Overview of Gamow-Teller Transitions in Nuclei

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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

Neptune driving Waves
波を操る海神ネプチューン

Neptune=弱い相互作用
(weak interaction)

Allowed Transitions in Weak Processes (e.g. β decay) are Fermi and Gamow-Teller transitions !

Fermi transitions are allowed only between IAS, and thus well understood !

On the other hand,
Gamow-Teller transitions are with large variety !

Gamow-Teller transitions are caused by $\sigma\tau$ operator !

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

Various Operators / Various Hammers!

wooden hammers

metal hammers

hammers
=operators

The sound from the bell is different depending on hammers!

The mode of nuclear excitation is determined by an operator!

Vibration Modes in Nuclei (Operators)

Microscopic classification of giant resonances

	$\Delta S = 0$, $\Delta T = 0$	$\Delta S = 0$, $\Delta T = 1$	$\Delta S = 1$, $\Delta T = 0$	$\Delta S = 1$, $\Delta T = 1$
$\Delta L = 0$		$\sum \tau_i$ 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
$\Delta L = 1$		$\sum r_i Y_m^1 \tau_i$ 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			
$\Delta L = 2$	$\sum r_i^2 Y_m^2$ 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
$\Delta L = 3$	$\sum r_i^3 Y_m^3$ 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

$\Delta S=1$: spin excitation

$\Delta T=1$: IV excitation (isospin related!)

Operators
σ: spin
τ: isospin
r: radial
Y^l_m: Spherical Harmonic

Gamow-Teller transitions

Mediated by $\sigma\tau$ operator (axial isovector-operator)

ΔS = -1, 0, +1 and ΔT = -1, 0, +1

(ΔL = 0, no change in radial w.f.)

➔ no change in spatial w.f.

Accordingly, transitions among $j_>$ and $j_<$ configurations

$j_> \rightarrow j_>$, $j_< \rightarrow j_<$, $j_> \leftrightarrow j_<$

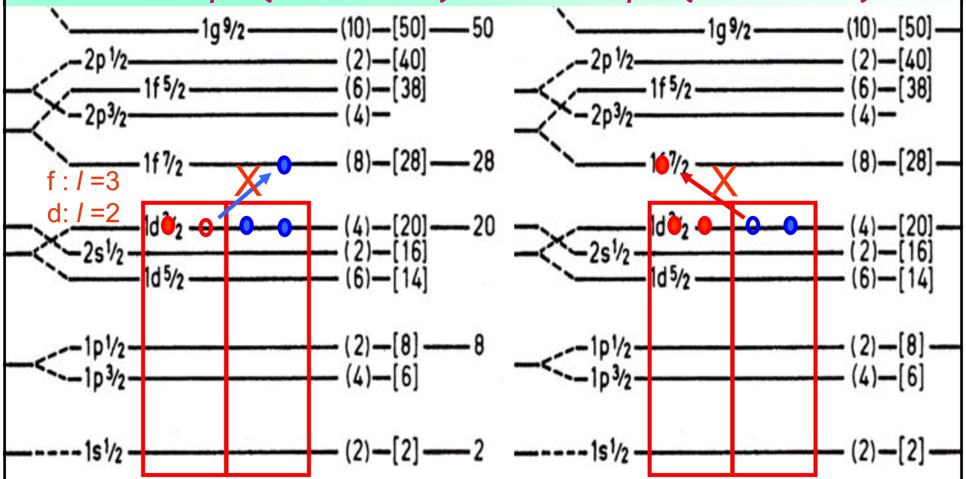
example $d_{5/2} \rightarrow d_{5/2}$, $d_{3/2} \rightarrow d_{3/2}$, $d_{5/2} \leftrightarrow d_{3/2}$

Note that Spin and Isospin are unique quantum numbers in atomic nuclei !

➔ GT transitions are sensitive to Nuclear Structure !

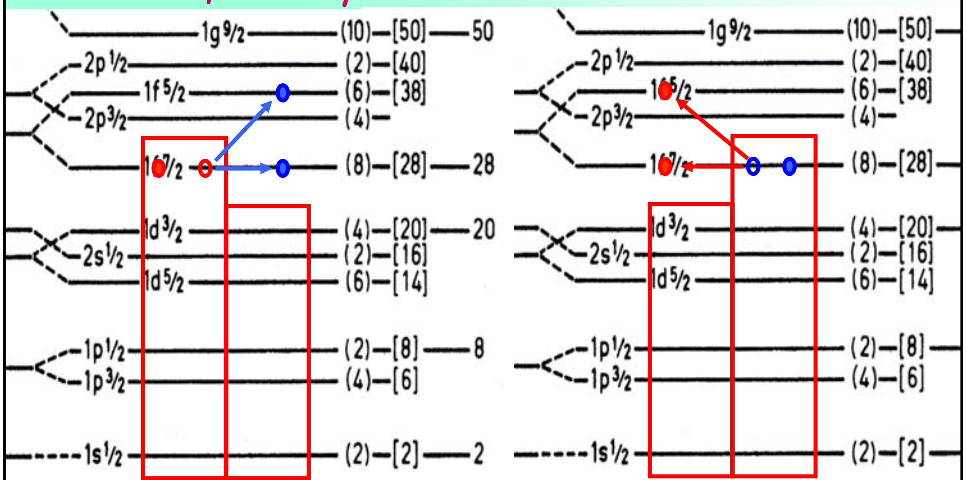
➔ GT transitions in each nucleus are UNIQUE !

1p-1h Excitations in
^{40}Ca: β^+ (reaction) ^{40}Ca : β^- (reaction)



from ^{4}He, ^{16}O, ^{40}Ca : no GT transition is allowed !
(no GT transition from *LS*-closed Doubly Magic Nuclei)

1p-1h Excitations in
^{42}Ti: β-decay ^{42}Ca : CE Reaction



proton: $f_{7/2}\rightarrow$ neutron $f_{7/2}$
proton: $f_{7/2}\rightarrow$ neutron $f_{5/2}$

proton: $f_{7/2}\leftarrow$ neutron $f_{7/2}$
proton: $f_{5/2}\leftarrow$ neutron $f_{7/2}$

β decay & Nuclear CE 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 = |<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)

