Koelner Dom

# Nuclei: Quantum Finite Many-Body System with Two Fermions

## "Isovector Excitations & Isospin Symmetry"



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Kyoto University
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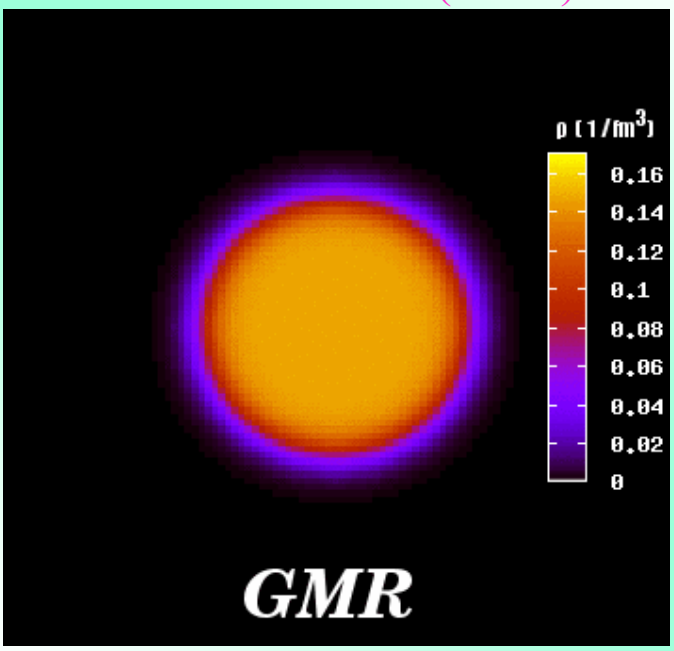
RCNP, Osaka Univ.

## ***Isovector Excitations & Isospin Symmetry

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

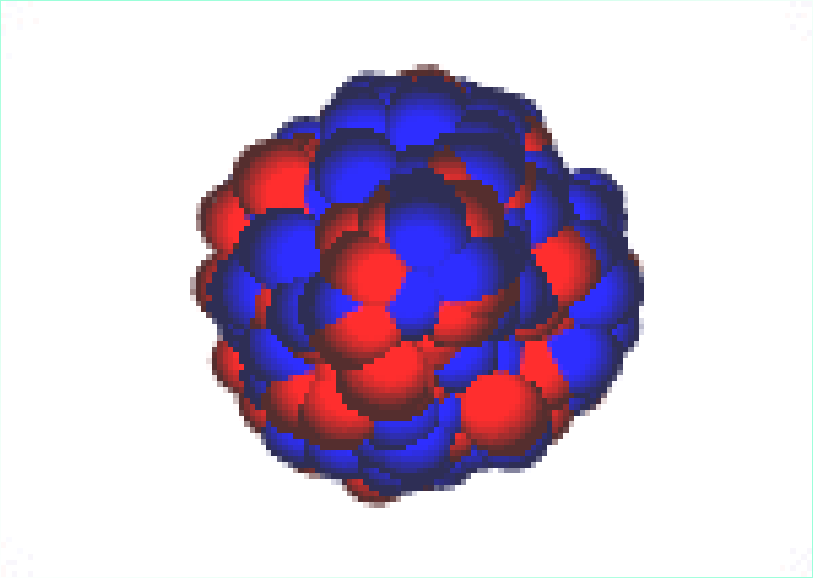
## Giant Resonance (GMR)

by M. Itoh




## IV Giant Monopole Resonance (IVGMR)

by P. Adrich



## Nucleon & Coin

back front

= Coin

proton neutron

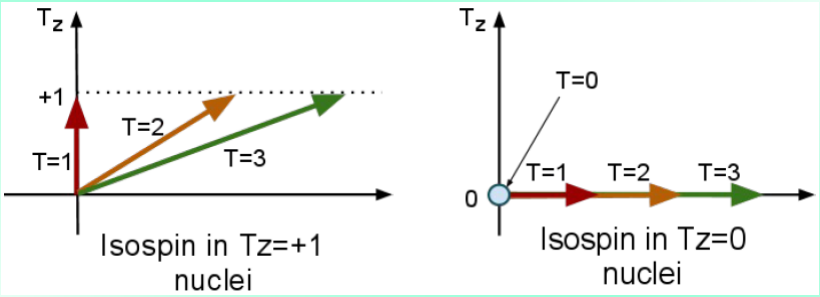
= Nucleon

similar mass
nearly the same interaction

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

## Size of Isospin T and its z-component $T_z$

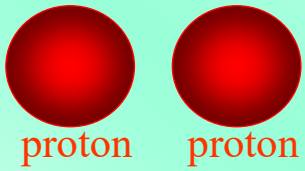
Isospin "T" has a similar (vector) structure to "J" !



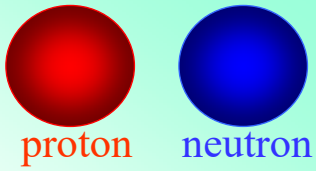

If $T_z$=+1 (or -1)
➔T = 1, 2, 3, …

If $T_z$= 0
➔T = 0, 1, 2 …

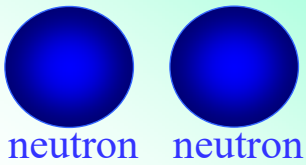
## Quantum Mechanics: Isospin




$T_z = -1/2 + (-1/2) = -1$ → $T = 1$
→ only IV !




$T_z = -1/2 + 1/2 = 0$ → $T = 0, 1$
→ IS + IV




$T_z = +1/2 + 1/2 = 1$ → $T = 1$
→ only IV !

## Symmetry Natures of Strong and EM Interactions

Strong interaction: between
proton-proton, proton-neutron, neutron-neutron

| IV int. | IV + IS int. | IV int. |
|---|---|---|
| (pp-aligned) | (p, n mixed) | (nn-aligned) |

Coulomb interaction: between
proton-proton, proton-neutron, neutron-neutron

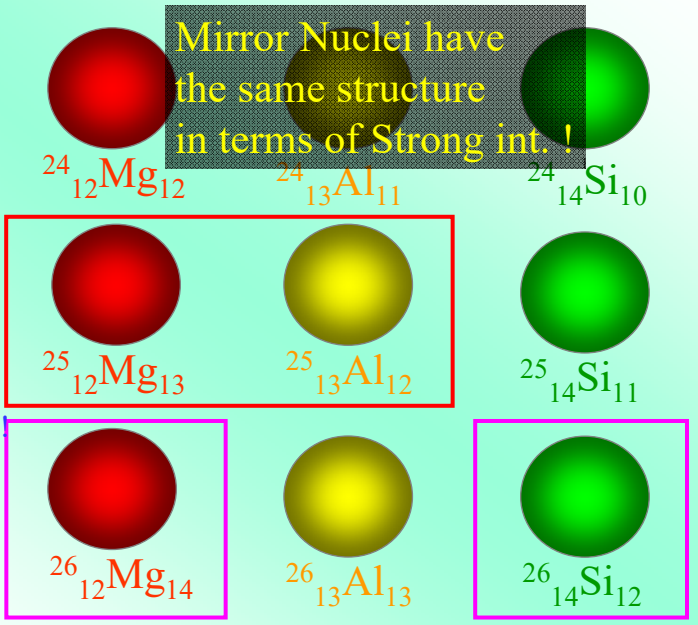
| Yes | No | No |
|---|---|---|

Properties of EM int. has nothing to do with Isospin !
→ EM int. distorts Quantum Number "Isospin."

## Isospin in simple terms

in their structure
Which are
the same?

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



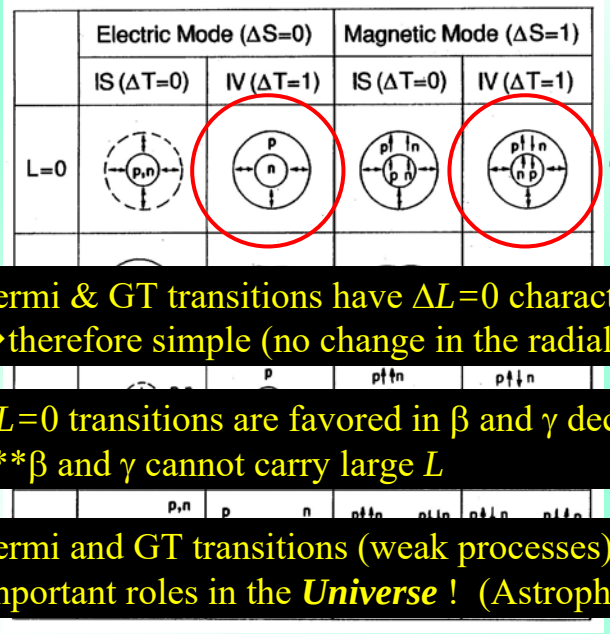

Hint:
Strong (Nuclear)
interaction is
responsible for
the main part of
Nuclear structure !

