *Ex* region cannot be reached !

Reduced transition strength $B(Op)$

A value proportional to (matrix element)^2

$|\langle f \,|\, Op \,|\, i \rangle|^2$

is called "reduced transition strength"

ex. B(GT), B(F), $B(M1)$, $B(E2)$,….

*representing only the structure part for a specific operator!

*reaction mechanism part is removed!

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 $\sigma(0^o)$

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

⇒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)

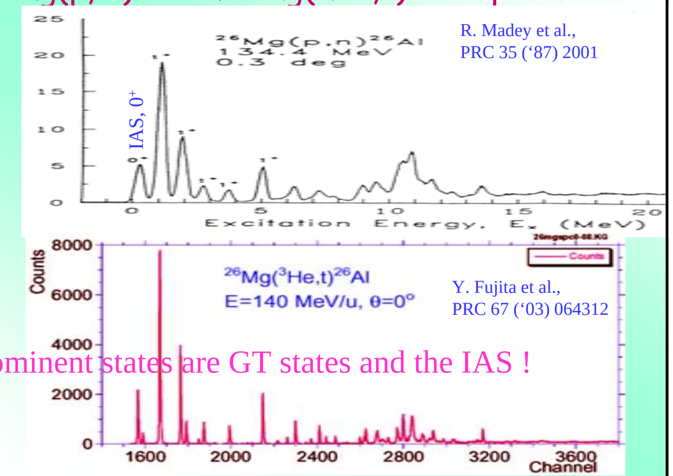
☆magnetic spectromerter, matching techniques

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

⇒Breakthrough against "Energy resolution limitation"

⇒Reliable B(GT) values for individual transitions

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



Prominent states are GT states and the IAS !

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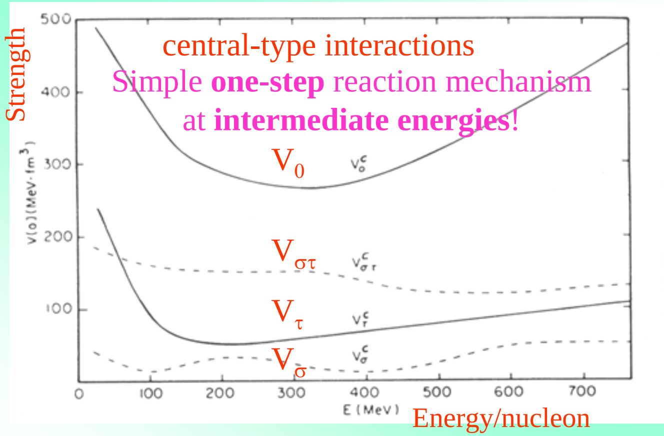
Nucleon-Nucleon Int. : E_{in} dependence at q=0



Love & Franey PRC 24 ('81) 1073

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$$\sigma(0^\circ) = KN_{\sigma\tau} \mid J_{\sigma\tau}(0^\circ) \mid^2 B(\mathrm{GT})$$

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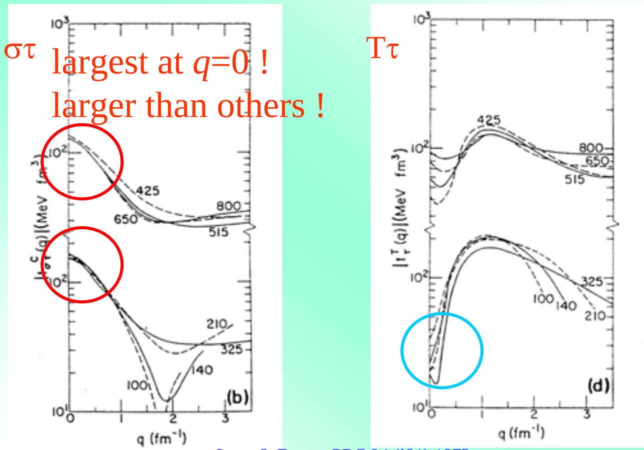
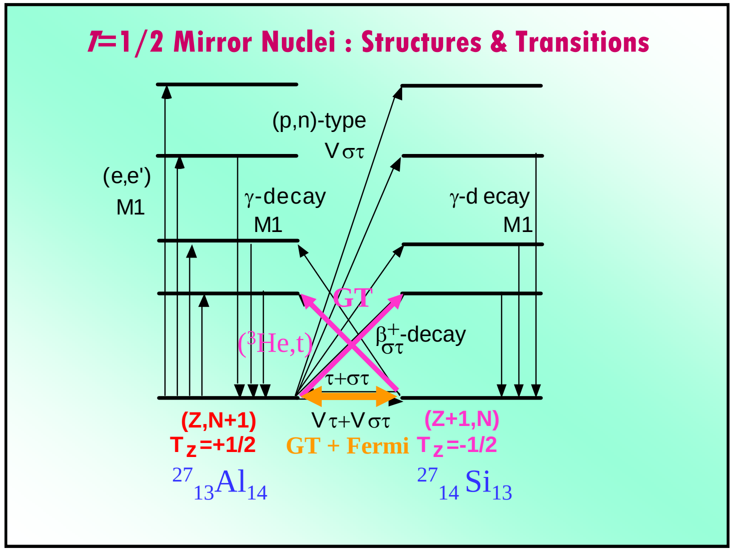
N.-N. Int. : στ & Tensor-τ *q*-dependence