β decay & Nuclear CE reaction

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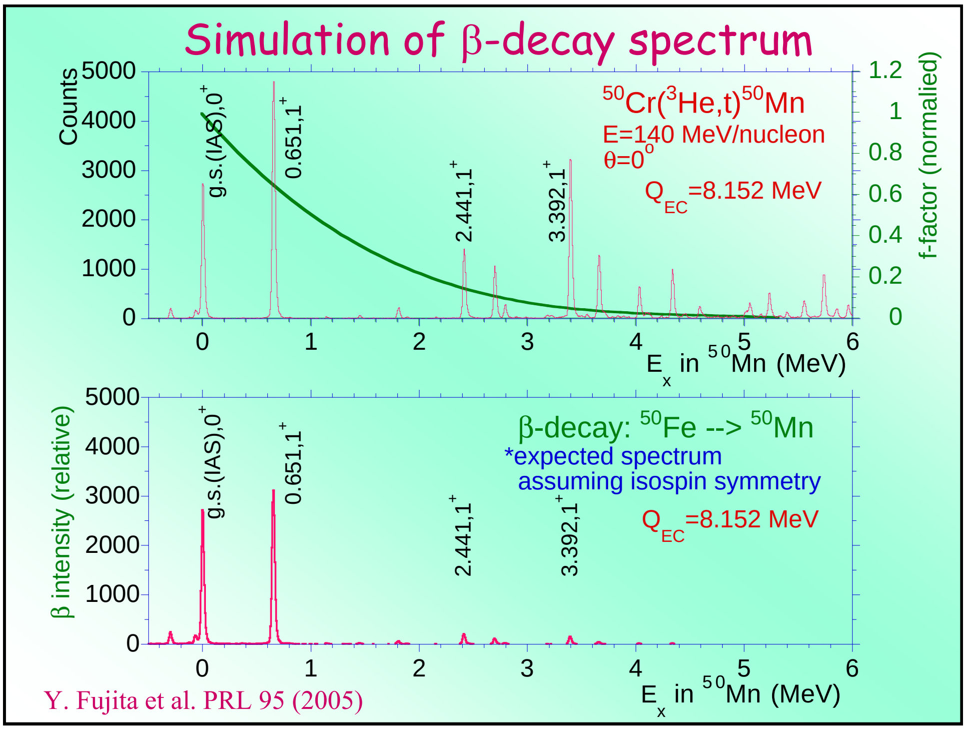
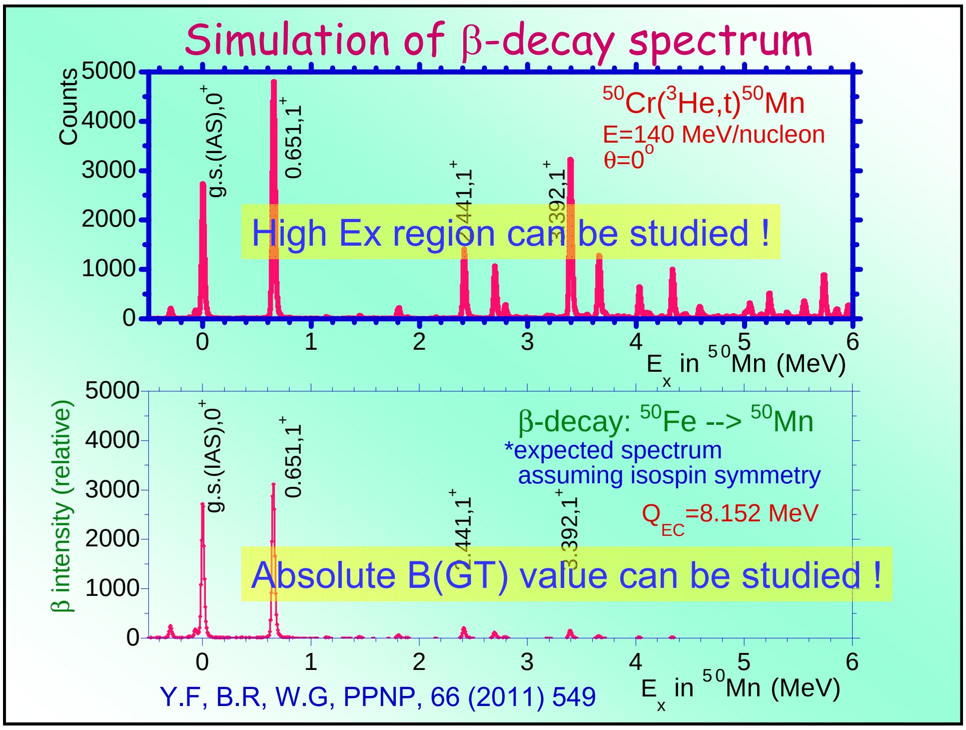
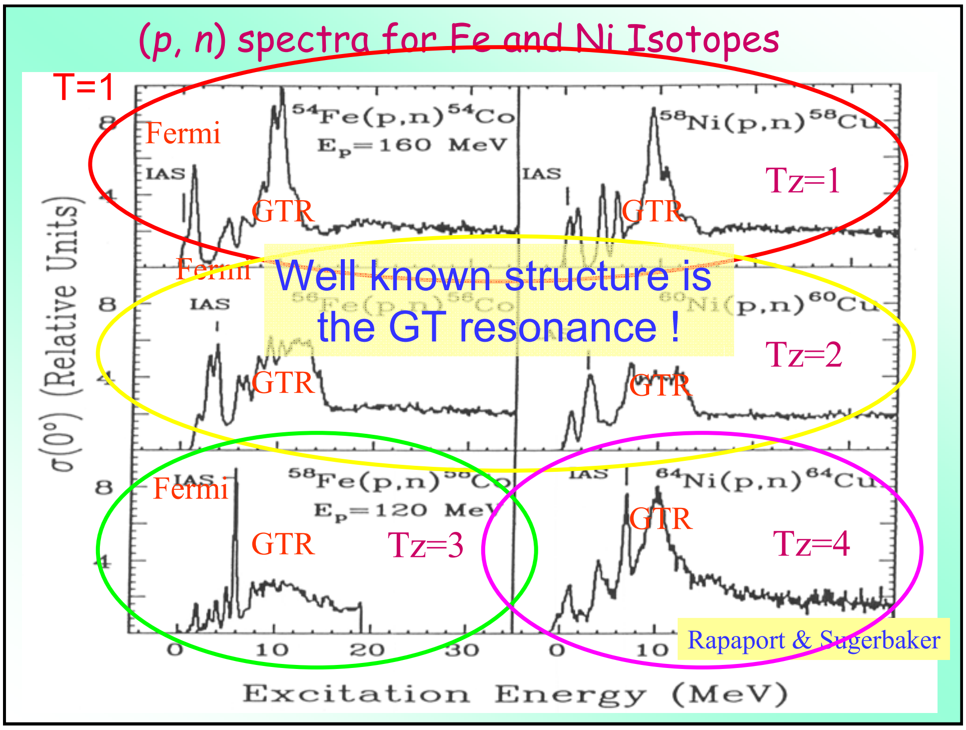
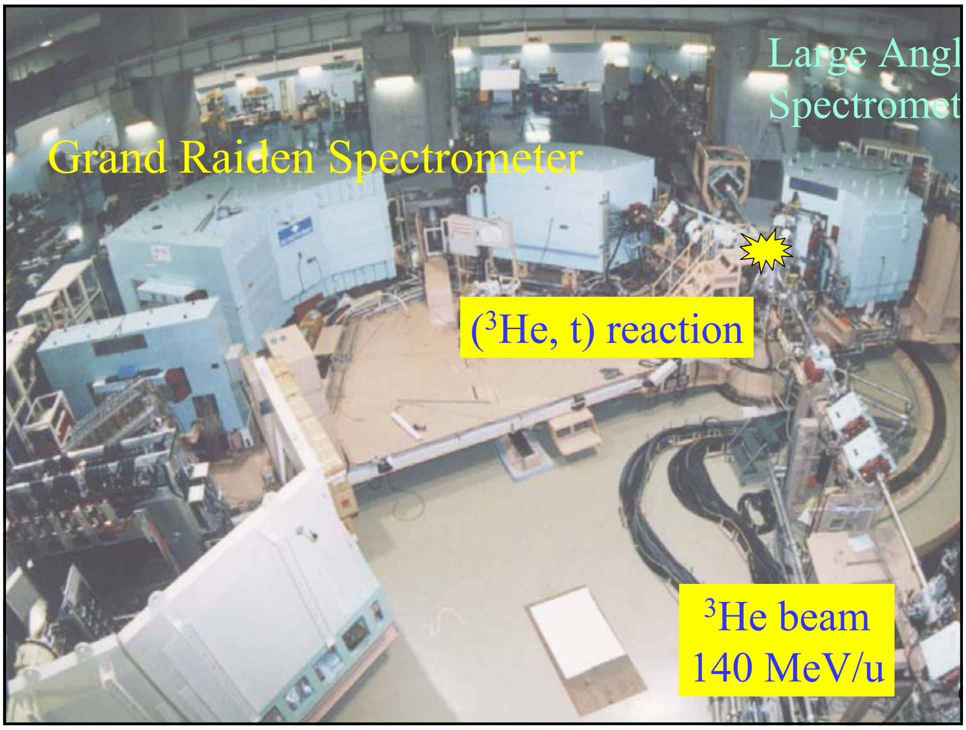
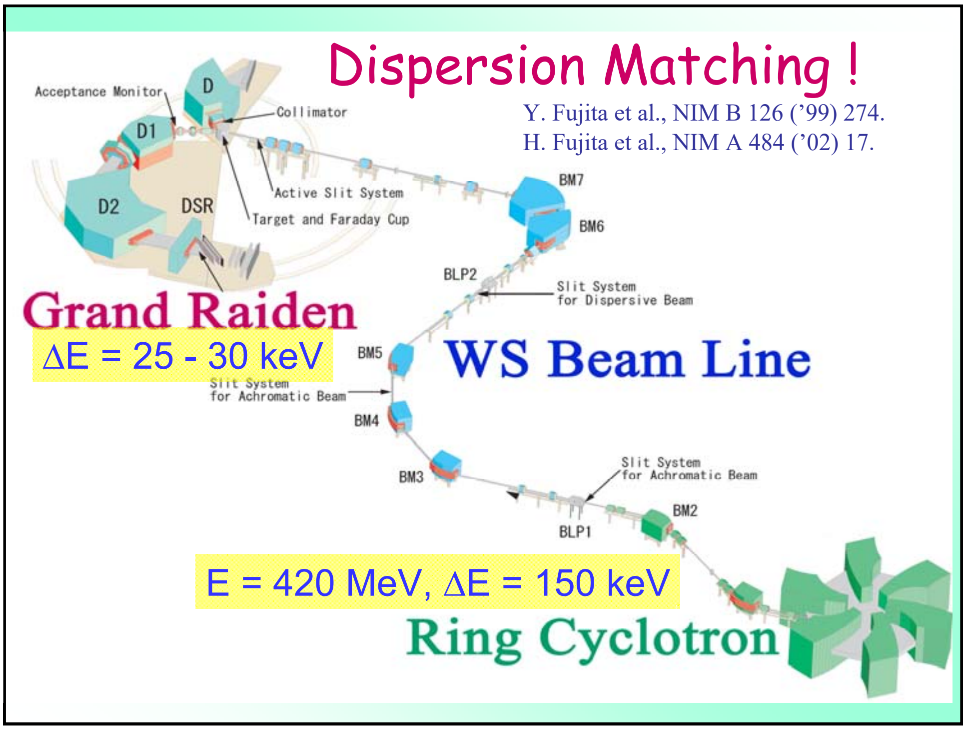
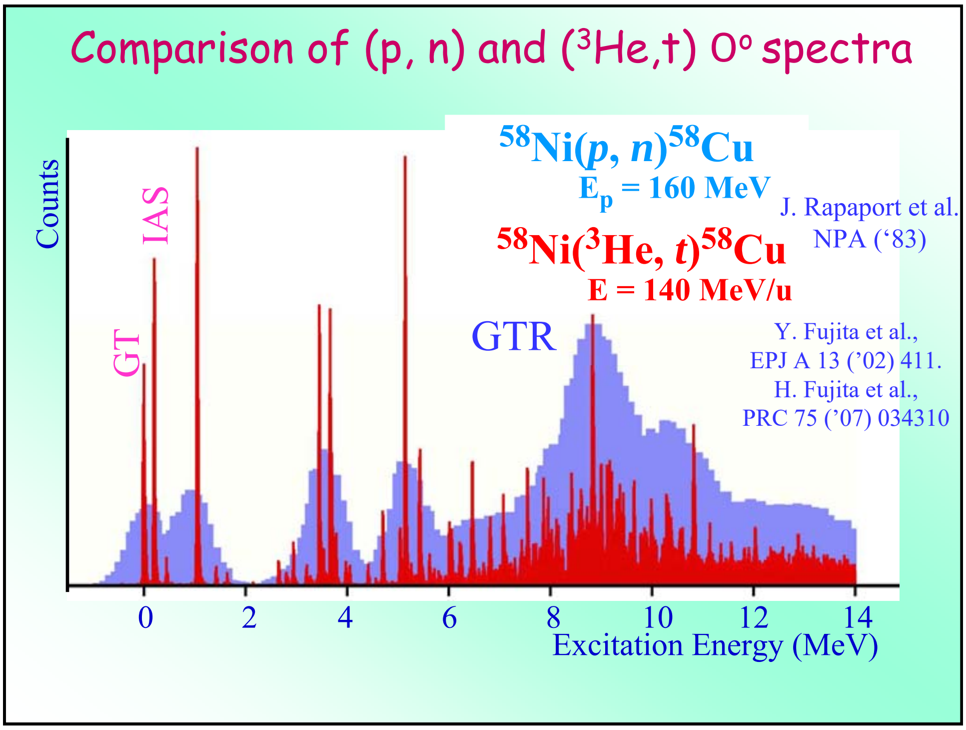

Simulation of β-decay spectrum
Counts
f-factor (normalied)
g.s.(IAS),0+
0.651,1+
2.441,1+
3.392,1+
50Cr(3He,t)50Mn
E=140 MeV/nucleon
θ=0°
QEC=8.152 MeV
Ex in 50Mn (MeV)
β intensity (relative)
β-decay: 50Fe --> 50Mn
*expected spectrum
assuming isospin symmetry
QEC=8.152 MeV
Ex in 50Mn (MeV)
Y. Fujita et al. PRL 95 (2005)


Simulation of β-decay spectrum
Counts
g.s.(IAS),0+
0.651,1+
50Cr(3He,t)50Mn
E=140 MeV/nucleon
θ=0°
High Ex region can be studied !
Ex in 50Mn (MeV)
β intensity (relative)
β-decay: 50Fe --> 50Mn
*expected spectrum
assuming isospin symmetry
QEC=8.152 MeV
Absolute B(GT) value can be studied !
Ex in 50Mn (MeV)
Y.F, B.R, W.G, PPNP, 66 (2011) 549


(p, n) spectra for Fe and Ni Isotopes
T=1
Fermi
IAS
GTR
^{54}Fe(p,n)^{54}Co
E_p=160 MeV
^{58}Ni(p,n)^{58}Cu
Tz=1
Well known structure is
the GT resonance !
^{60}Ni(p,n)^{60}Cu
Tz=2
^{58}Fe(p,n)^{58}Co
E_p=120 MeV
Tz=3
^{64}Ni(p,n)^{64}Cu
Tz=4
Rapaport & Sugerbaker
σ(0°) (Relative Units)
Excitation Energy (MeV)


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


Dispersion Matching !
Y. Fujita et al., NIM B 126 ('99) 274.
H. Fujita et al., NIM A 484 ('02) 17.
Acceptance Monitor
D
Collimator
D1
D2
DSR
Active Slit System
Target and Faraday Cup
BM7
BM6
BLP2
Slit System for Dispersive Beam
Grand Raiden
ΔE = 25 - 30 keV
BM5
WS Beam Line
Slit System for Achromatic Beam
BM4
BM3
Slit System for Achromatic Beam
BM2
BLP1
E = 420 MeV, ΔE = 150 keV
Ring Cyclotron


Comparison of (p, n) and (3He,t) 0° spectra
58Ni(p, n)58Cu
Ep = 160 MeV
J. Rapaport et al. NPA ('83)
58Ni(3He, t)58Cu
E = 140 MeV/u
Y. Fujita et al., EPJ A 13 ('02) 411.
H. Fujita et al., PRC 75 ('07) 034310
Counts
IAS
GT
GTR
0
2
4
6
8
10
12
14
Excitation Energy (MeV)

***Isospin Symmetry and Isoscalar - Isovector

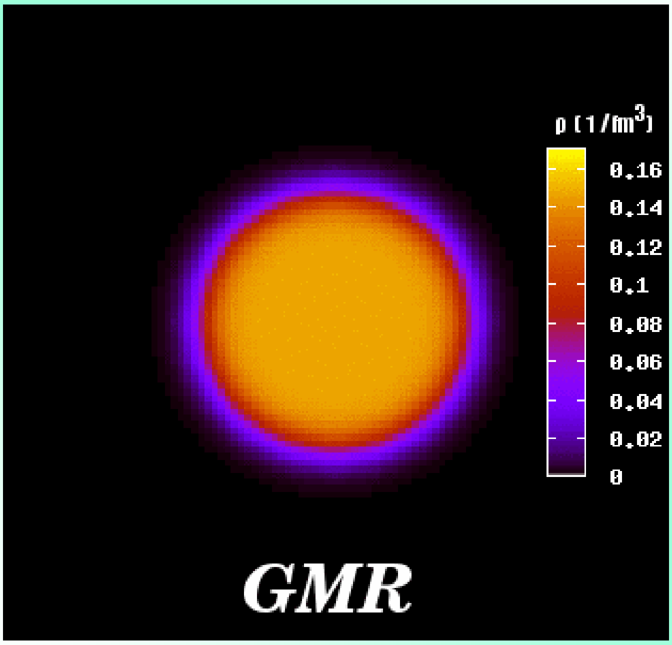
In transitions: without τ with τ operator
as a result
In structures : protons and neutron contributions are
in phase out of phase (opposite)

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.