## **Fermi & Gamow-Teller Excitations

**Simplest nuclear excitations
that include $\tau$ operator.

**Especially, GT includes both $\tau$ and $\sigma$
that are unique in nuclei.

## Vibration Modes in Nuclei (Schematic)



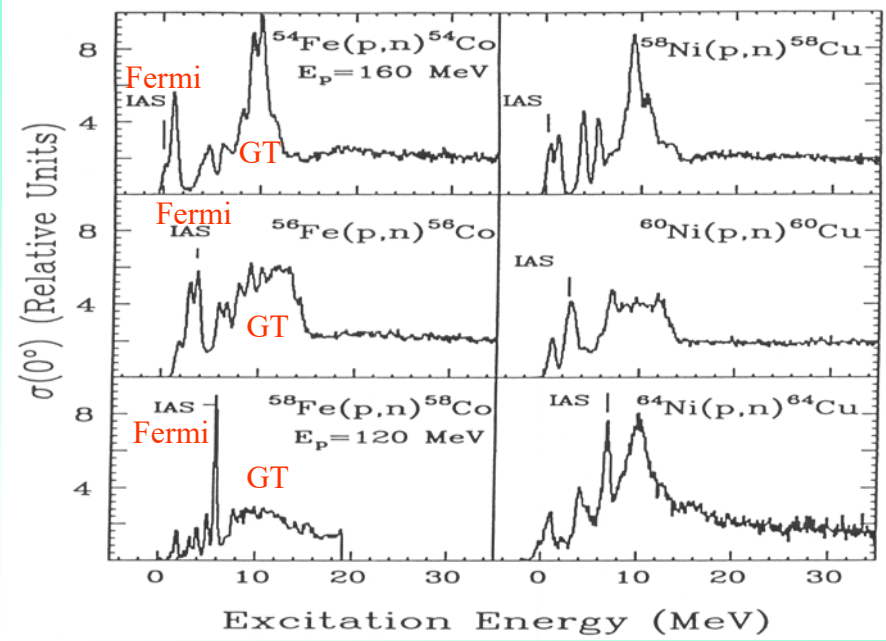

Gamow-Teller mode ($\sigma\tau$)

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

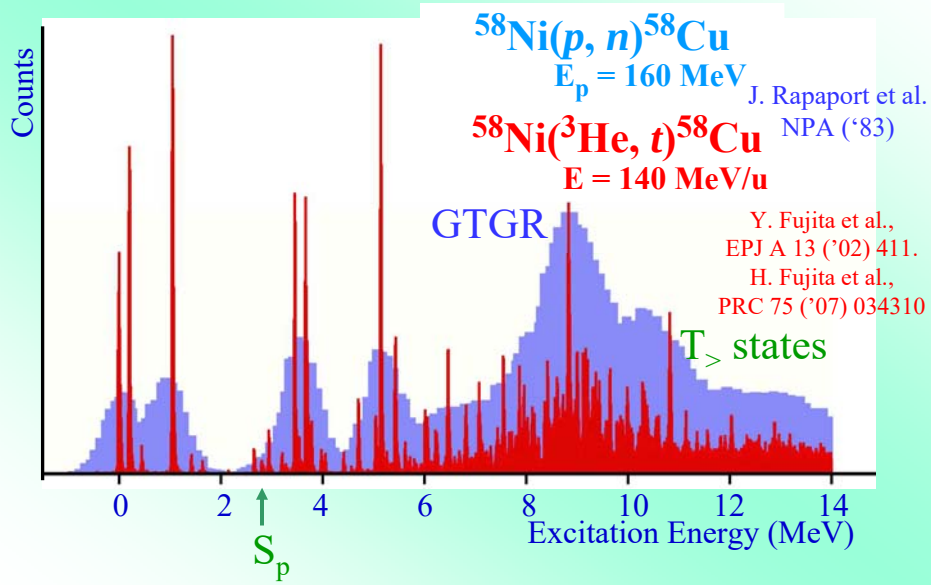
$\Delta L=0$ transitions are favored in β and γ decays
***β and γ cannot carry large $L$

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

## (p, n) spectra for Fe and Ni Isotopes



## Comparison of (p, n) and ($^3$He,t) 0° spectra



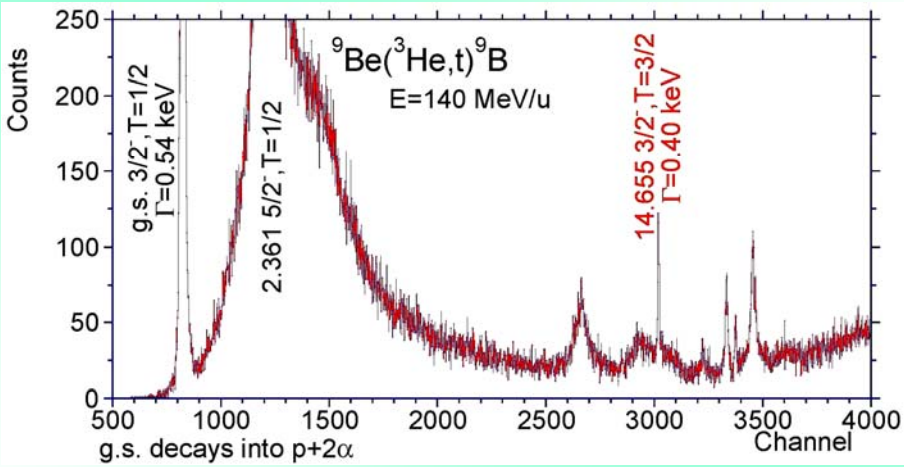

## **Properties of GT transitions

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) $\sigma$ operator: states with $j_>$ and $j_<$ configurations are connected. (ex. $j_> = f_{7/2}$ and $j_< = f_{5/2}$)
3) $\tau$ 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)

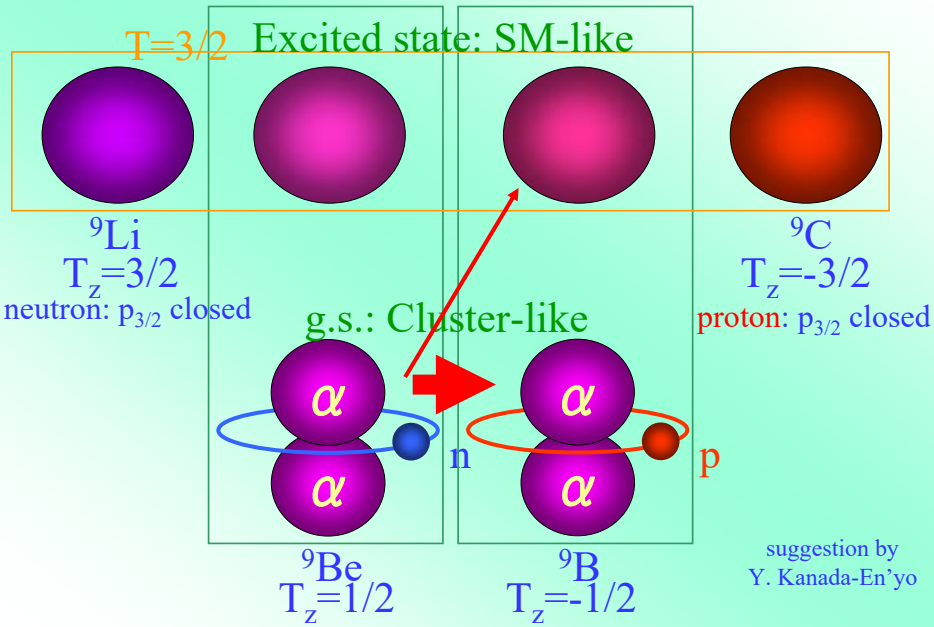
## $^9Be(^3He,t)^9B$ spectrum (III)




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

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

## Shell Structure and Cluster Structure



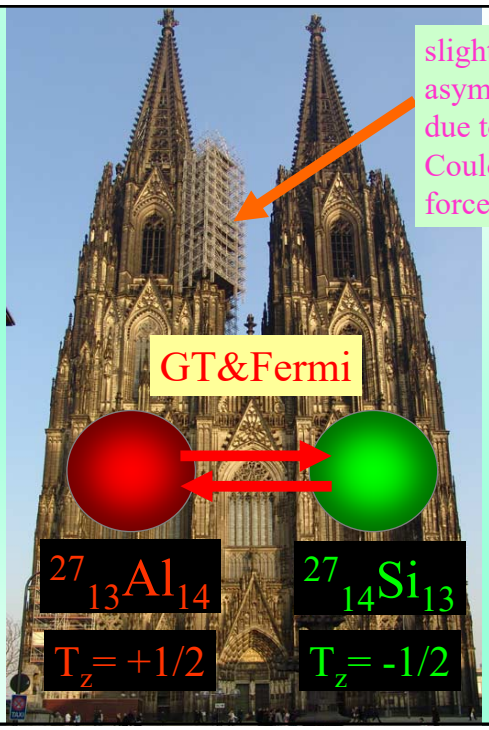

suggestion by
Y. Kanada-En'yo

# ***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.

# T=1/2 Isospin Symmetry

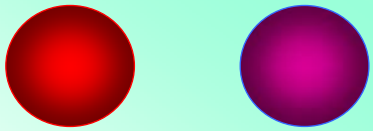



Koelner Dom
in Germany
(157m high)