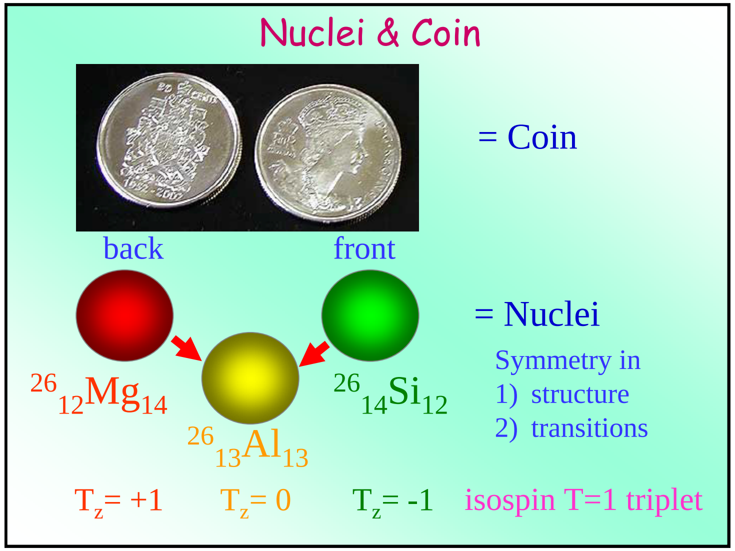


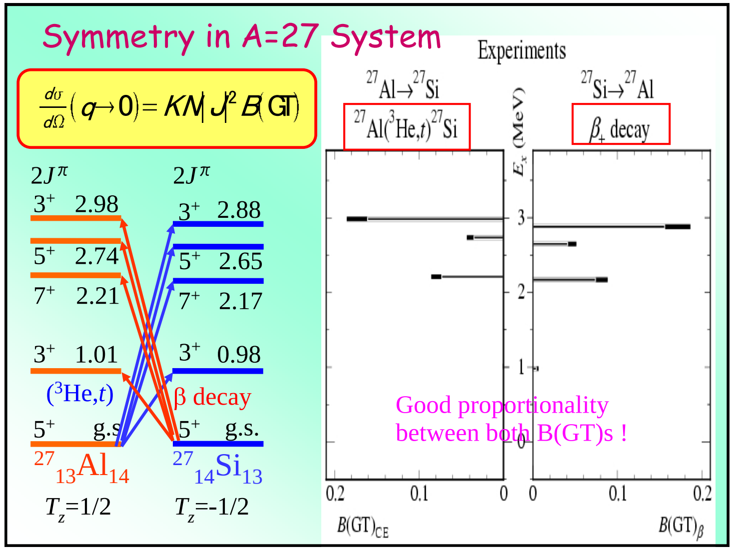
Love & Franey PRC 24 ('81) 1073

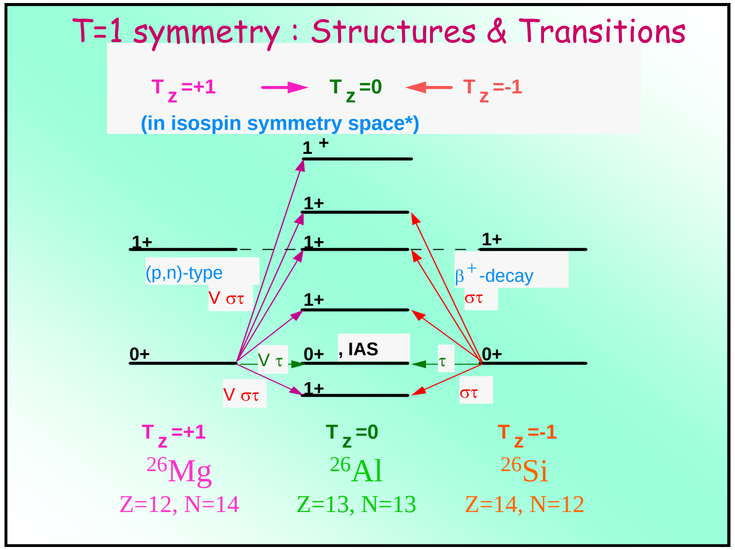
T=1/2 Isospin Symmetry

Koelner Dom
in Germany
(157m high)

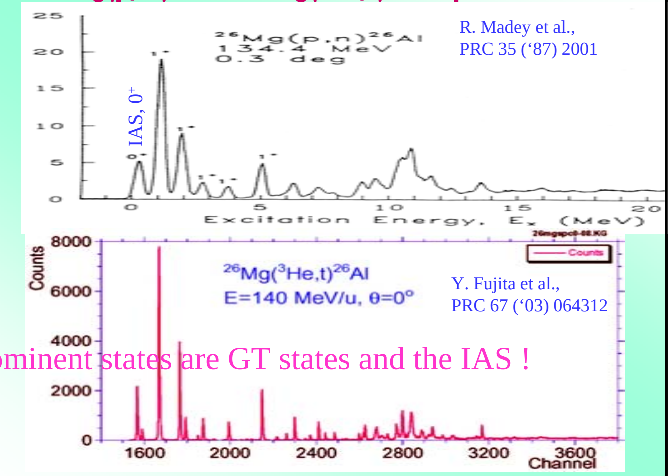

T=1/2 Mirror Nuclei : Structures & Transitions
(p,n)-type
Vστ
(e,e')
M1
γ-decay
M1
γ-d ecay
M1
GT
(³He,t)
β⁺-decay
στ
τ+στ
(Z,N+1)
Tz=+1/2
Vτ+Vστ
GT + Fermi
(Z+1,N)
Tz=-1/2
$^{27}_{13}Al_{14}$
$^{27}_{14}Si_{13}$