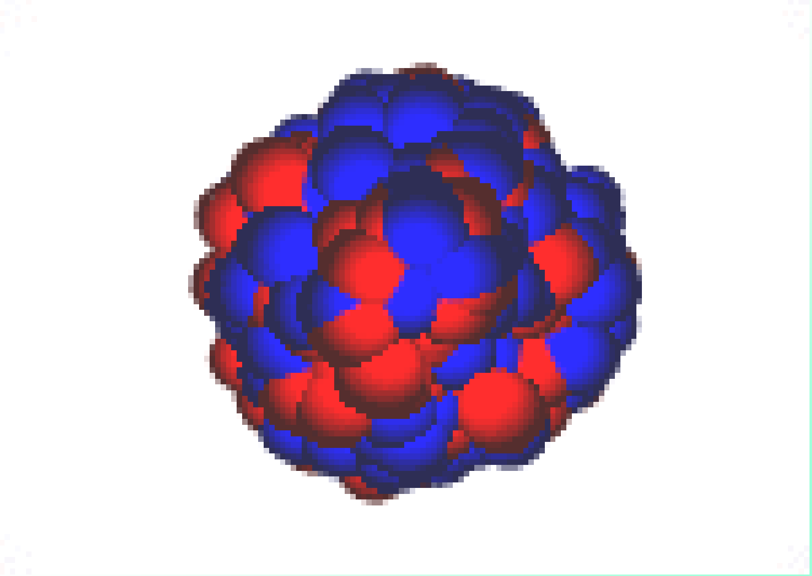
Giant Resonance (GMR)

by M. Itoh



IV Giant Monopole Resonance (IVGMR)

by P. Adrich



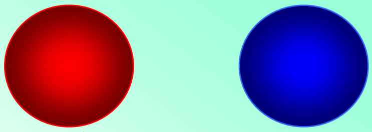
T=1/2 Isospin Symmetry

Koelner Dom
in Germany
(157m high)

Nucleon & Coin

back face

= Coin



proton neutron

= Nucleon

similar mass

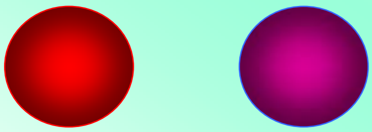
nearly the same interaction

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

Nucleus & Coin

back front

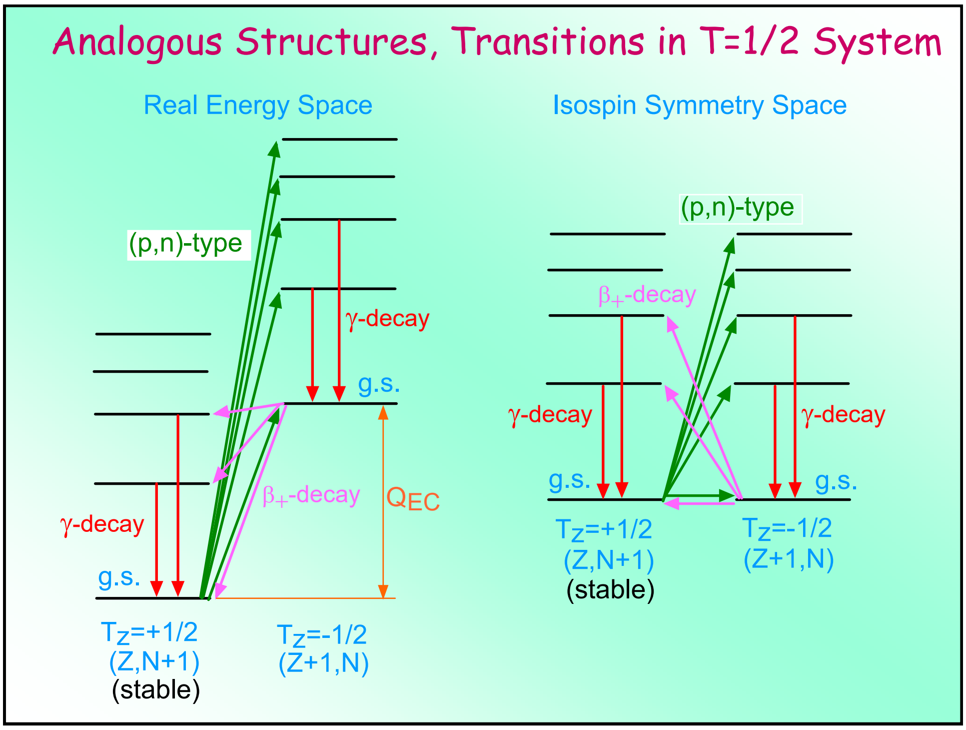
= Coin



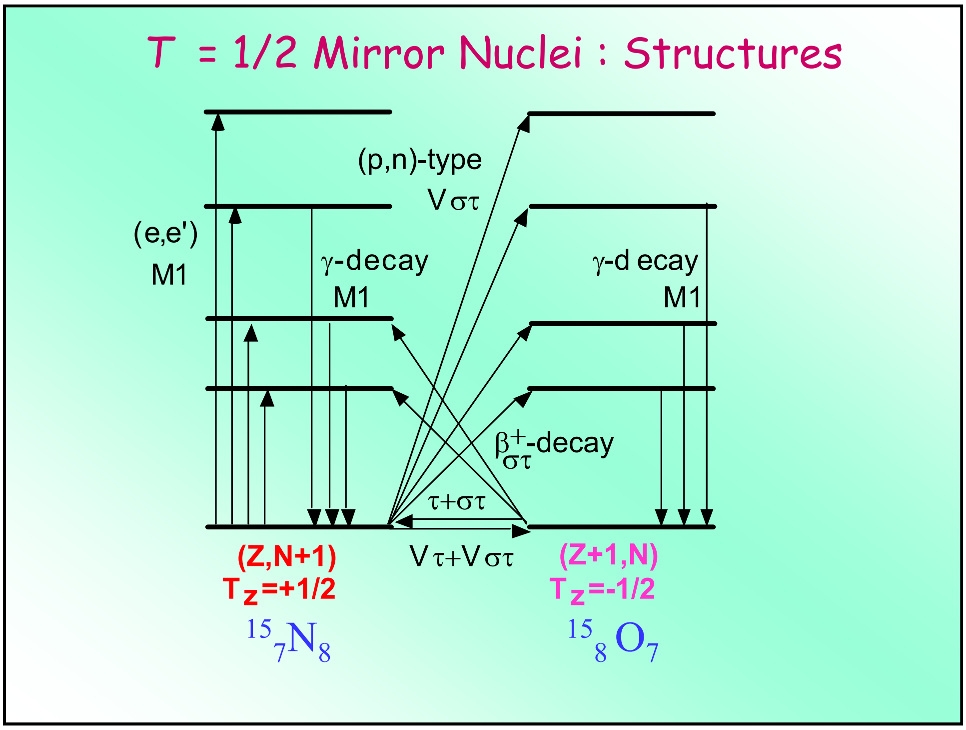
= Nuclei

$^{15}_{7}N_8$ $^{15}_{8}O_7$ $T_z = (1/2)N + (-1/2)Z$

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

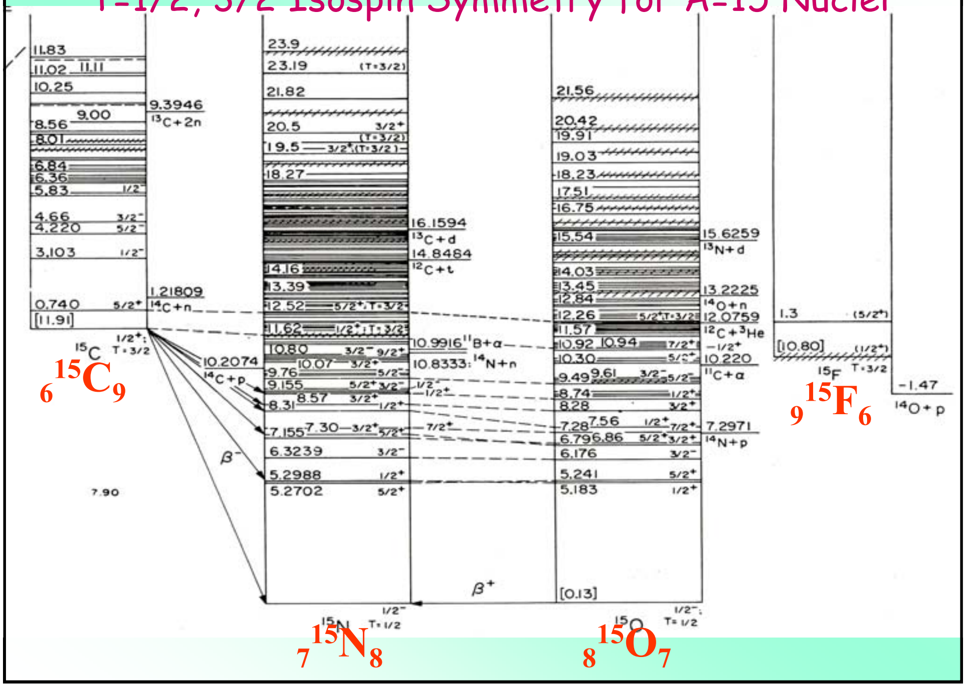


Analogous Structures, Transitions in T=1/2 System
Real Energy Space
Isospin Symmetry Space
(p,n)-type
γ-decay
g.s.
β+-decay
QEC
Tz=+1/2
(Z,N+1)
(stable)
Tz=-1/2
(Z+1,N)