## Nucleus & Coin

back front

= Coin

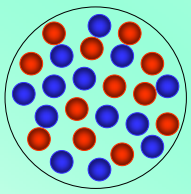


= Nuclei

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

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

## 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!

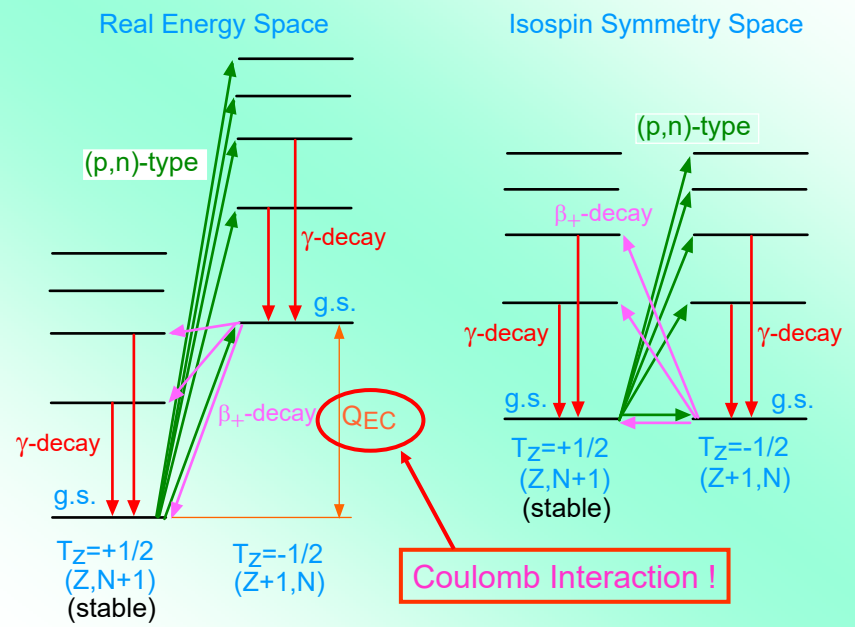
$T = \text{or} > |T_z|$

*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, …

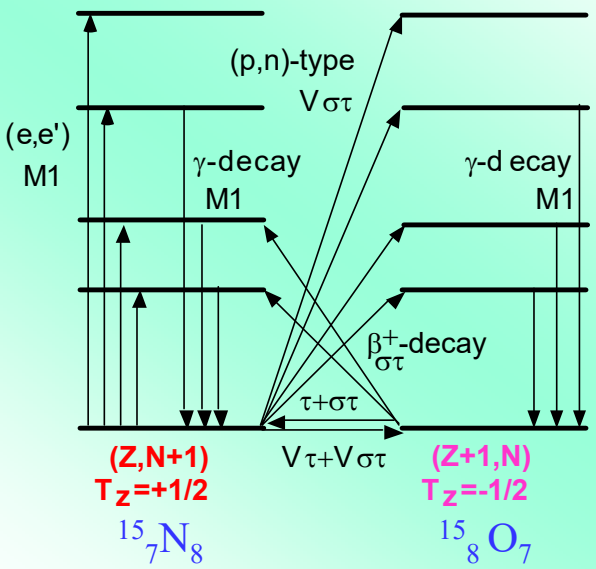
**only Z and N numbers are reversed !

Isospin Analogous Structure is expected !

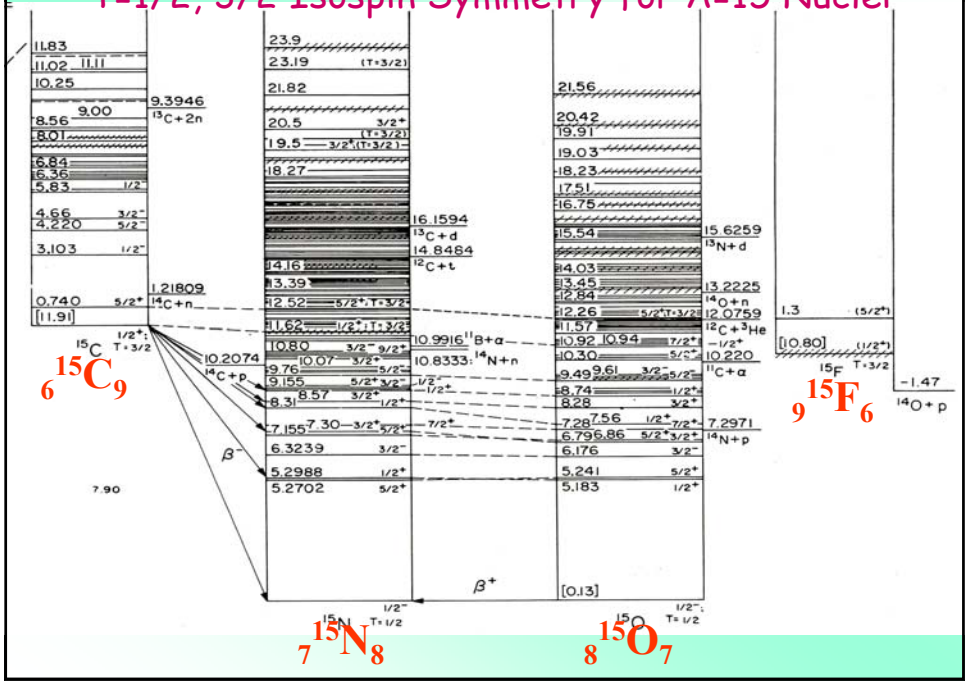
## Analogous Structures, Transitions in T=1/2 System



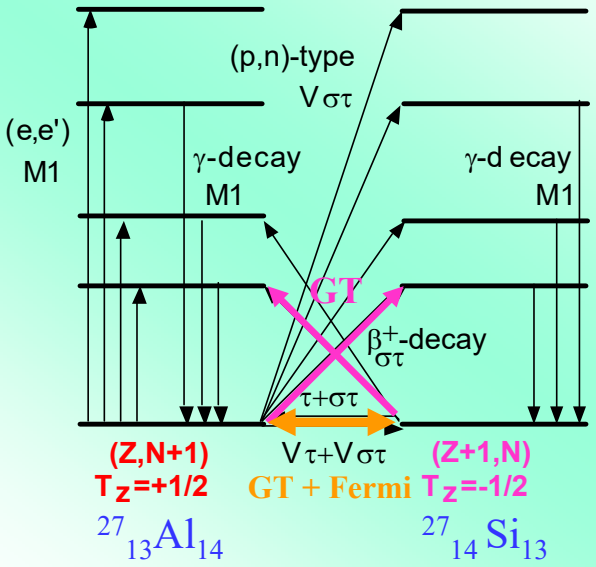

## T = 1/2 Mirror Nuclei : Structures



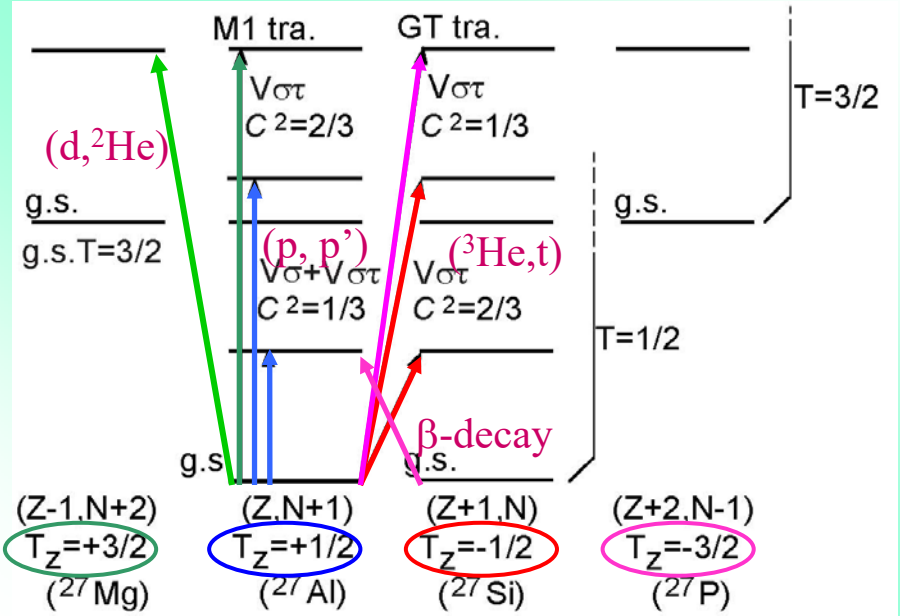
## T=1/2, 3/2 Isospin Symmetry for A=15 Nuclei




## T =1/2 Mirror Nuclei : Structures & Transitions

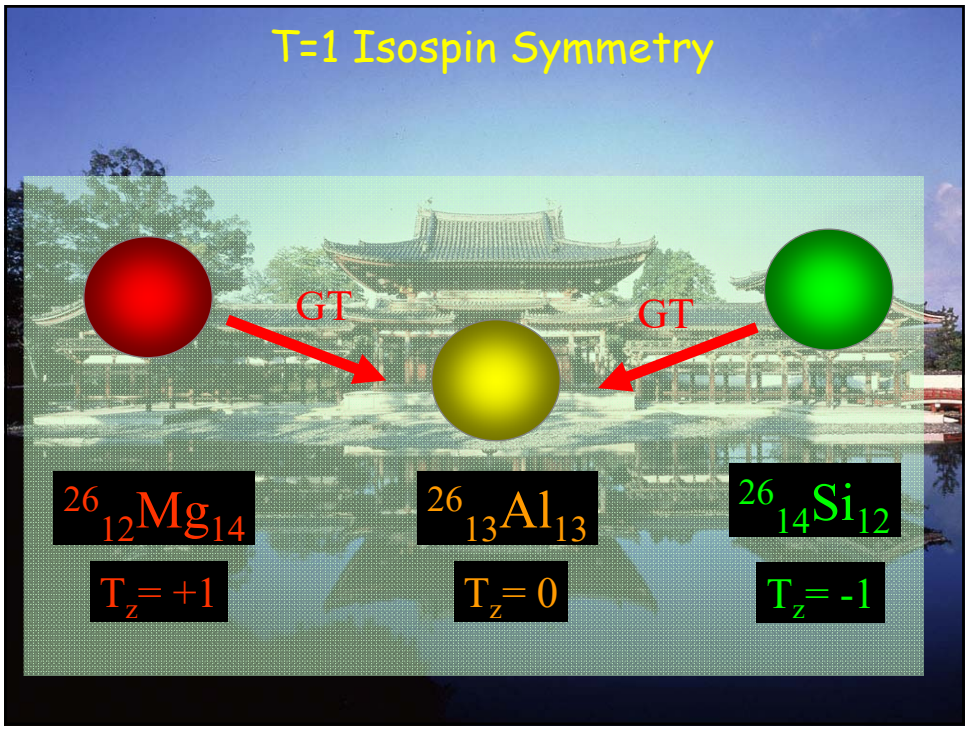


## T=1/2 & 3/2 Symmetry




## **Higher T Symmetry

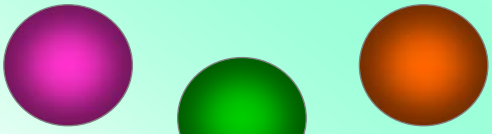

T=1 Isospin Symmetry
Byodoin-temple,
Uji, Kyoto


T=1 Isospin Symmetry
GT
GT
$^{26}_{12}Mg_{14}$
$T_z = +1$
$^{26}_{13}Al_{13}$
$T_z = 0$
$^{26}_{14}Si_{12}$
$T_z = -1$