Nuclei & Coin
= Coin
back
front
= Nuclei
Symmetry in
1) structure
2) transitions
$^{26}_{12}Mg_{14}$
$^{26}_{14}Si_{12}$
$^{26}_{13}Al_{13}$
T_z= +1
T_z= 0
T_z= -1
isospin T=1 triplet


Symmetry in A=27 System
$\frac{d\sigma}{d\Omega}(q\to 0) = KN|J|^2 B(GT)$
Experiments
$^{27}Al \to {}^{27}Si$
$^{27}Al(^3He,t)^{27}Si$
$^{27}Si \to {}^{27}Al$
β_+ decay
$2J^\pi$
3⁺ 2.98
5⁺ 2.74
7⁺ 2.21
3⁺ 1.01
(³He,t)
5⁺ g.s
3⁺ 2.88
5⁺ 2.65
7⁺ 2.17
3⁺ 0.98
β decay
5⁺ g.s.
$^{27}_{13}Al_{14}$
$^{27}_{14}Si_{13}$
T_z=1/2
T_z=-1/2
E_x (MeV)
Good proportionality
between both B(GT)s !
$B(GT)_{CE}$
$B(GT)_\beta$


T=1 symmetry : Structures & Transitions
Tz=+1 → Tz=0 ← Tz=-1
(in isospin symmetry space*)
(p,n)-type
V στ
β⁺-decay
στ
V τ
τ
0+, IAS
Tz=+1
^{26}Mg
Z=12, N=14
Tz=0
^{26}Al
Z=13, N=13
Tz=-1
^{26}Si
Z=14, N=12

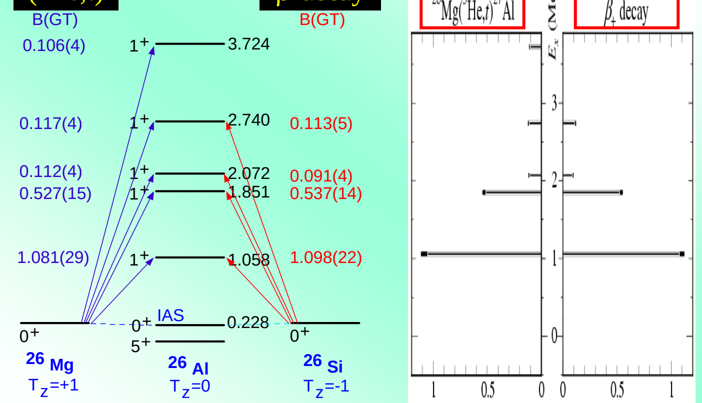
^{26}Mg(p, n)^{26}Al & ^{26}Mg(^{3}He,t)^{26}Al spectra



Prominent states are GT states and the IAS !

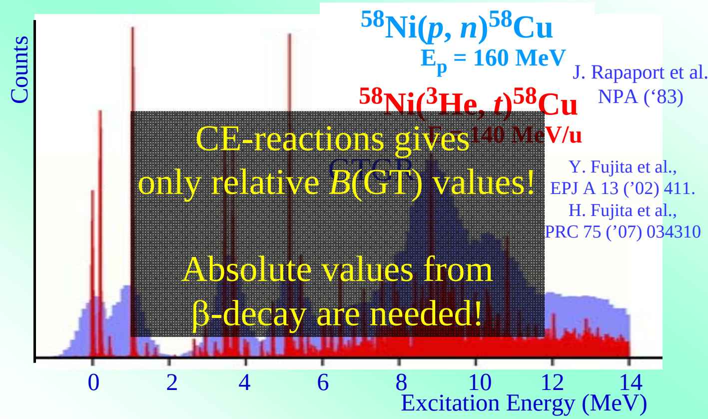
**CE reaction and β-decay: complementary tools

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



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

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



CE-reactions gives only relative *B*(GT) values!

Absolute values from β-decay are needed!

β-decay & Nuclear Reaction

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

$B(GT)$: reduced GT transition strength

$\propto$ (matrix element)^2

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

= reaction mechanism

⊗ operator

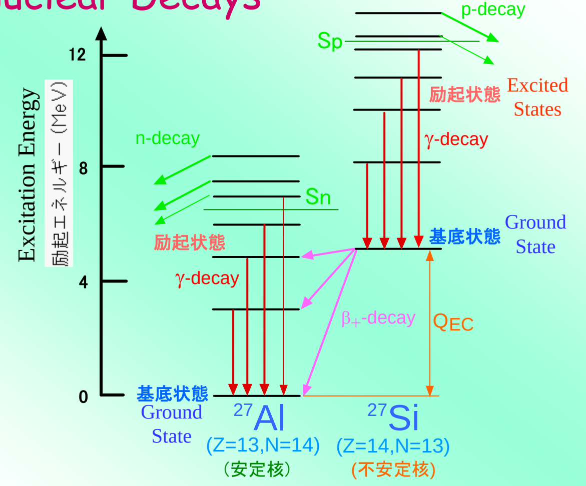
⊗ structure

=(matrix element)^2

A simple reaction mechanism should be achieved !