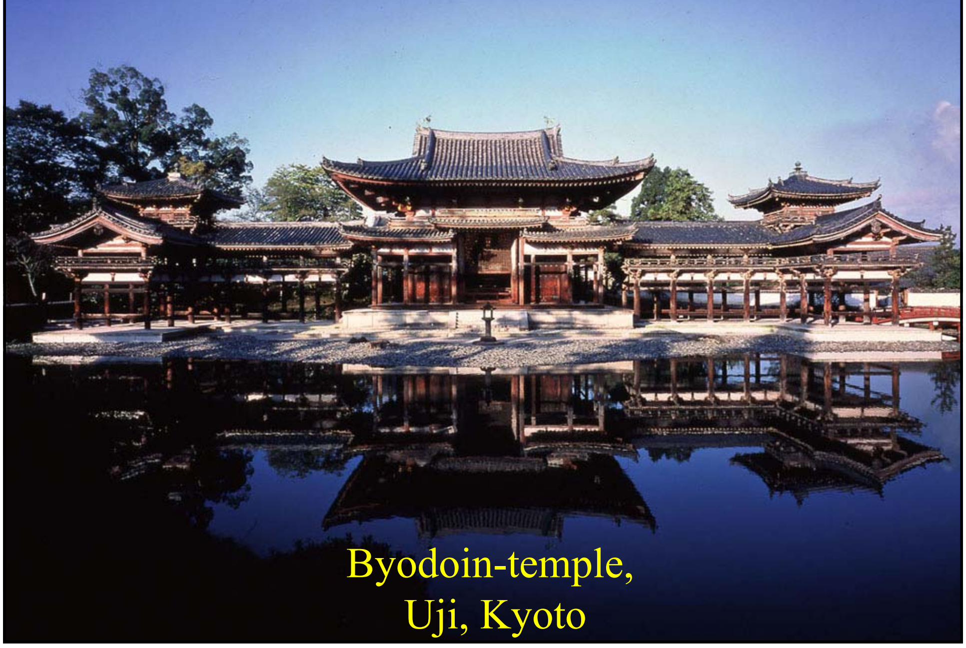


T = 1/2 Mirror Nuclei : Structures
(p,n)-type
Vστ
(e,e')
M1
γ-decay
M1
γ-d ecay
M1
β+στ-decay
τ+στ
Vτ+Vστ
(Z,N+1)
Tz=+1/2
15 7N8
(Z+1,N)
Tz=-1/2
15 8 O7

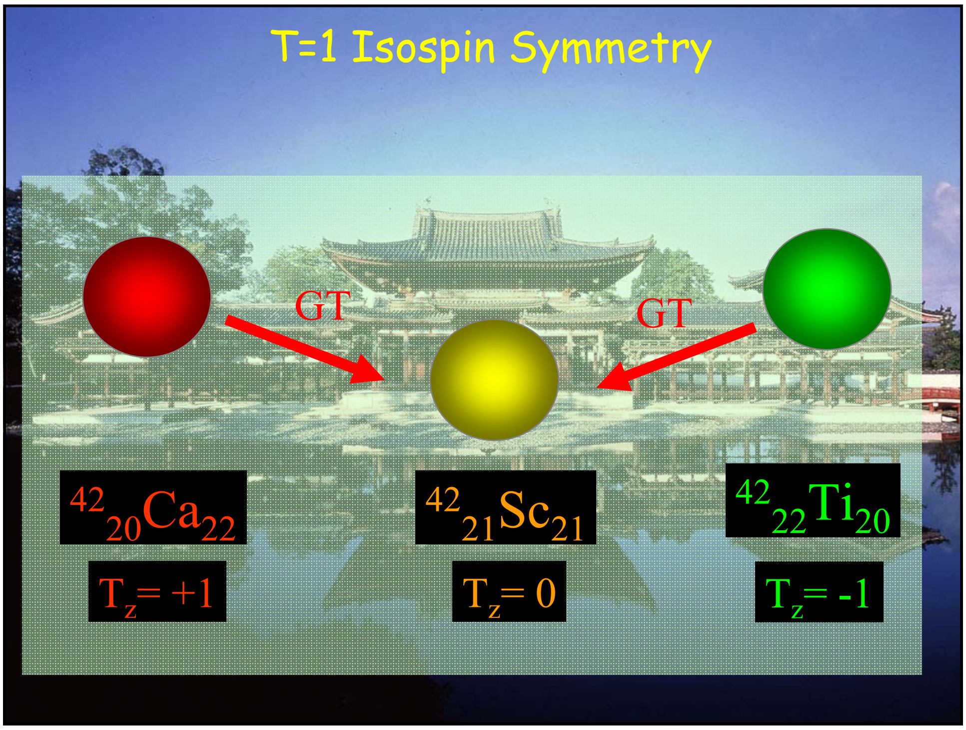
T=1/2, 3/2 Isospin Symmetry for A=15 Nuclei

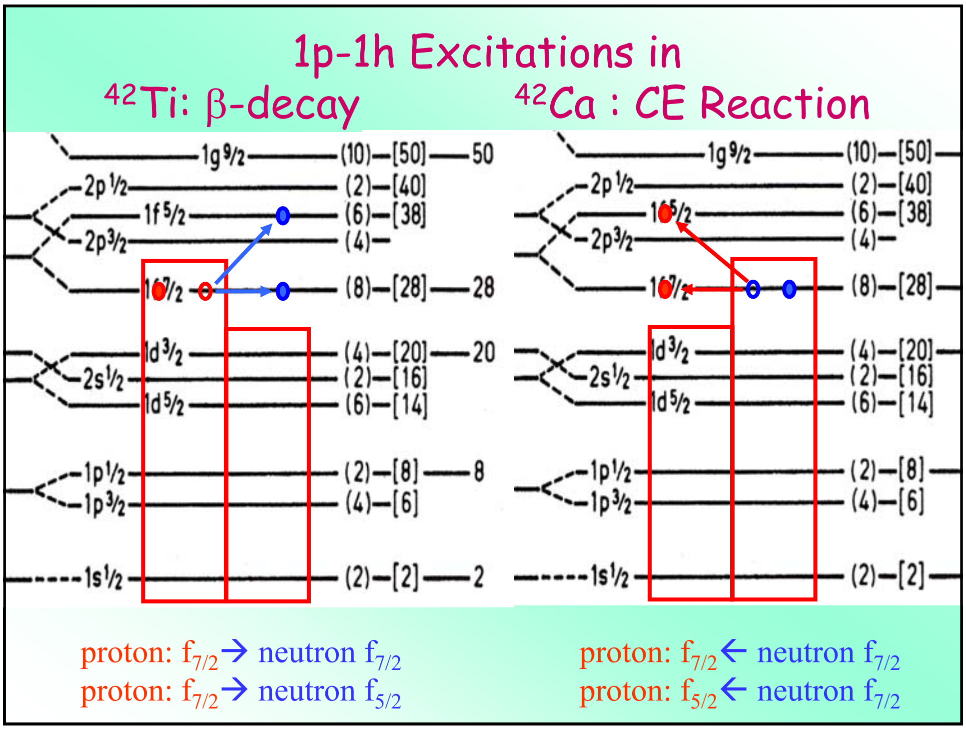


T=1 Isospin Symmetry



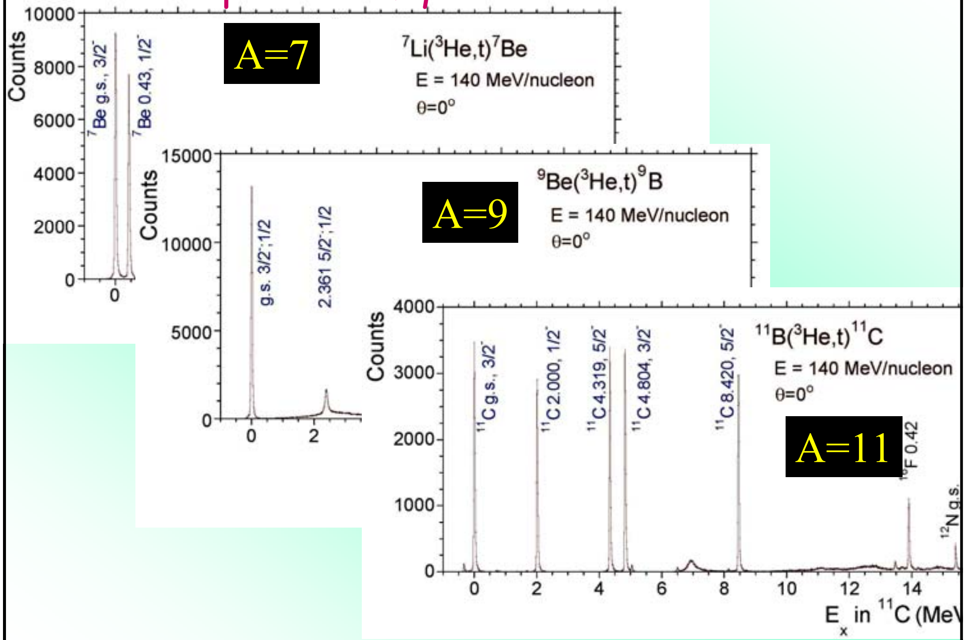
Byodoin-temple,
Uji, Kyoto


T=1 Isospin Symmetry
GT
GT
$^{42}_{20}Ca_{22}$
$^{42}_{21}Sc_{21}$
$^{42}_{22}Ti_{20}$
$T_z = +1$
$T_z = 0$
$T_z = -1$

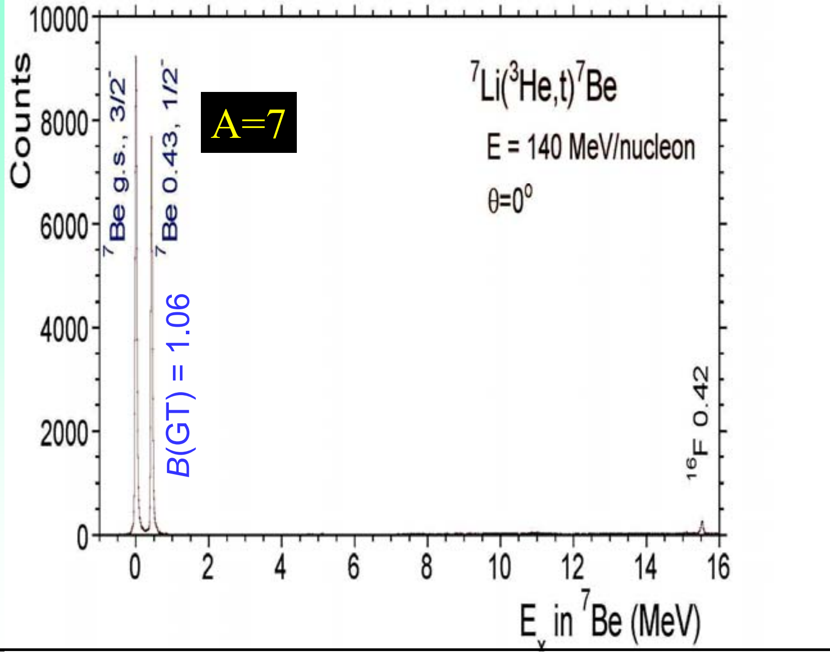

1p-1h Excitations in
^{42}Ti: β-decay
^{42}Ca : CE Reaction
proton: $f_{7/2}$→ neutron $f_{7/2}$
proton: $f_{7/2}$→ neutron $f_{5/2}$
proton: $f_{7/2}$← neutron $f_{7/2}$
proton: $f_{5/2}$← neutron $f_{7/2}$