# Nuclei & Coin

Coin

back front



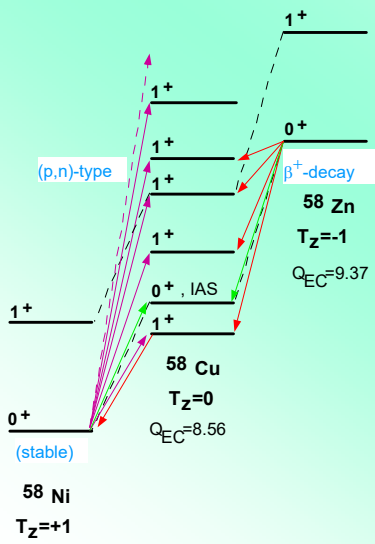
Nuclei

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

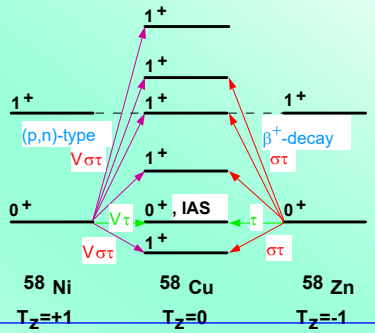
$T_z = 1$ $T_z = 0$ $T_z = -1$ isospin T=1 triplet

# Transitions in real & isospin space (T=1)

Symmetry Transitions from T=1 Nuclei
$T_z$=+1 → $T_z$=0 ← $T_z$=-1
(in real energy space)



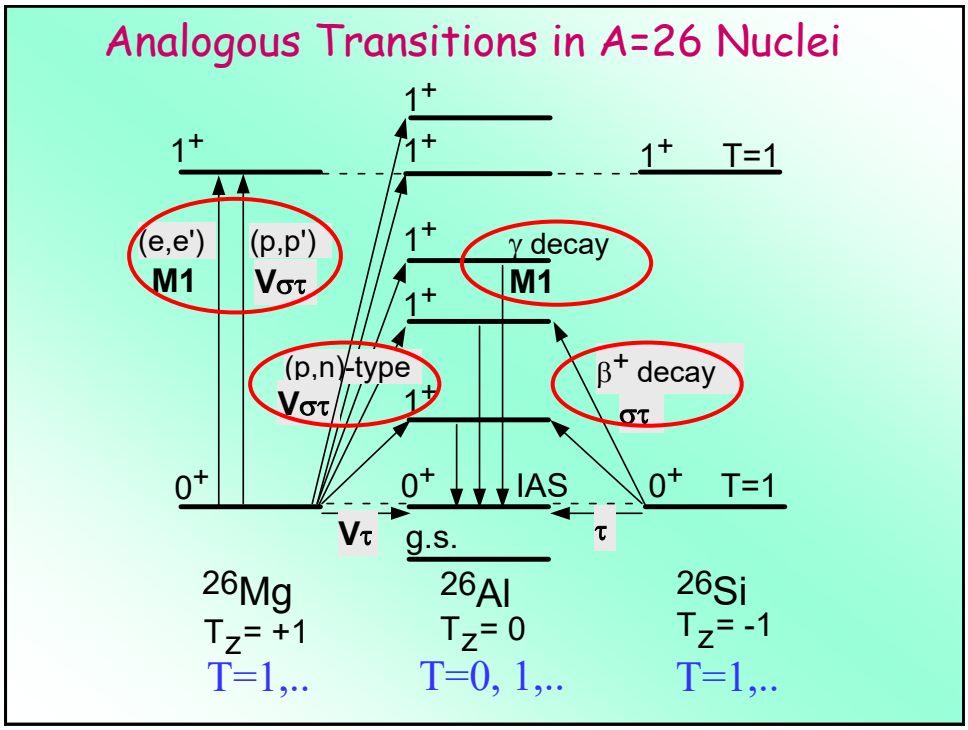

Symmetry Transitions from T=1 Nuclei
$T_z$=+1 → $T_z$=0 ← $T_z$=-1
(in isospin symmetry space*)