➡ we have to go to high incoming energy

Nuclear Decays



β-decay & Nuclear Reaction

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

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

$B(GT)$: reduced GT transition strength

$\propto$ (matrix element)^2

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

= reaction mechanism

⊗ operator

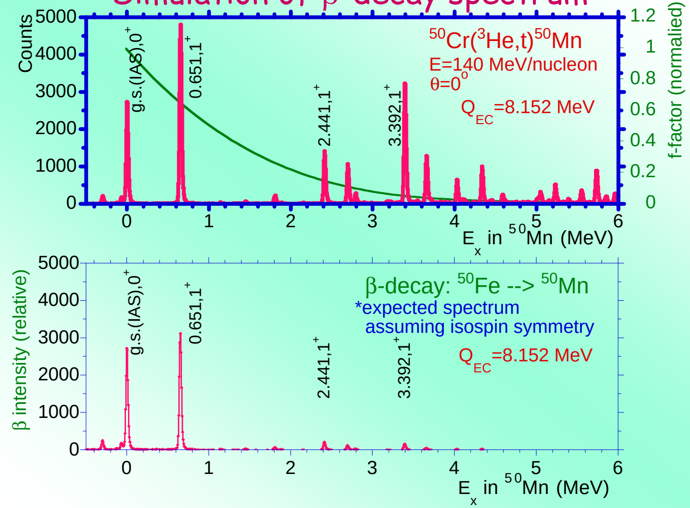
⊗ structure

=(matrix element)^2

A simple reaction mechanism should be achieved !