*** GT transitions
in T = 1/2
A = 7, 9, 11 mirror nuclei

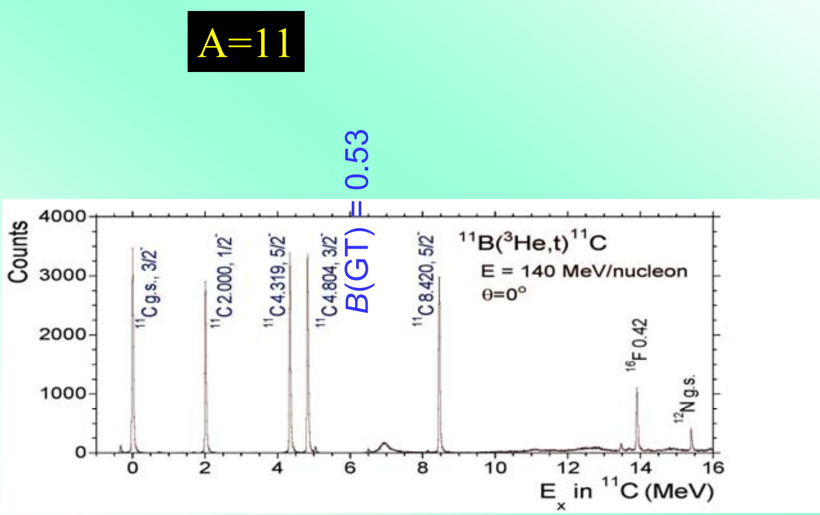
Spectra of *p*-shell Mirror Nuclei



B(GT) - normalized Spectra



B(GT) - normalized Spectra

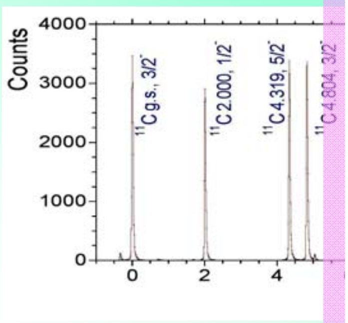


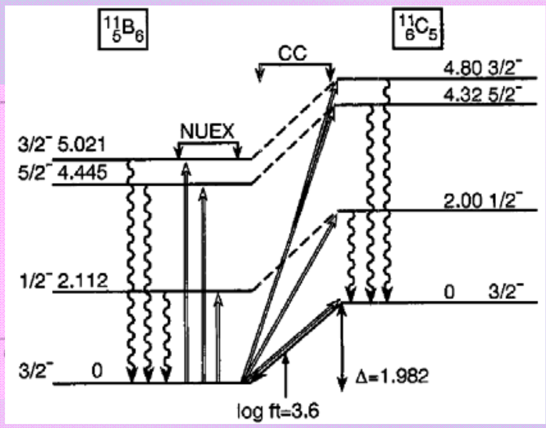
B(GT) - normalized Spectra

A=11

BOREX:

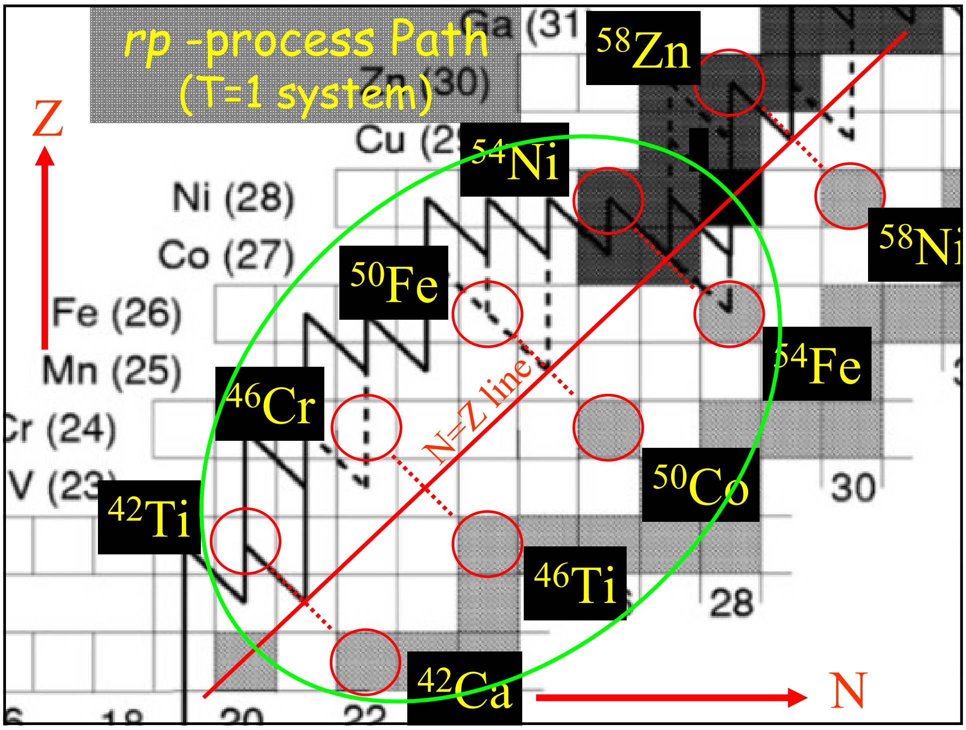
a program to study
Solar neutrino via weak
Neutral & Charged currents

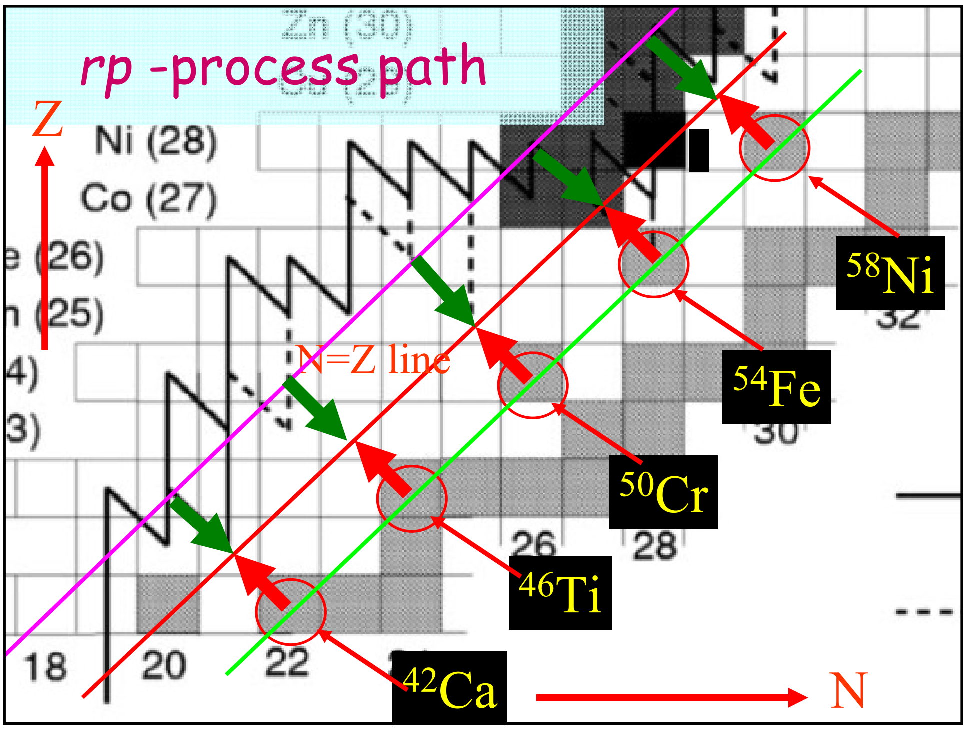




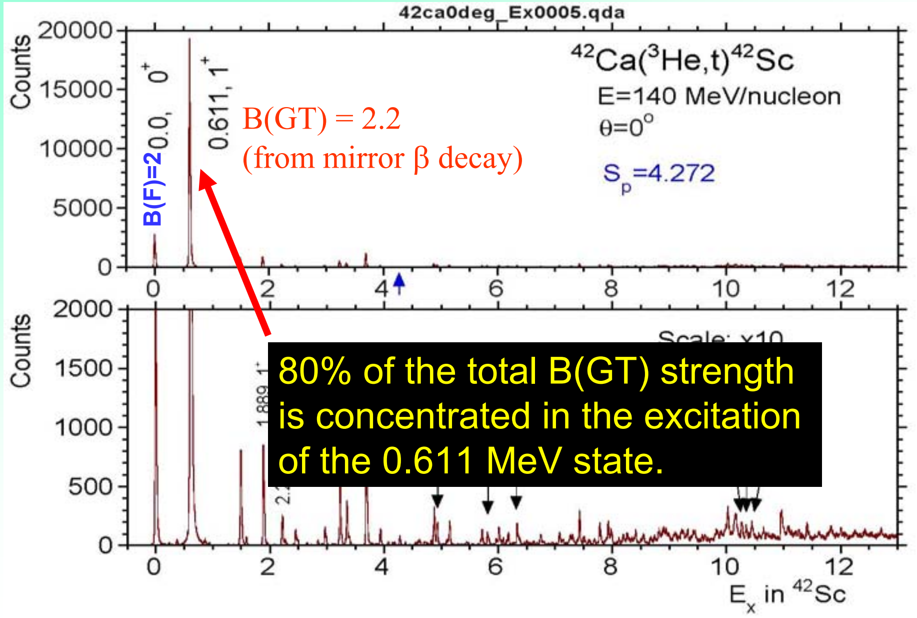
**GT transitions in each nucleus are UNIQUE !

- *pf*-shell nuclei -

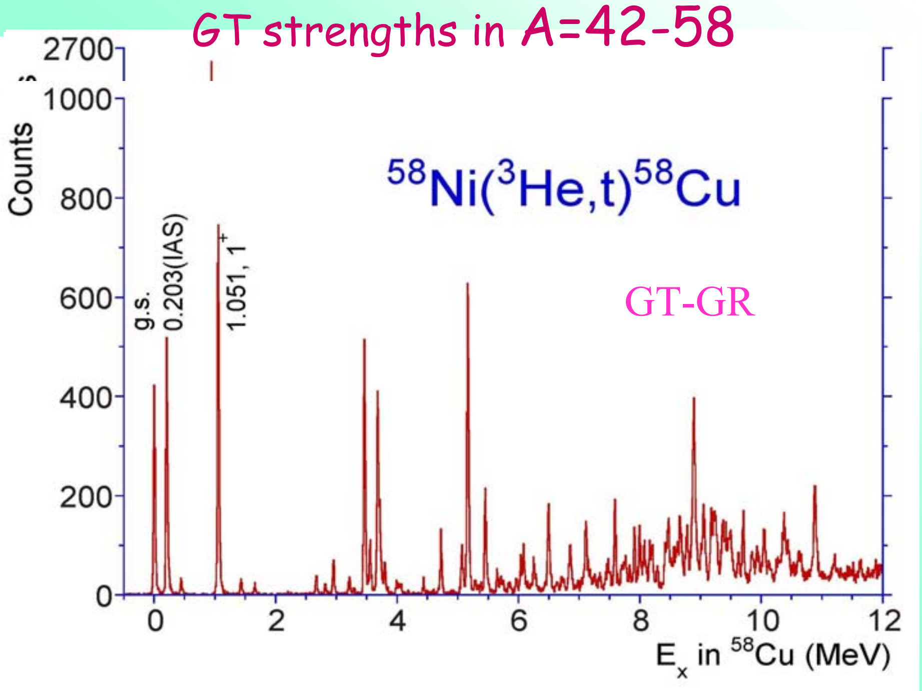

rp -process Path
(T=1 system)
Z
N
N=Z line
Ga (31)
Zn (30)
Cu (29)
Ni (28)
Co (27)
Fe (26)
Mn (25)
Cr (24)
V (23)
58Zn
54Ni
58Ni
50Fe
54Fe
46Cr
50Co
42Ti
46Ti
42Ca
18
20
22
28
30


rp -process path
Zn (30)
Cu (29)
Z
N
Ni (28)
Co (27)
N=Z line
58Ni
54Fe
50Cr
46Ti
42Ca
18
20
22
26
28
30
32