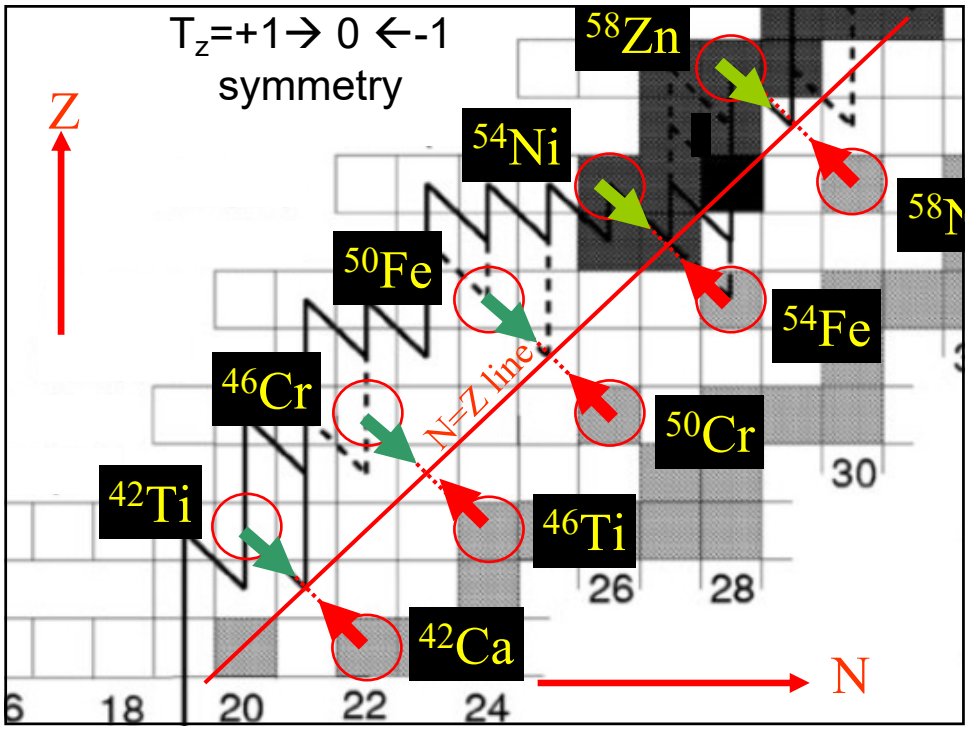


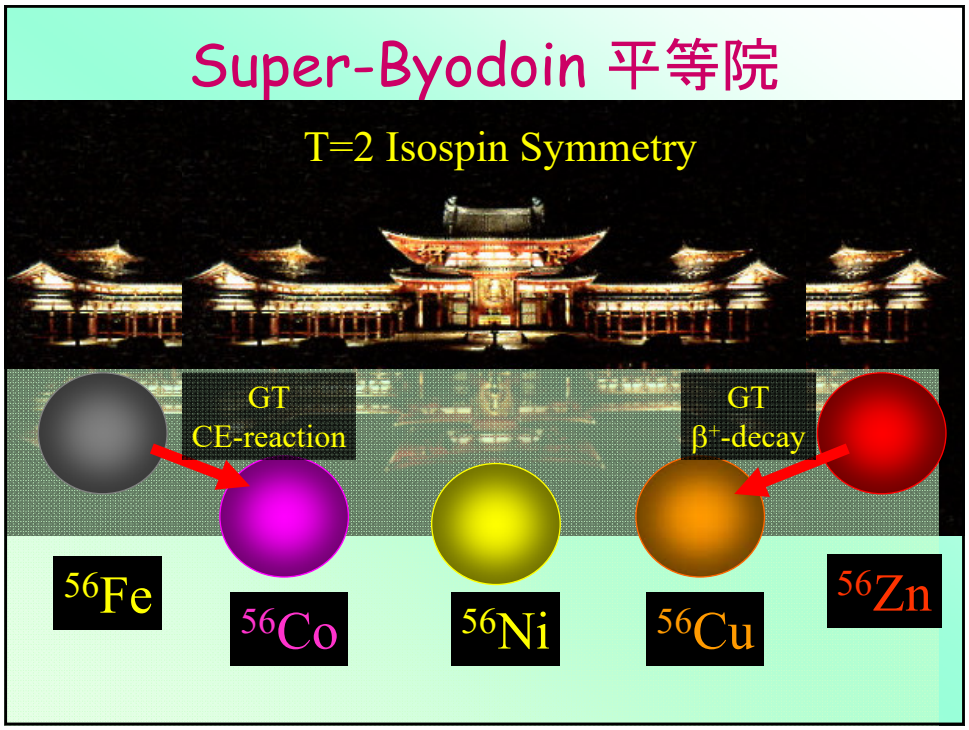

$^{58}_{28}Ni_{30}$ $^{58}_{29}Cu_{29}$ $^{58}_{30}Zn_{28}$

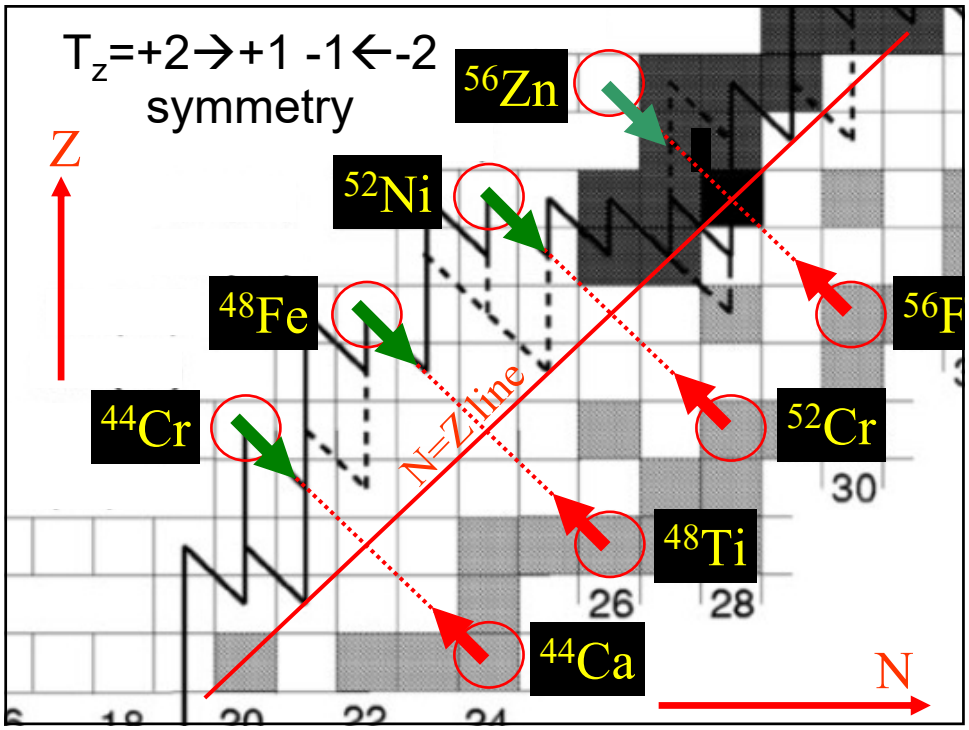
$^{26}_{12}Mg_{14}$ $^{26}_{13}Al_{13}$ $^{26}_{14}Si_{12}$

*after the correction of Coulomb displacement energy


Analogous Transitions in A=26 Nuclei
1+
1+
1+
1+
1+
1+
1+
1+
T=1
(e,e')
M1
(p,p')
Vστ
γ decay
M1
(p,n)-type
Vστ
β+ decay
στ
0+
0+
IAS
0+
T=1
Vτ
g.s.
τ
26Mg
Tz= +1
T=1,..
26Al
Tz= 0
T=0, 1,..
26Si
Tz= -1
T=1,..


Tz=+1→ 0 ←-1
symmetry
Z
N
58Zn
54Ni
50Fe
46Cr
42Ti
54Fe
50Cr
46Ti
42Ca
N=Z line
30
26
28
6
18
20
22
24

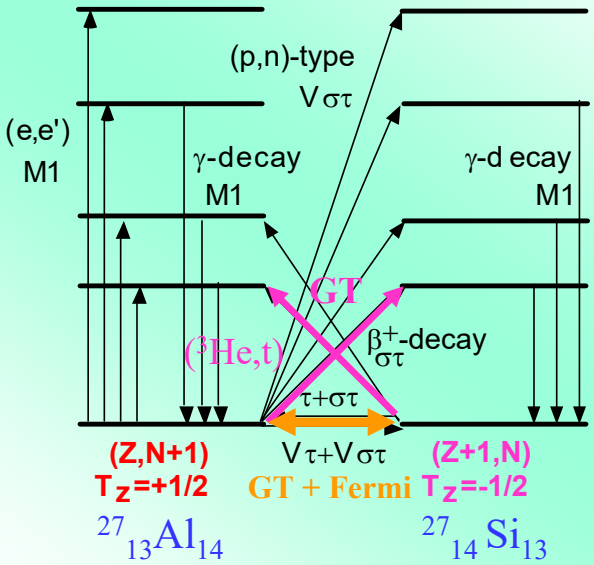

Super-Byodoin 平等院
T=2 Isospin Symmetry
GT
CE-reaction
GT
β+-decay
56Fe
56Co
56Ni
56Cu
56Zn

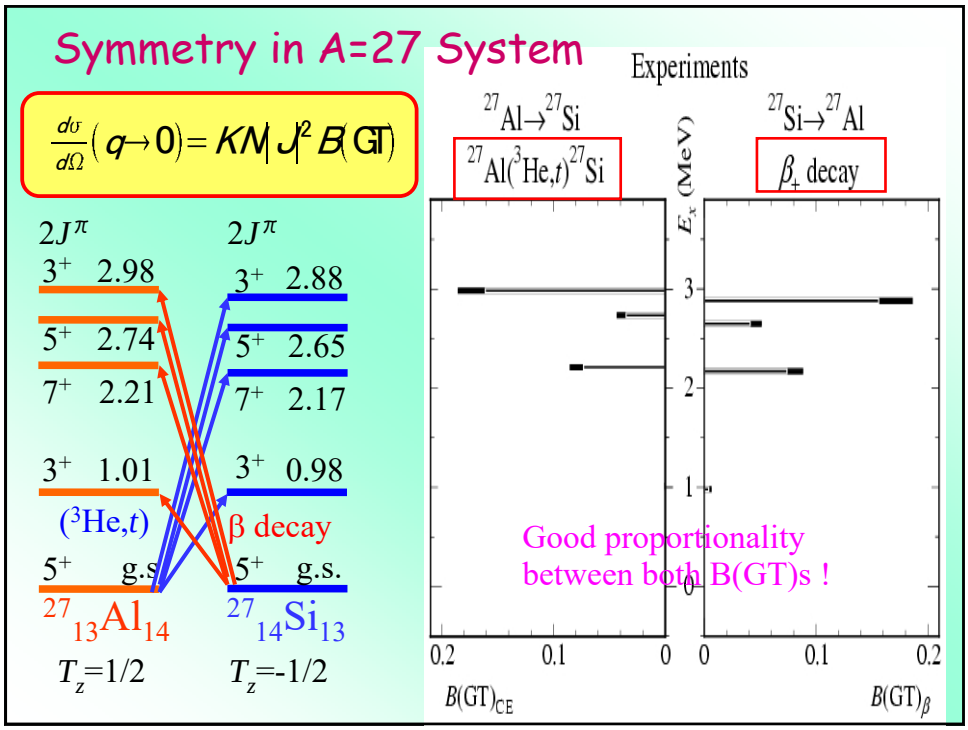

Tz=+2→+1 -1←-2
symmetry
Z
N
56Zn
52Ni
48Fe
44Cr
56F
52Cr
48Ti
44Ca
N=Z line
30
26
28

# T=1/2 Isospin Symmetry

Koelner Dom
in Germany
(157m high)

## T=1/2 Mirror Nuclei : Structures & Transitions



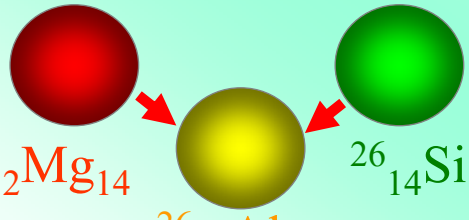

Symmetry in A=27 System
$\frac{d\sigma}{d\Omega}(q\to 0) = KN|J|^2 B(GT)$
$2J^\pi$
$3^+$ 2.98
$5^+$ 2.74
$7^+$ 2.21
$3^+$ 1.01
($^3$He,$t$)
$5^+$ g.s
$^{27}_{13}Al_{14}$
$T_z$=1/2
$2J^\pi$
$3^+$ 2.88
$5^+$ 2.65
$7^+$ 2.17
$3^+$ 0.98
β decay
$5^+$ g.s.
$^{27}_{14}Si_{13}$
$T_z$=-1/2
Experiments
$^{27}$Al→$^{27}$Si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


T=1 Isospin Symmetry
Byodoin-temple
宇治・平等院

## Nuclei & Coin

= Coin

back front



= Nuclei

Symmetry in
1) structure
2) transitions

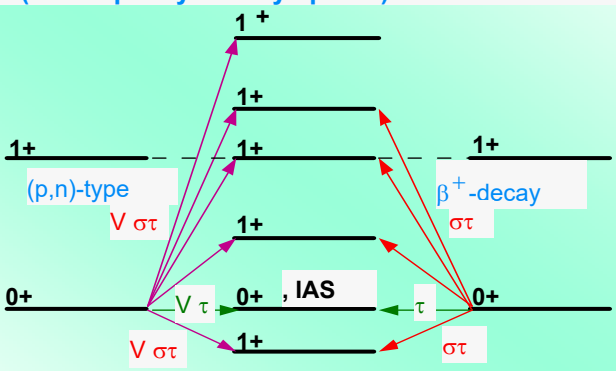
$^{26}_{12}Mg_{14}$ $^{26}_{13}Al_{13}$ $^{26}_{14}Si_{12}$

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

## T=1 symmetry : Structures & Transitions

$T_z=+1$ → $T_z=0$ ← $T_z=-1$

(in isospin symmetry space*)