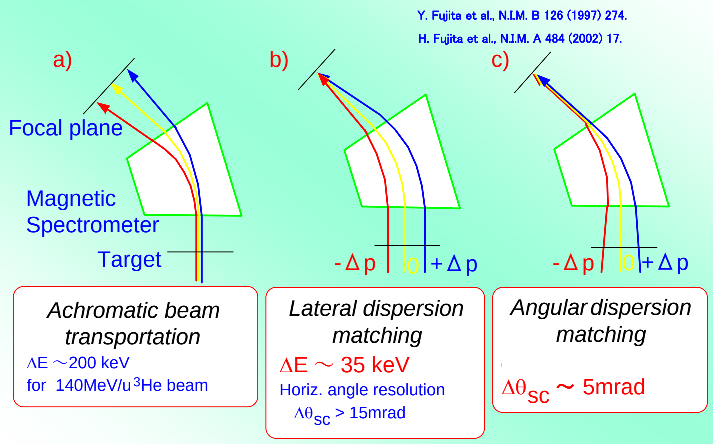
➡ we have to go to high incoming energy

Simulation of β-decay spectrum

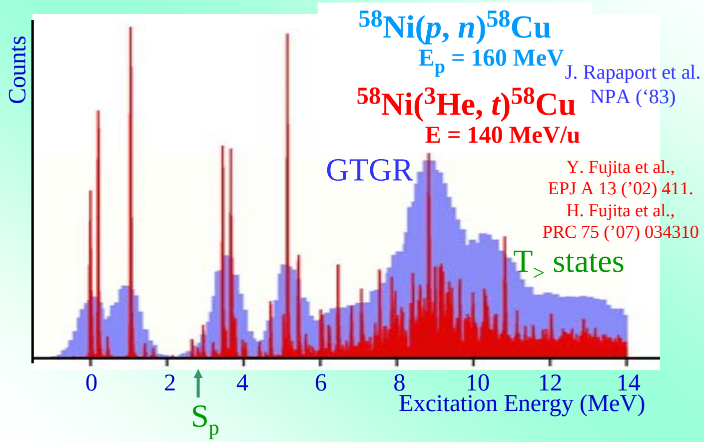


High Resolution Experiment

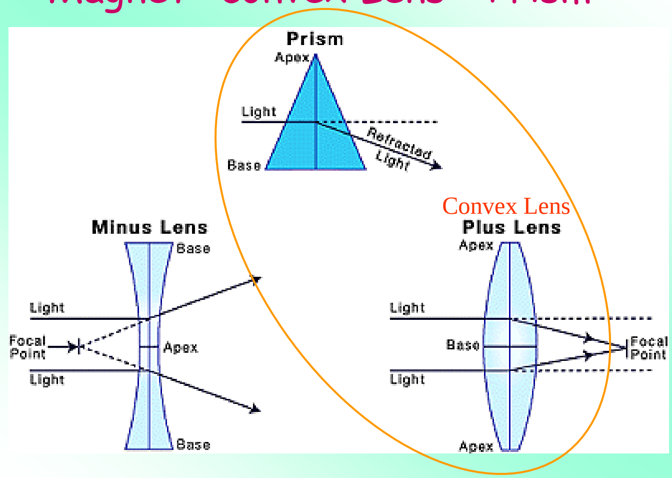
Matching Techniques

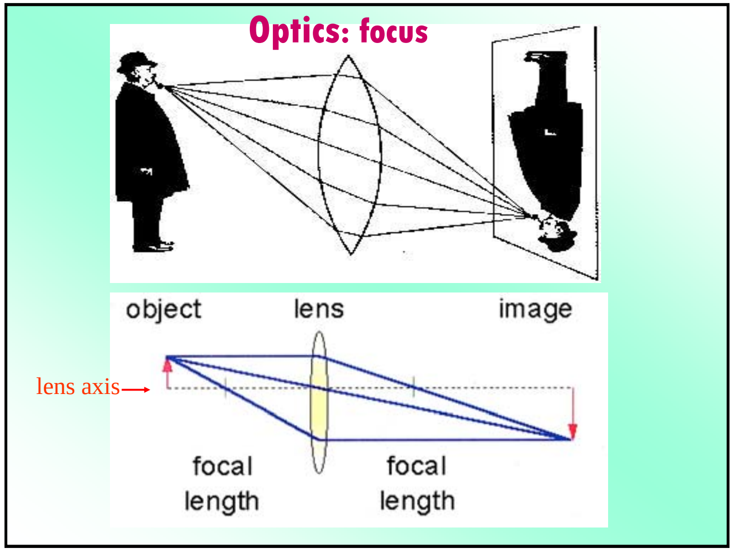


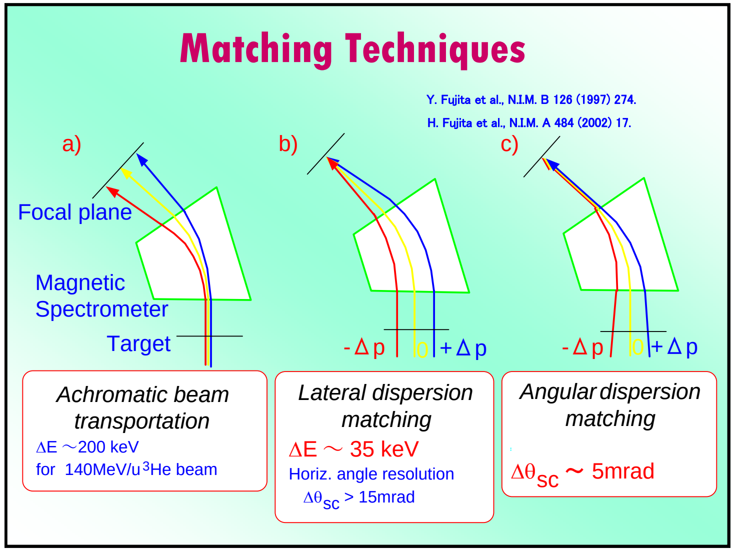
Comparison of (p, n) and (^{3}He,t) 0° spectra