$^{42}Ca(^3He,t)^{42}Sc$ in 2 scales



GT strengths in A=42-58



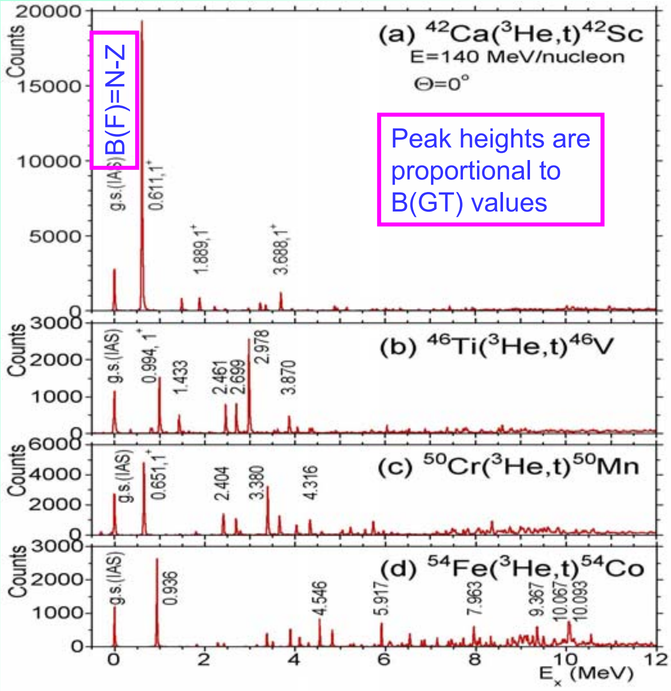
GT states in A=42-54 T_z=0 nuclei

Y. Fujita et al.
PRL 2014
PRC 2015

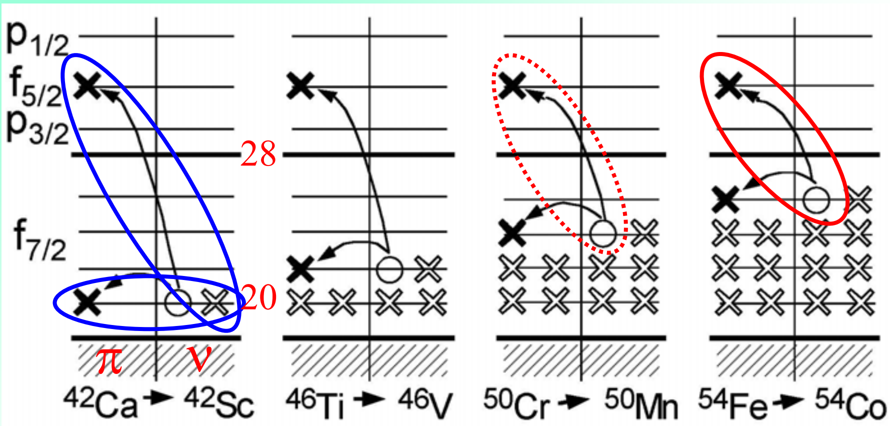
T. Adachi et al.
PRC 2006

Y. Fujita et al.
PRL 2005

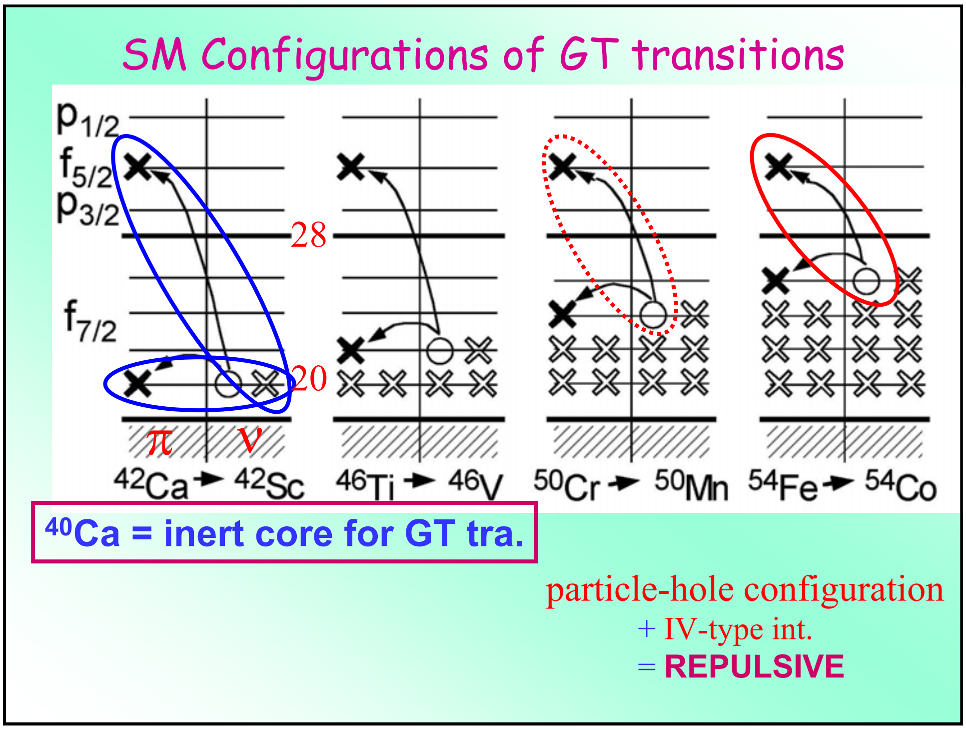
T. Adachi et al.
PRC 2012

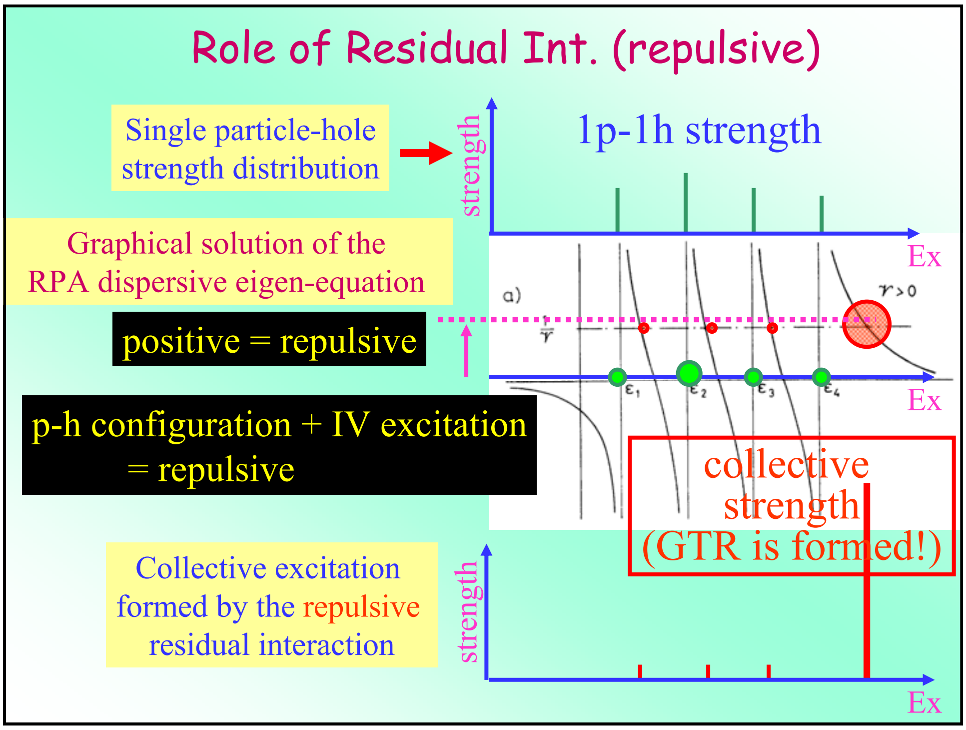


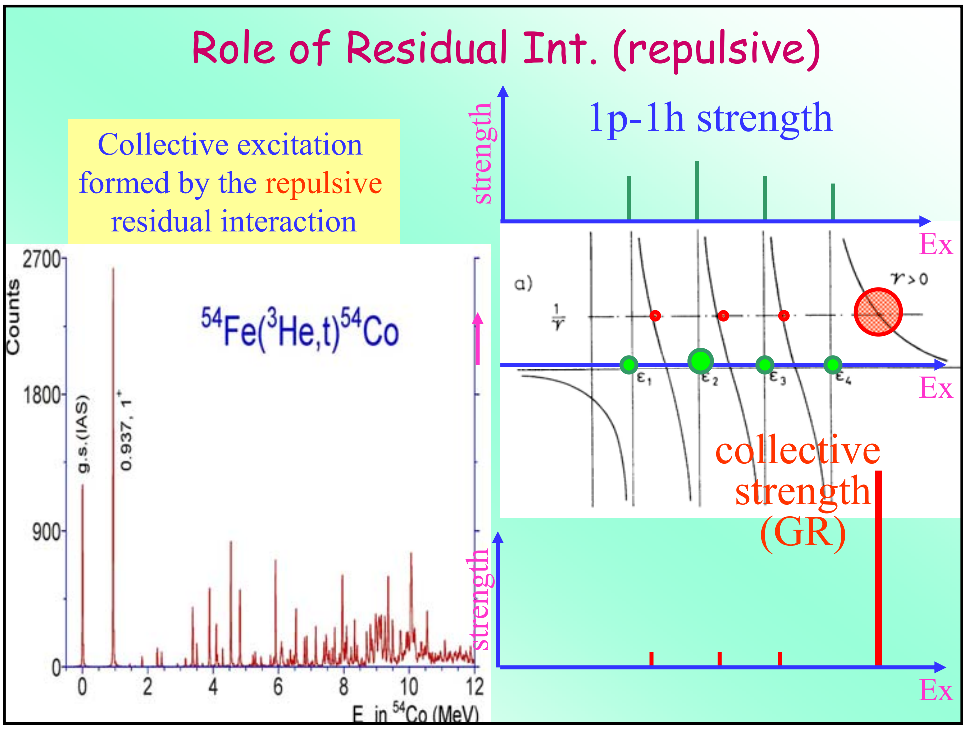
SM Configurations of GT transitions

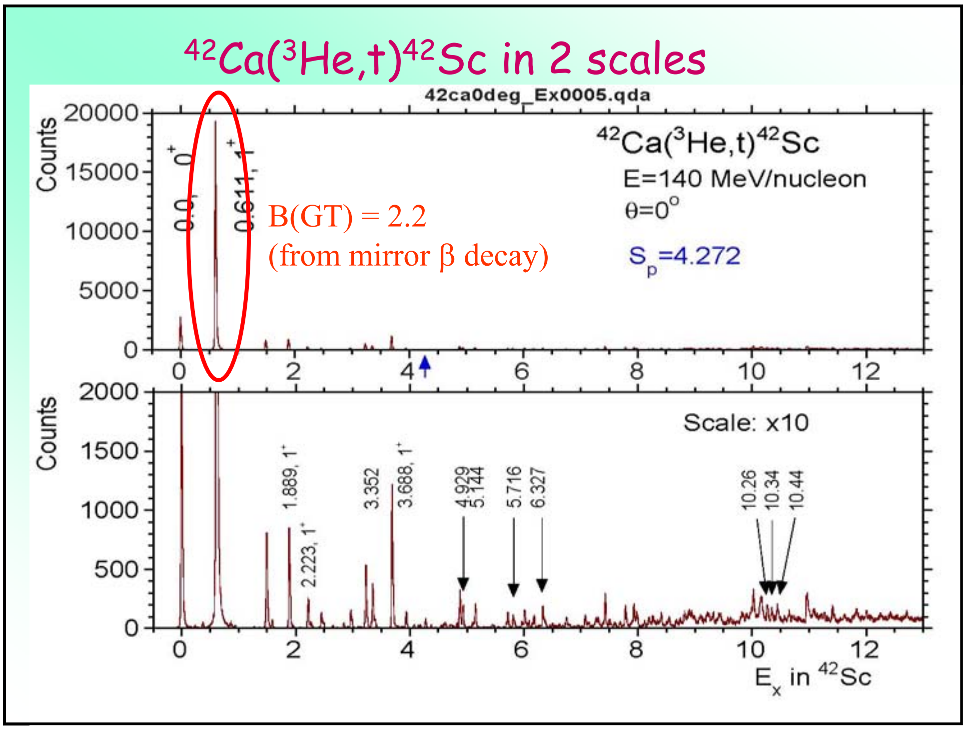


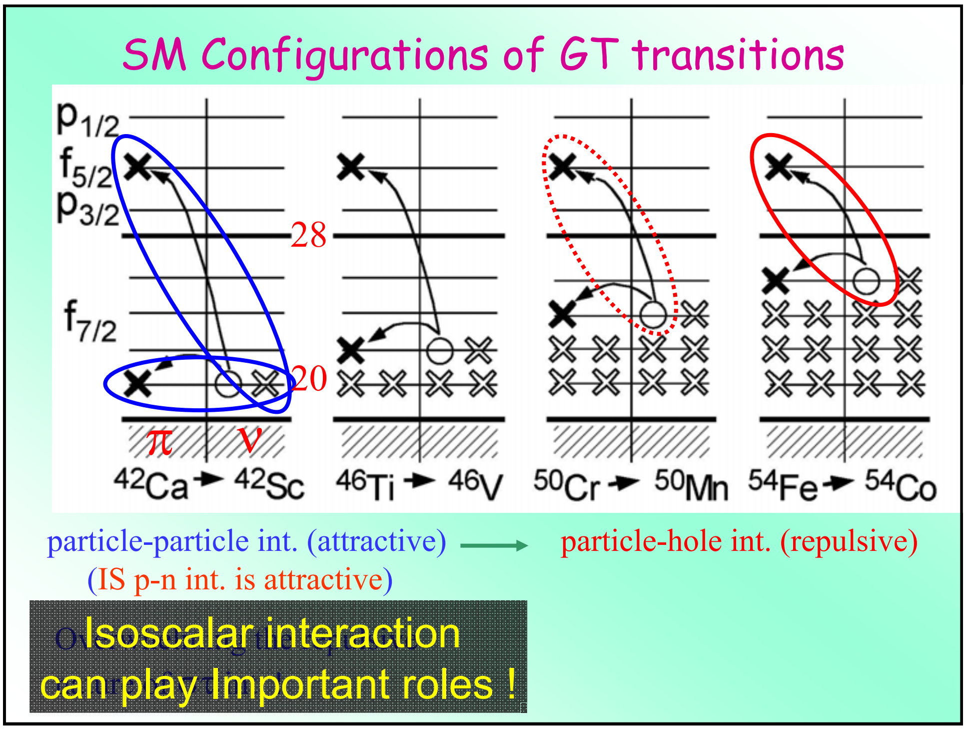
Target nuclei: $N = Z + 2$ ($T_z = +1$)
Final nuclei : $N = Z$ ($T_z = 0$)

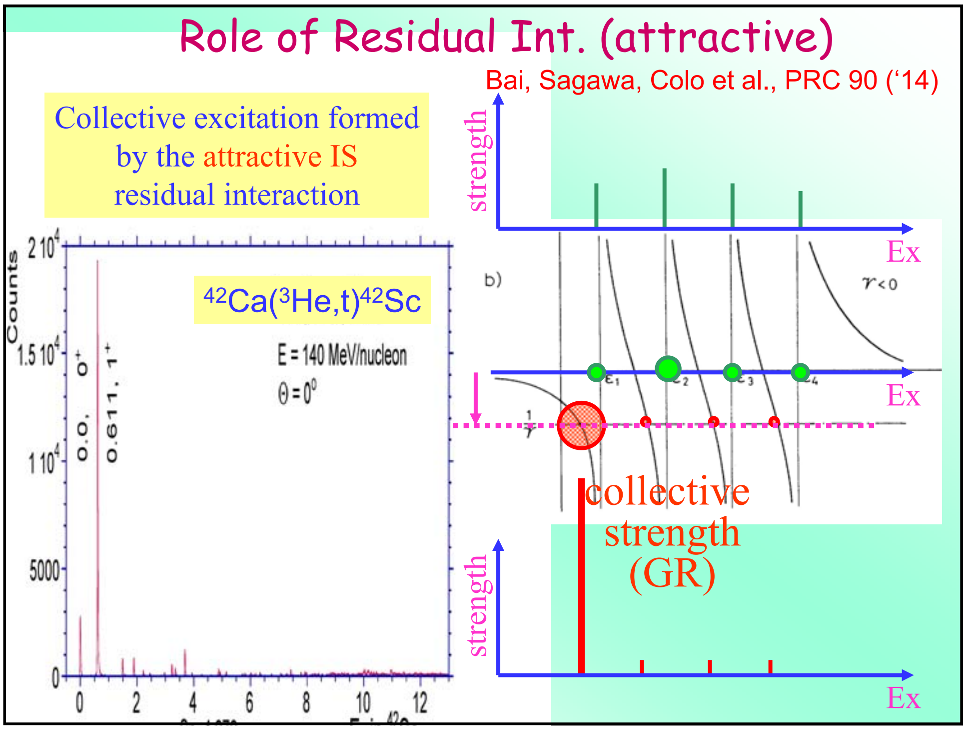

SM Configurations of GT transitions
p1/2
f5/2
p3/2
f7/2
28
20
π
ν
42Ca → 42Sc
46Ti → 46V
50Cr → 50Mn
54Fe → 54Co
40Ca = inert core for GT tra.
particle-hole configuration
+ IV-type int.
= REPULSIVE

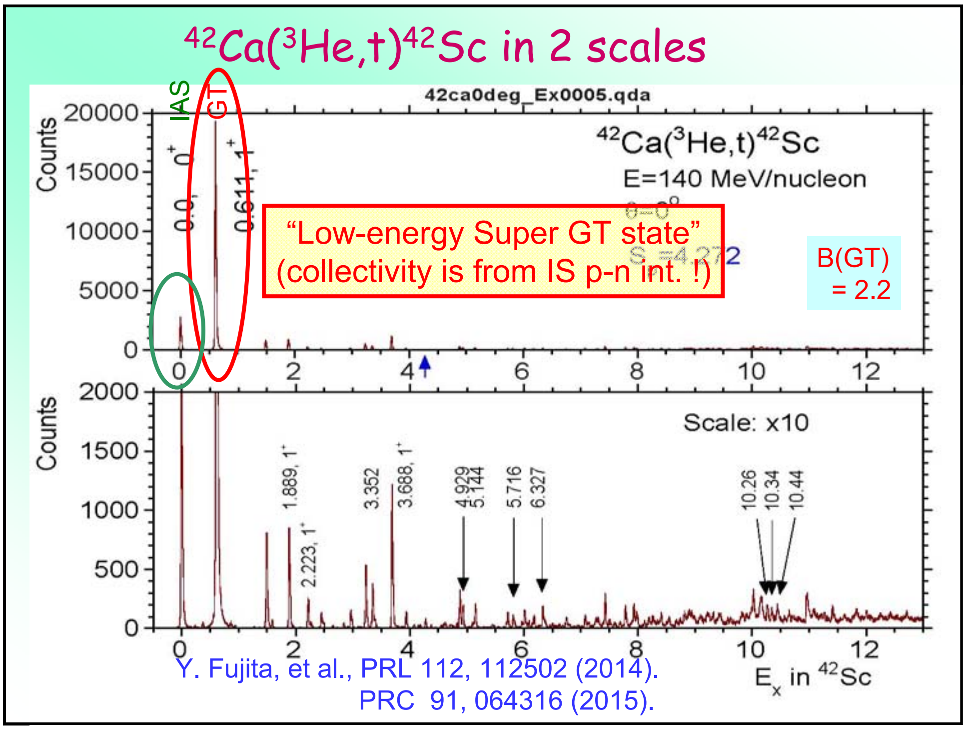

Role of Residual Int. (repulsive)
Single particle-hole
strength distribution
strength
1p-1h strength
Ex
Graphical solution of the
RPA dispersive eigen-equation
positive = repulsive