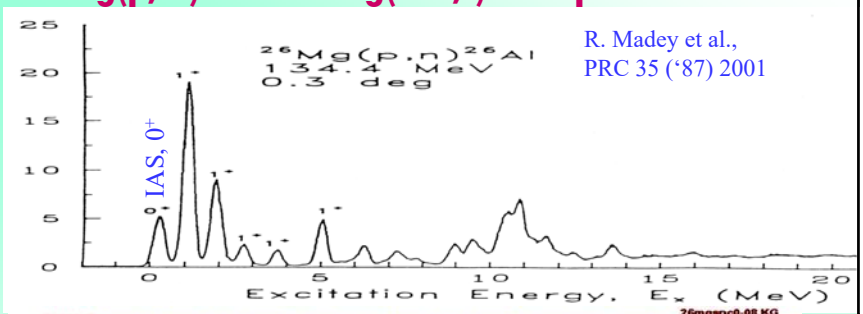



$T_z=+1$ $^{26}Mg$ Z=12, N=14

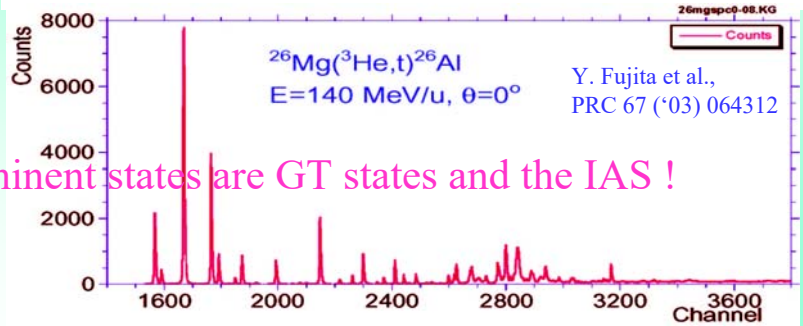
$T_z=0$ $^{26}Al$ Z=13, N=13

$T_z=-1$ $^{26}Si$ Z=14, N=12

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



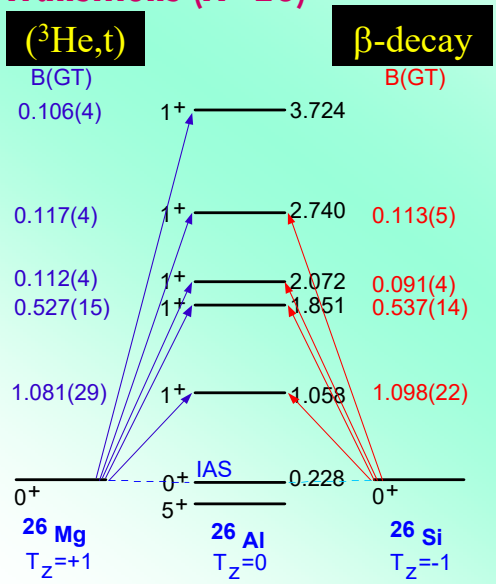

R. Madey et al., PRC 35 ('87) 2001



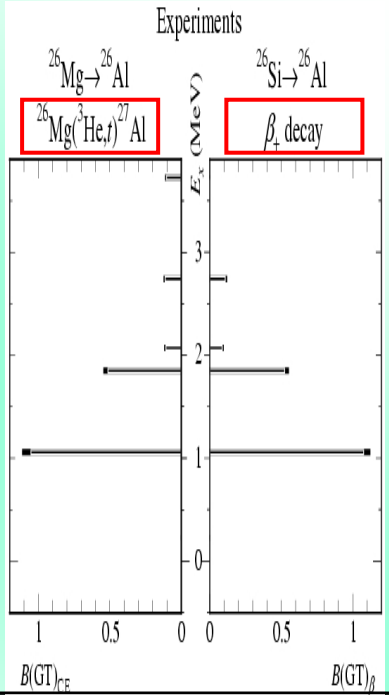

Y. Fujita et al., PRC 67 ('03) 064312

Prominent states are GT states and the IAS !

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

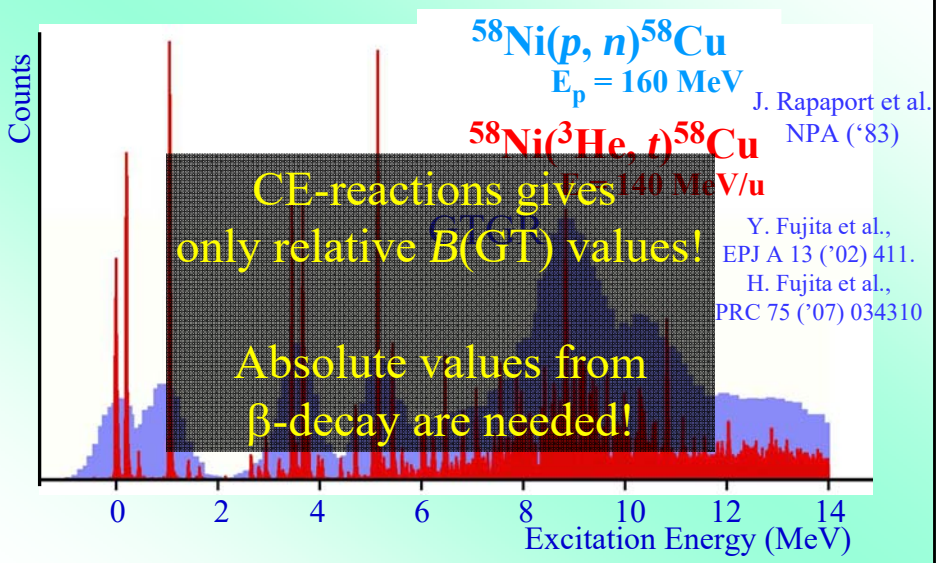



Y. Fujita et al., PRC 67 ('03) 064312



## **CE reaction and β-decay: complementary tools

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

$B$(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

## β-decay & Nuclear Reaction

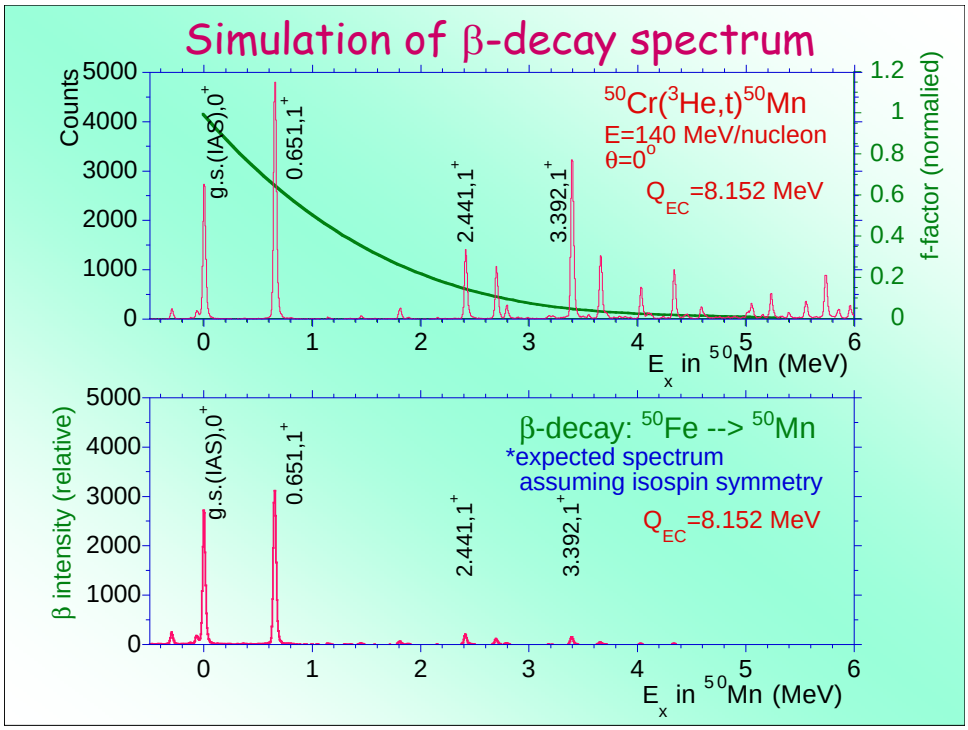
*β-decay GT tra. rate = $\frac{1}{t_{1/2}} = f\frac{\lambda^2}{K}B(\mathrm{GT})$

$B$(GT) : reduced GT transition strength
$\propto$ (matrix element)$^2$

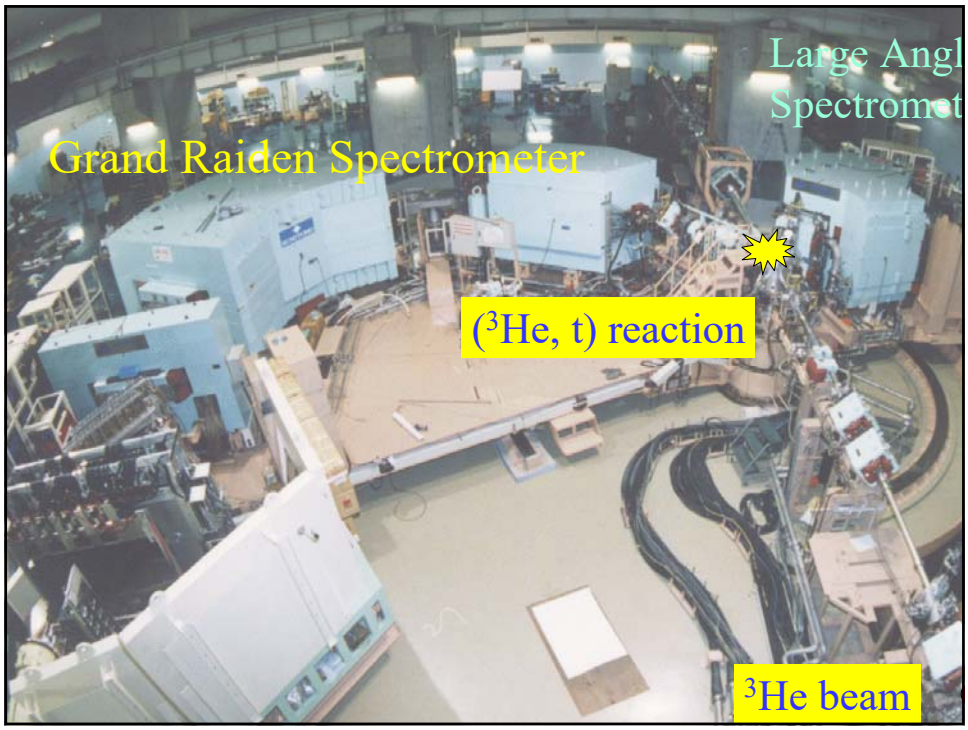
Study of Weak Response of Nuclei
by means of
Strong Interaction !
using β-decay as a reference