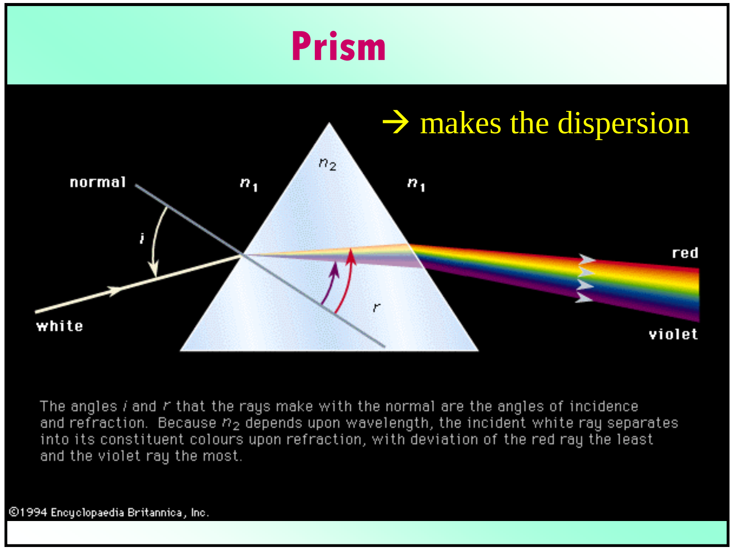


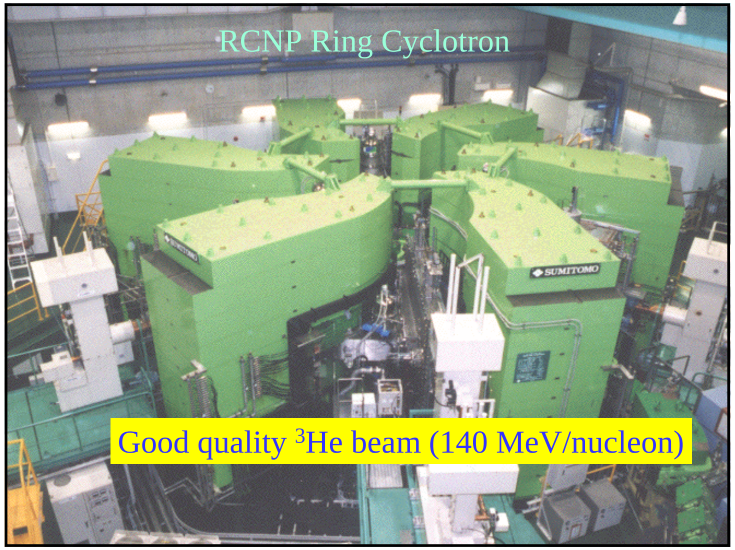
Magnet= convex Lens + Prism

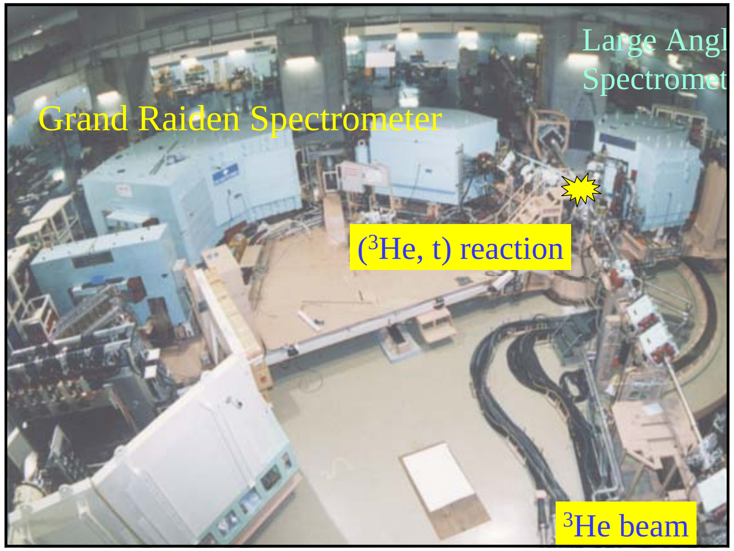


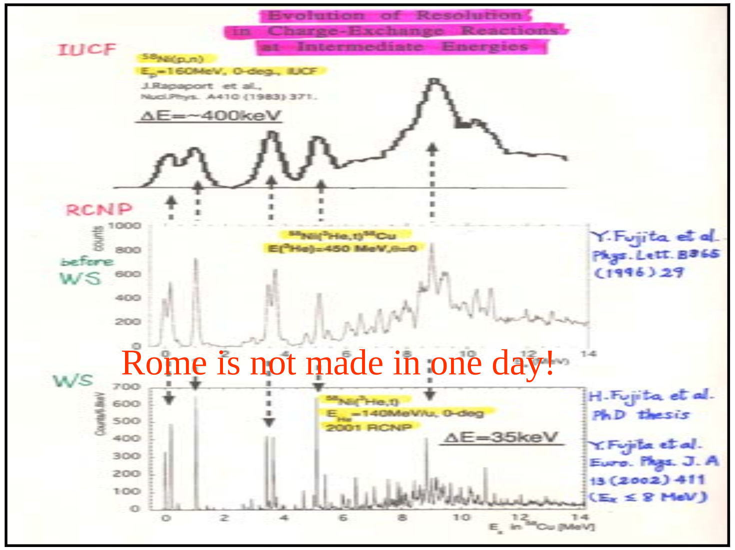

Optics: focus
object
lens
image
lens axis
focal length
focal length

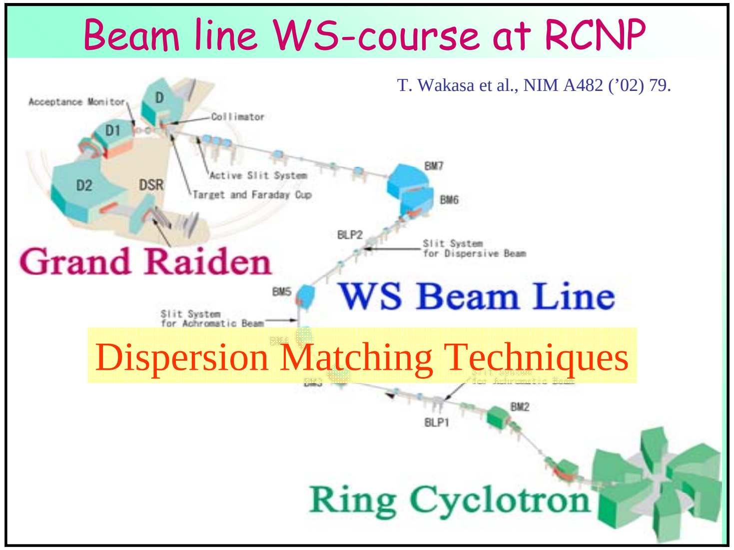

Matching Techniques
Y. Fujita et al., N.I.M. B 126 (1997) 274.
H. Fujita et al., N.I.M. A 484 (2002) 17.
a)
b)
c)
Focal plane
Magnetic Spectrometer
Target
-Δp
0
+Δp
-Δp
0
+Δp
Achromatic beam transportation
ΔE ~200 keV
for 140MeV/u 3He beam
Lateral dispersion matching
ΔE ~ 35 keV
Horiz. angle resolution
Δθsc > 15mrad
Angular dispersion matching
Δθsc ~ 5mrad