p-h configuration + IV excitation
= repulsive
collective
strength
(GTR is formed!)
Collective excitation
formed by the repulsive
residual interaction
strength
Ex


Role of Residual Int. (repulsive)
Collective excitation formed by the repulsive residual interaction
1p-1h strength
strength
Ex
a)
γ > 0
1/γ
ε1 ε2 ε3 ε4
Ex
collective strength (GR)
strength
Ex
54Fe(3He,t)54Co
Counts
2700
1800
900
0
g.s.(IAS)
0.937, 1+
0 2 4 6 8 10 12
E in 54Co (MeV)

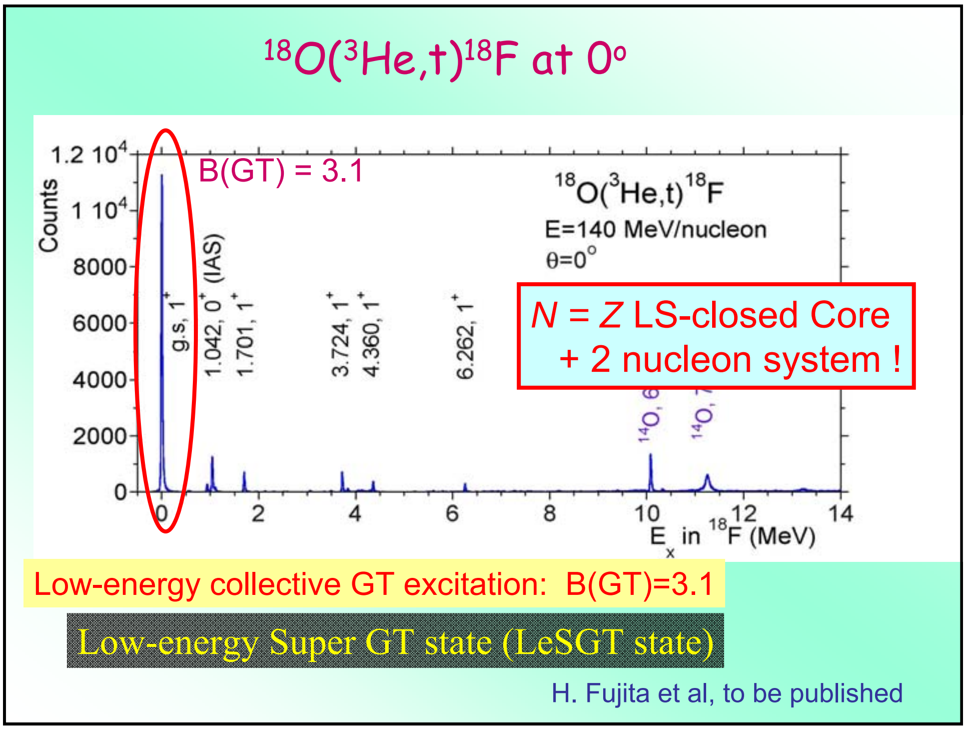

42Ca(3He,t)42Sc in 2 scales
42ca0deg_Ex0005.qda
42Ca(3He,t)42Sc
E=140 MeV/nucleon
θ=0°
Sp=4.272
B(GT) = 2.2
(from mirror β decay)
0.0, 0+
0.611, 1+
Counts
20000
15000
10000
5000
0
0 2 4 6 8 10 12
Counts
2000
1500
1000
500
0
Scale: x10
1.889, 1+
2.223, 1+
3.352
3.688, 1+
4.929
5.144
5.716
6.327
10.26
10.34
10.44
0 2 4 6 8 10 12
Ex in 42Sc


SM Configurations of GT transitions
p1/2
f5/2
p3/2
f7/2
28
20
π
ν
42Ca → 42Sc
46Ti → 46V
50Cr → 50Mn
54Fe → 54Co
particle-particle int. (attractive)
particle-hole int. (repulsive)
(IS p-n int. is attractive)
Isoscalar interaction
can play Important roles !