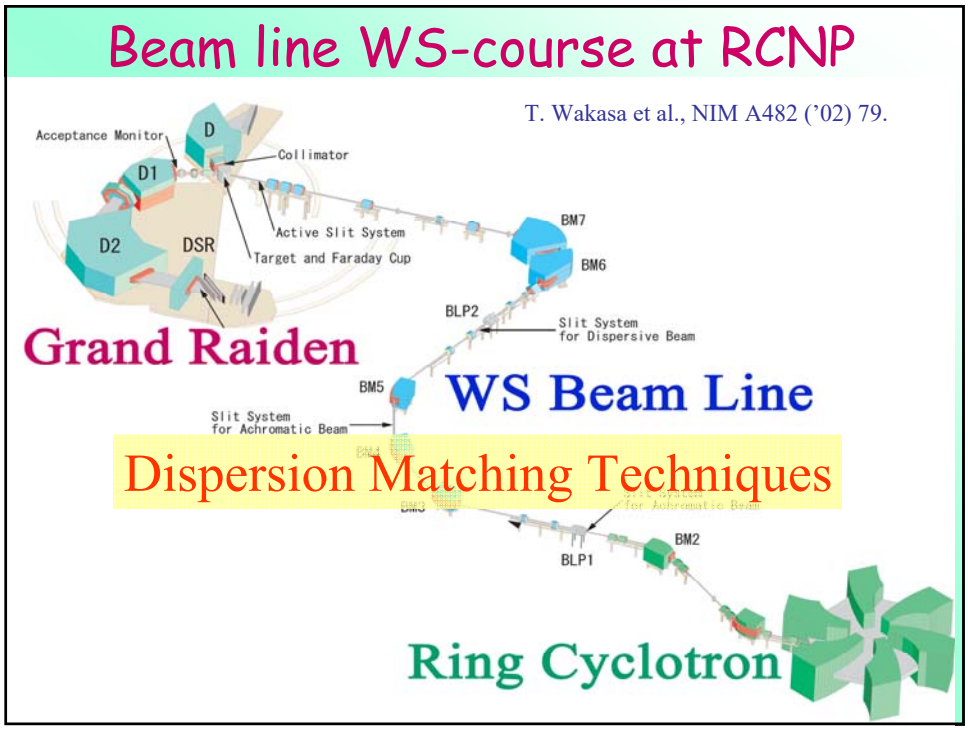
*Nuclear (CE) reaction rate (cross-section)
= reaction mechanism
⊗ operator
⊗ structure
=(matrix element)$^2$

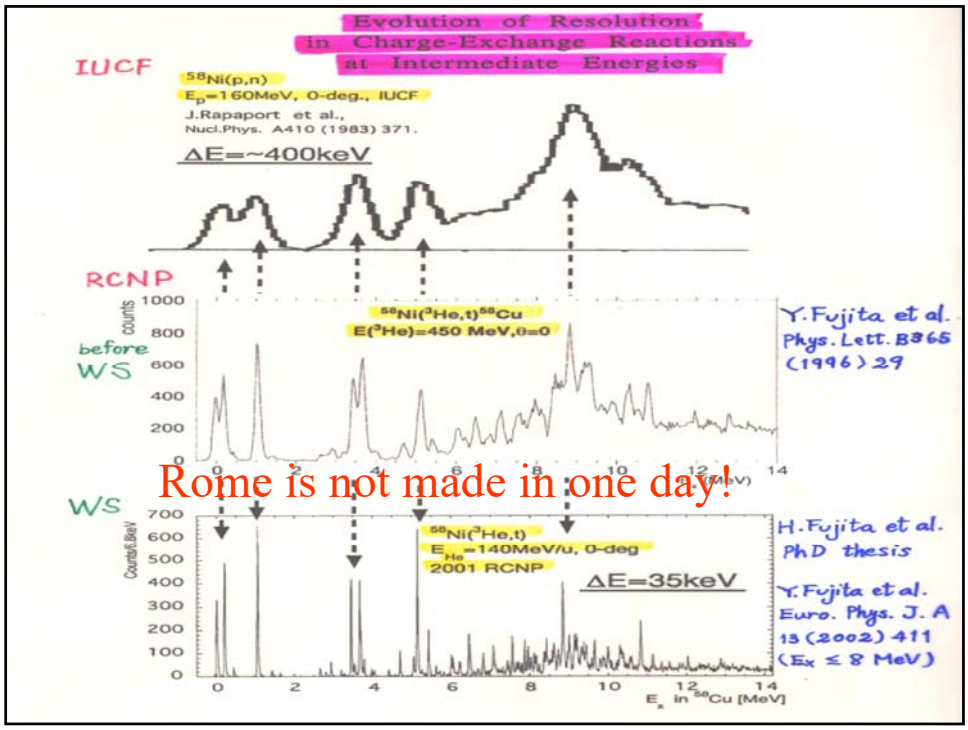
A simple reaction mechanism should be achieved !
➡ we have to go to high incoming energy

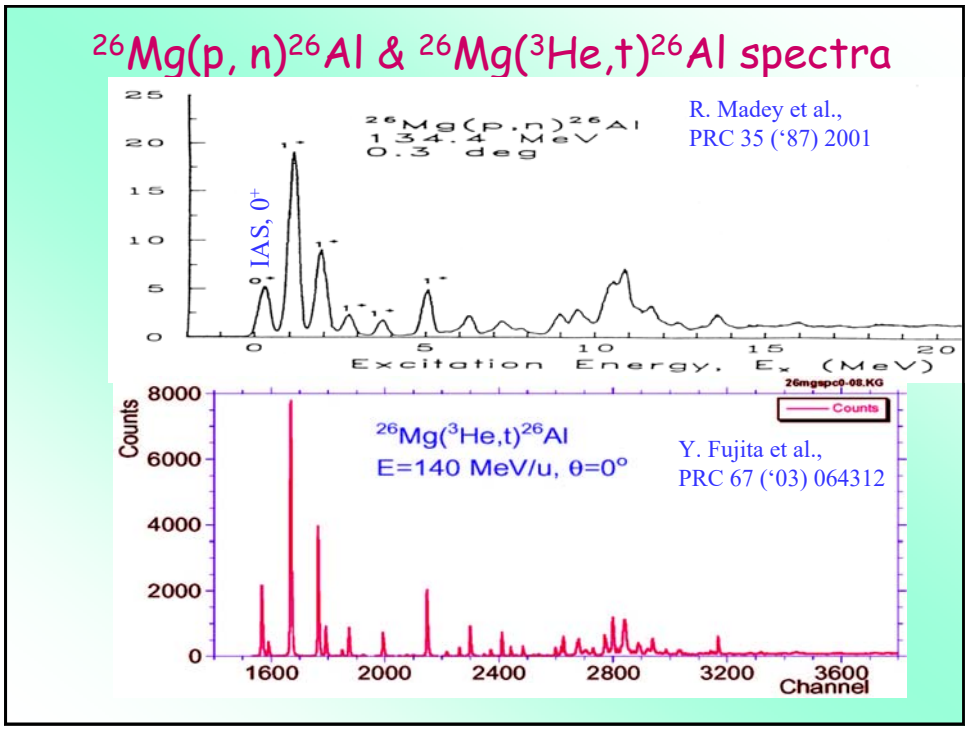

Simulation of β-decay spectrum
Counts
f-factor (normalied)
$^{50}$Cr($^{3}$He,t)$^{50}$Mn
E=140 MeV/nucleon
θ=0°
$Q_{EC}$=8.152 MeV
g.s.(IAS),0+
0.651,1+
2.441,1+
3.392,1+
$E_x$ in $^{50}$Mn (MeV)
β intensity (relative)
β-decay: $^{50}$Fe --> $^{50}$Mn
*expected spectrum
assuming isospin symmetry
$Q_{EC}$=8.152 MeV


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

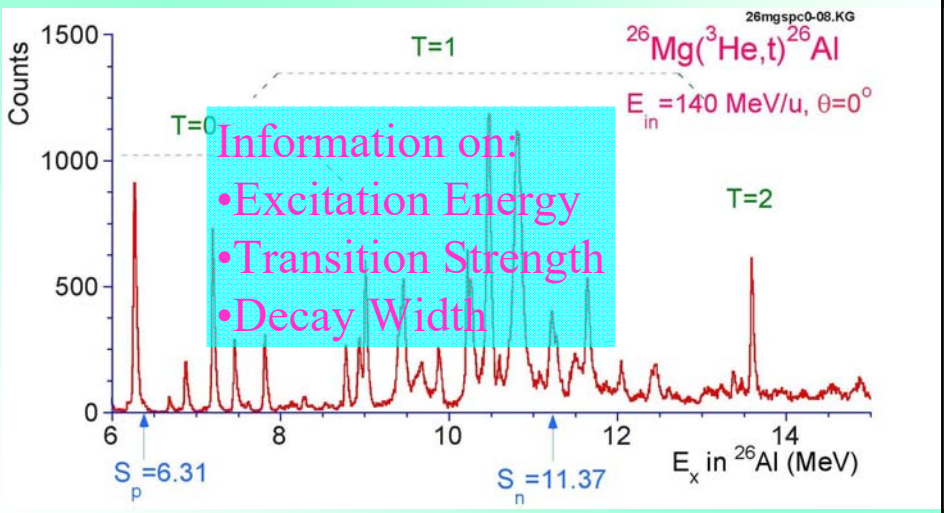

Large Angl
Spectromet
Grand Raiden Spectrometer
($^3$He, t) reaction
$^3$He beam


Beam line WS-course at RCNP
T. Wakasa et al., NIM A482 ('02) 79.
Acceptance Monitor
D
D1
Collimator
D2
DSR
Active Slit System
Target and Faraday Cup
BM7
BM6
BLP2
Slit System
for Dispersive Beam
Grand Raiden
BM5
WS Beam Line
Slit System
for Achromatic Beam
Dispersion Matching Techniques
BLP1
BM2
Ring Cyclotron