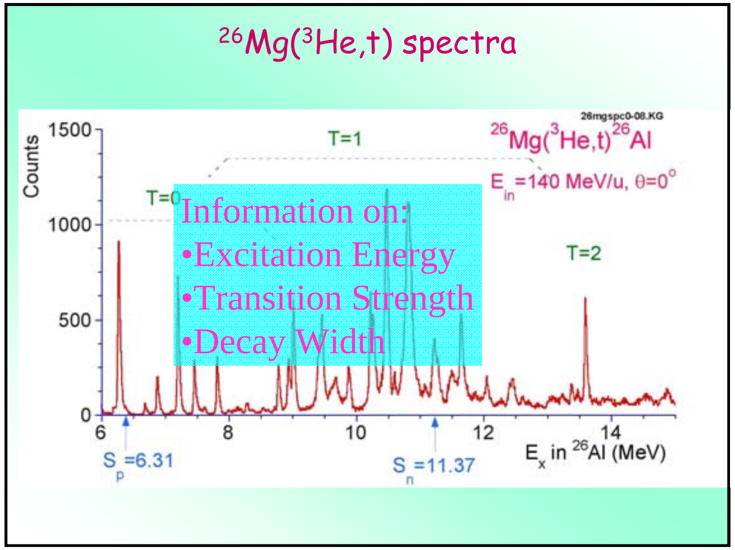

Prism
→ makes the dispersion
normal
n1
n2
n1
i
r
white
red
violet
The angles i and r that the rays make with the normal are the angles of incidence and refraction. Because n2 depends upon wavelength, the incident white ray separates into its constituent colours upon refraction, with deviation of the red ray the least and the violet ray the most.
©1994 Encyclopaedia Britannica, Inc.


RCNP Ring Cyclotron
Good quality 3He beam (140 MeV/nucleon)


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

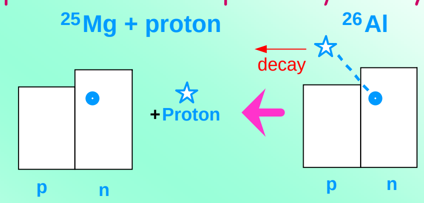

Evolution of Resolution
in Charge-Exchange Reactions
at Intermediate Energies
IUCF
ΔE=~400keV
RCNP
before
WS
Y. Fujita et al.
Phys. Lett. B365
(1996) 29
Rome is not made in one day!
WS
ΔE=35keV
H. Fujita et al.
PhD thesis
Y. Fujita et al.
Euro. Phys. J. A
13 (2002) 411


Beam line WS-course at RCNP
T. Wakasa et al., NIM A482 ('02) 79.
Acceptance Monitor
Collimator
Active Slit System
Target and Faraday Cup
Grand Raiden
WS Beam Line
Slit System
for Dispersive Beam
Slit System
for Achromatic Beam
Dispersion Matching Techniques
Ring Cyclotron


26Mg(3He,t) spectra
26Mg(3He,t)26Al
Ein=140 MeV/u, θ=0°
T=0
T=1
T=2
Counts
Ex in 26Al (MeV)
Sp=6.31
Sn=11.37
Information on:
•Excitation Energy
•Transition Strength
•Decay Width

**T (Isospin) Selection Rules

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



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

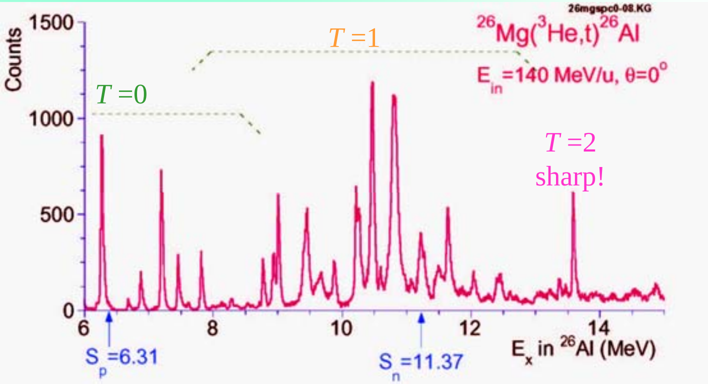
T : 1/2 ⊕ 1/2 = 0 or 1
3/2 ⊕ 1/2 = 1 or 2

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

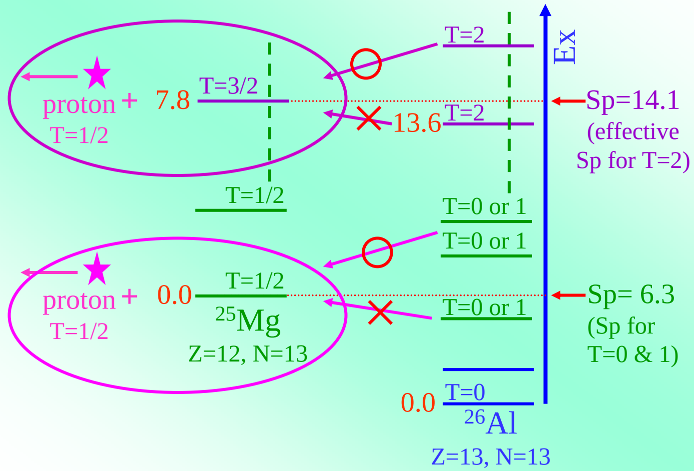
#T=3/2 state in ^{25}Mg : E_X > 7.79 MeV

→ 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

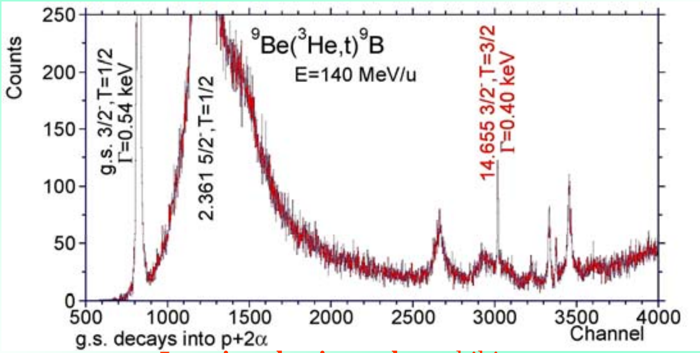
Higher-E_x region in ^{26}Al : *T*=1 & *T*=2 states



p-decay energy relationship

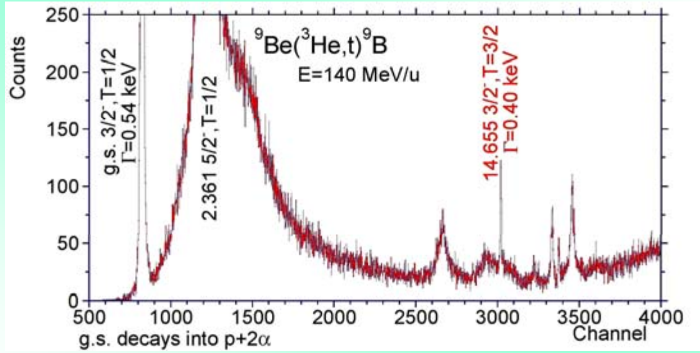


^{9}Be(^{3}He,t)^{9}B spectrum (II)



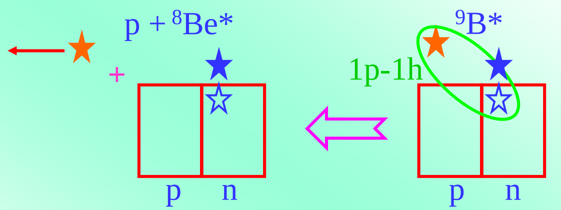
Isospin selection rule prohibits
proton decay of **T=3/2** state!

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



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

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



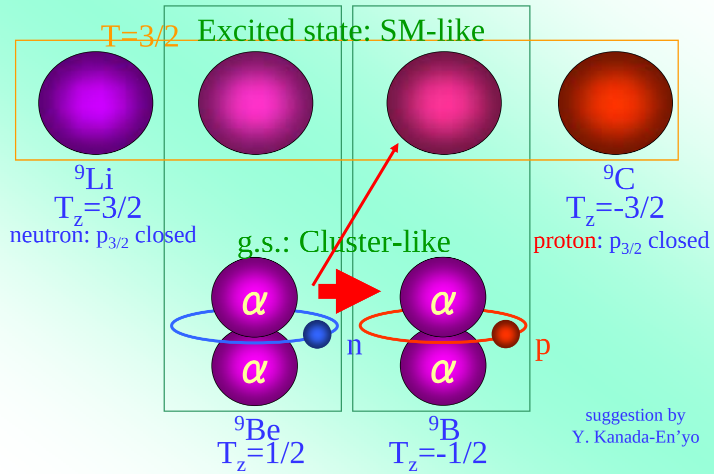
T_z : -1/2 + 0 = -1/2

T : 1/2 ⊕ 0 (low lying) **= 1/2**

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

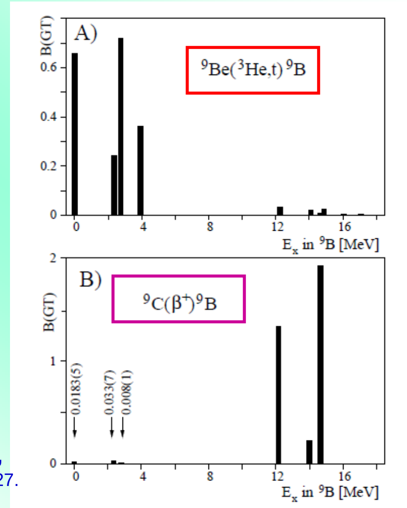
*T=1 state in ^{8}Be is
only above
E_x=16.6 MeV

Shell Structure and Cluster Structure



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.

Summary

Isospin quantum number: connects mass A nuclei
-unique in nuclei-

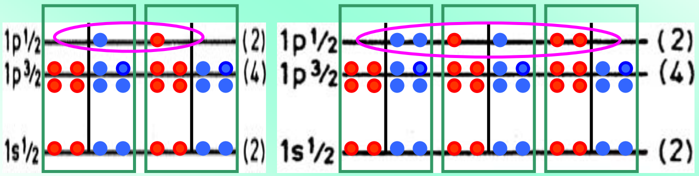
High Resolution: brings something new!
-one order difference makes the quality different-

Charge Symmetry / Charge Invariance

荷電対称性 荷電不変性

Charge Symmetry
equality of
p-p & n-n
interactions

Charge Invariance
equality of
p-p n-p n-n
interactions



^{13}C ^{13}N
(^{14}C and ^{14}O)

^{14}C ^{14}N ^{14}O

T=1/2 doublet

T=1 triplet