Evolution of Resolution in Charge-Exchange Reactions at Intermediate Energies
IUCF
58Ni(p,n)
Ep=160MeV, 0-deg., IUCF
J.Rapaport et al.,
Nucl.Phys. A410 (1983) 371.
ΔE=~400keV
RCNP
before WS
counts
58Ni(3He,t)58Cu
E(3He)=450 MeV,θ=0
Y.Fujita et al.
Phys.Lett. B365 (1996) 29
Rome is not made in one day!
WS
Counts/6.8keV
58Ni(3He,t)
E3He=140MeV/u, 0-deg
2001 RCNP
ΔE=35keV
H.Fujita et al.
PhD thesis
Y.Fujita et al.
Euro. Phys. J. A 13 (2002) 411
(Ex ≤ 8 MeV)
Ex in 58Cu [MeV]


26Mg(p, n)26Al & 26Mg(3He,t)26Al spectra
26Mg(p,n)26Al
134.4 MeV
0.3 deg
R. Madey et al.,
PRC 35 ('87) 2001
IAS, 0+
Excitation Energy, Ex (MeV)
Counts
26Mg(3He,t)26Al
E=140 MeV/u, θ=0°
Y. Fujita et al.,
PRC 67 ('03) 064312
Channel

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

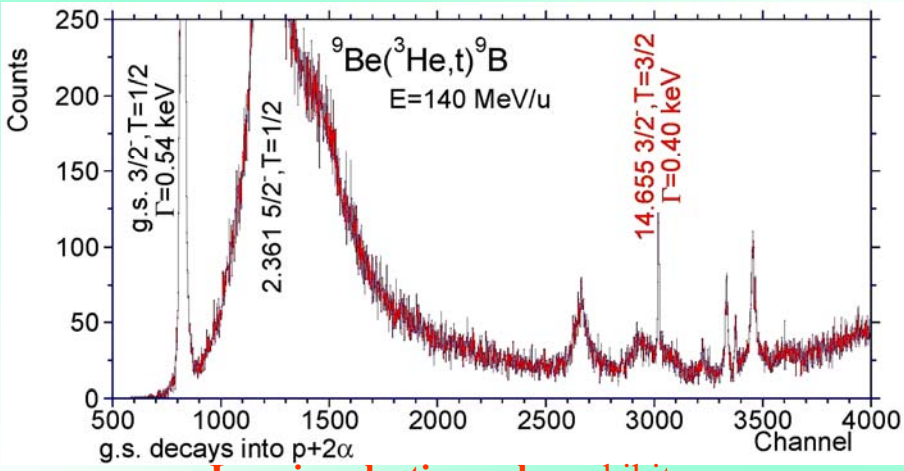



Information on:
- Excitation Energy
- Transition Strength
- Decay Width

## ***Selection Rules***

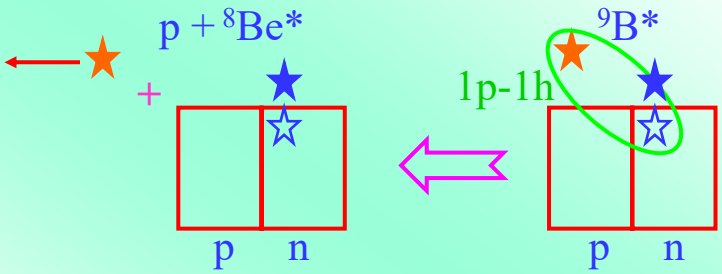
Selection rules: associated with good Q-numbers

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




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

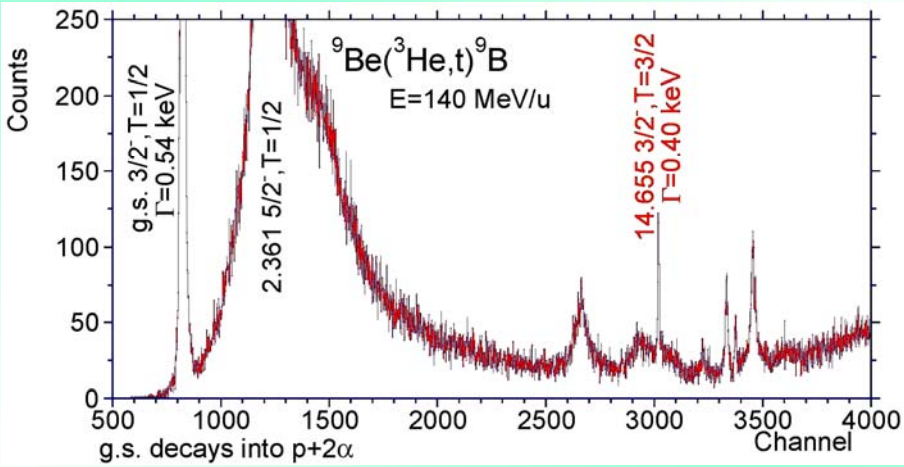
## Isospin Selection Rule : in *p*-decay of $^9B$




| | | | | |
|---|---|---|---|---|
| $T_z$ : -1/2 | + 0 | | = | -1/2 |
| T : 1/2 | ⊕ 0 (low lying) | | = | 1/2 |
| T : 1/2 | ⊕ 1 (higher Ex) | | = | 1/2 & 3/2 |

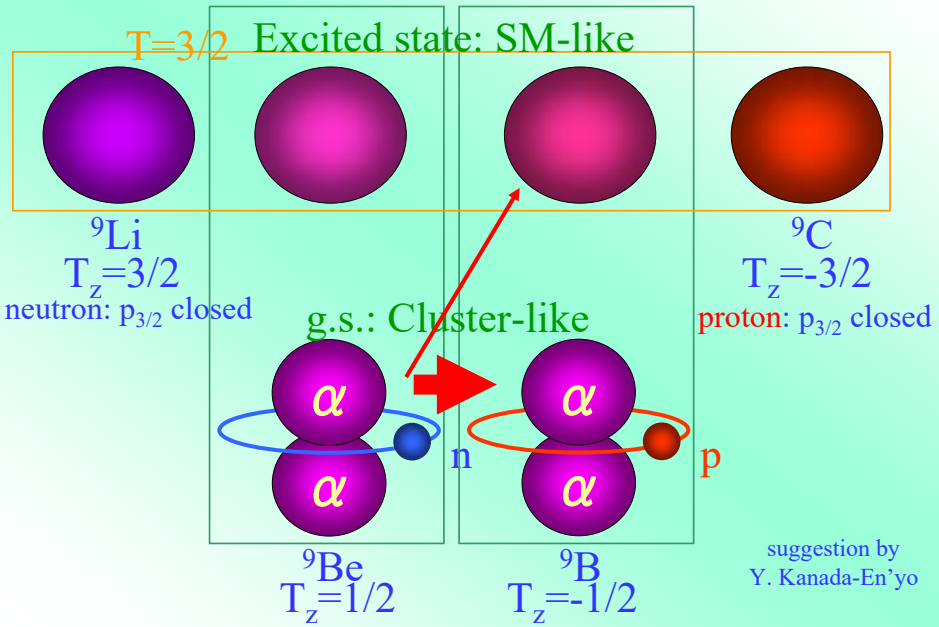
*T=1 state in $^8Be$ is only above $E_x$=16.6 MeV

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




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

## Shell Structure and Cluster Structure

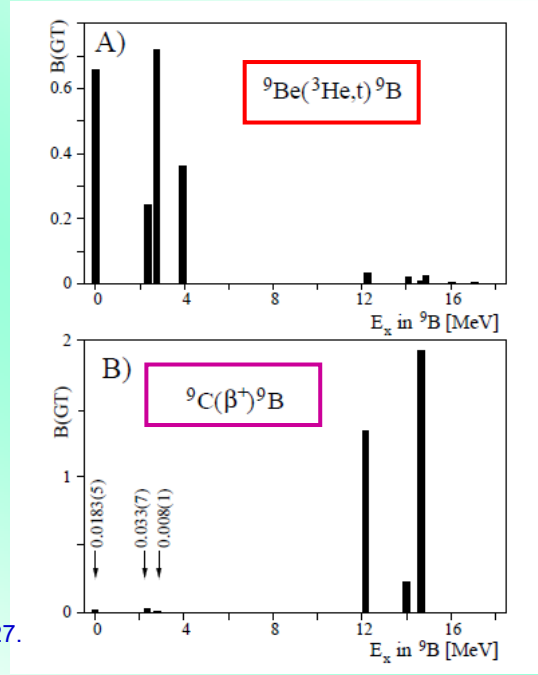



suggestion by
Y. Kanada-En'yo

## 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.




## Summary

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

Selection rules: associated with good Q-numbers

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