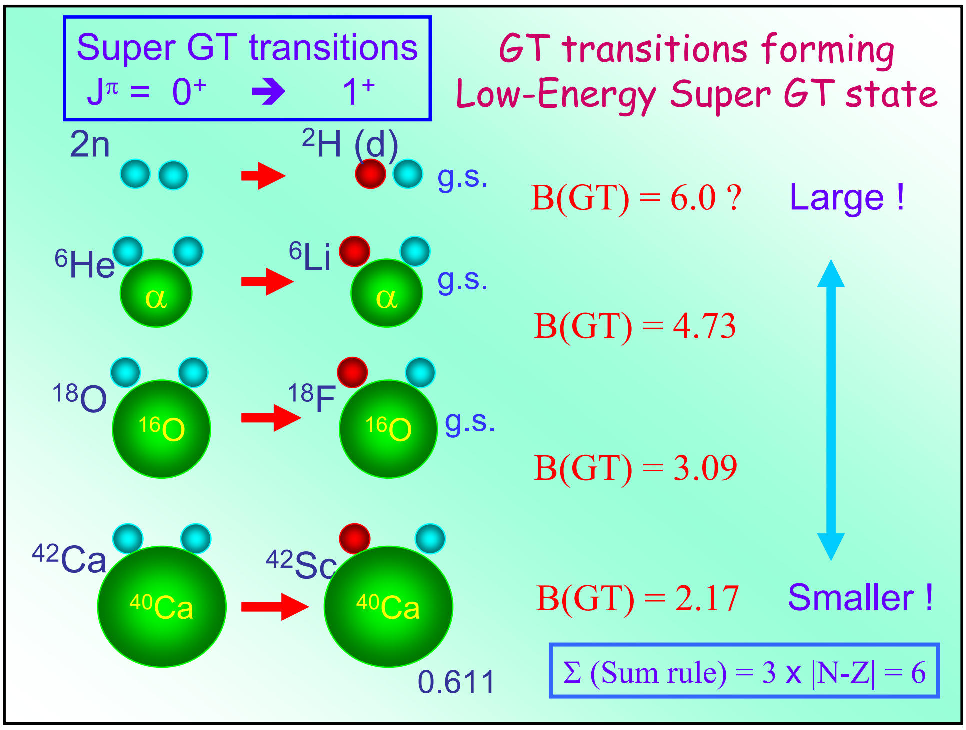

Role of Residual Int. (attractive)
Bai, Sagawa, Colo et al., PRC 90 ('14)
Collective excitation formed
by the attractive IS
residual interaction
42Ca(3He,t)42Sc
E = 140 MeV/nucleon
Θ = 0°
Counts
0.0, 0+
0.611, 1+
strength
Ex
b)
collective
strength
(GR)

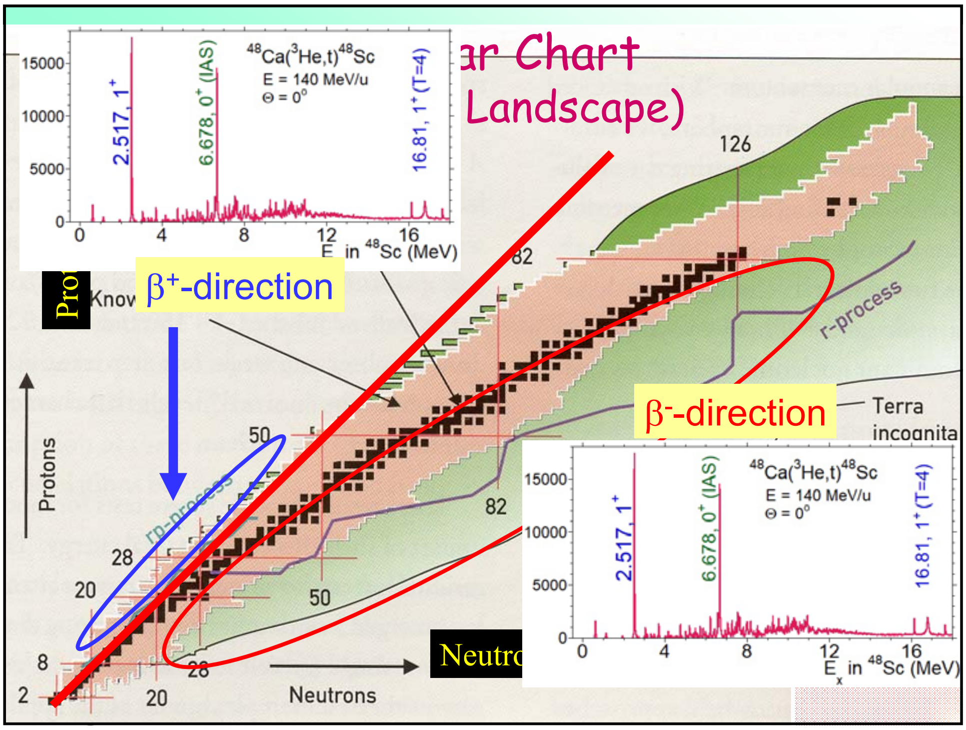


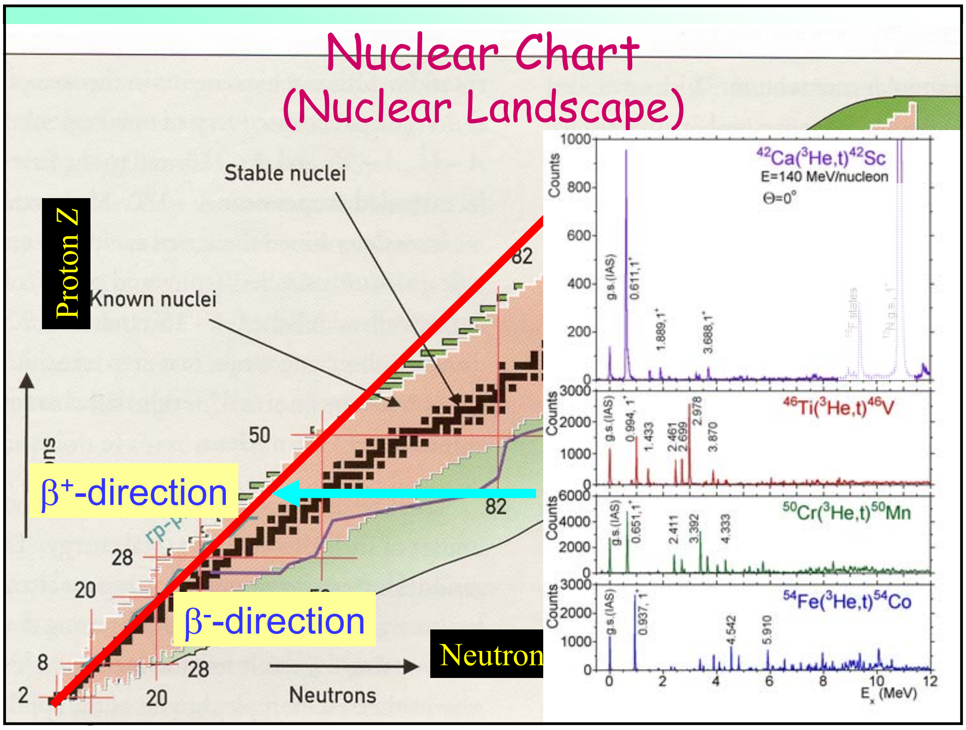
42Ca(3He,t)42Sc in 2 scales
42ca0deg_Ex0005.qda
IAS
GT
42Ca(3He,t)42Sc
E=140 MeV/nucleon
“Low-energy Super GT state”
(collectivity is from IS p-n int. !)
B(GT) = 2.2
Counts
Scale: x10
1.889, 1+
2.223, 1+
3.352
3.688, 1+
4.929
5.144
5.716
6.327
10.26
10.34
10.44
Ex in 42Sc
Y. Fujita, et al., PRL 112, 112502 (2014).
PRC 91, 064316 (2015).

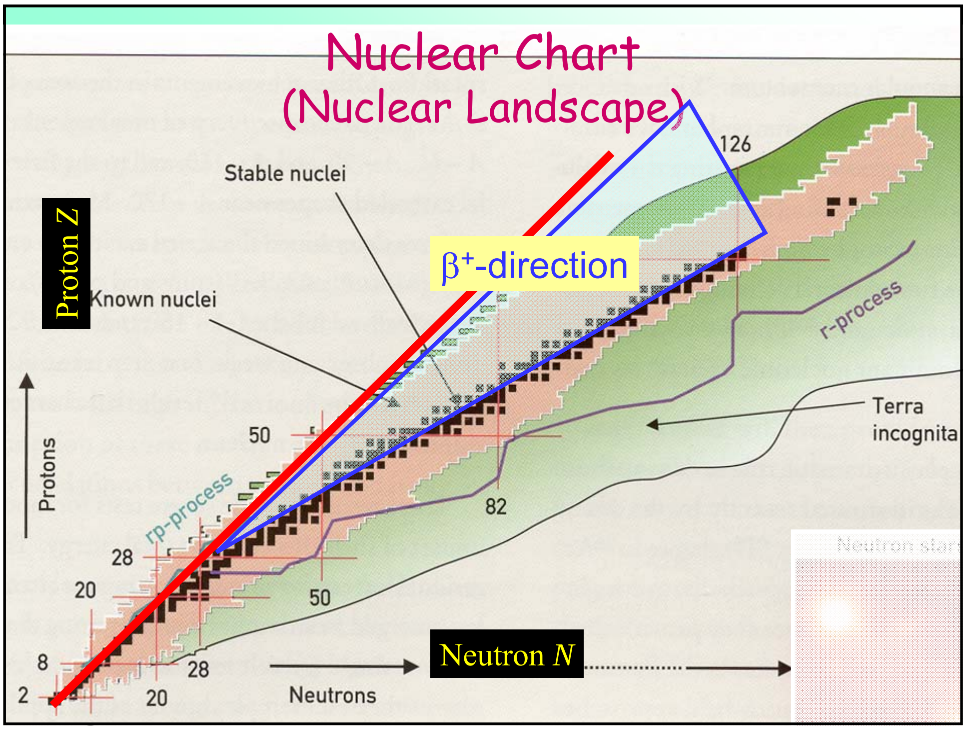


18O(3He,t)18F at 0°
B(GT) = 3.1
18O(3He,t)18F
E=140 MeV/nucleon
θ=0°
Counts
g.s, 1+
1.042, 0+ (IAS)
1.701, 1+
3.724, 1+
4.360, 1+
6.262, 1+
N = Z LS-closed Core
+ 2 nucleon system !
Ex in 18F (MeV)
Low-energy collective GT excitation: B(GT)=3.1
Low-energy Super GT state (LeSGT state)
H. Fujita et al, to be published


Super GT transitions
Jπ = 0+ ➔ 1+
GT transitions forming
Low-Energy Super GT state
2n
2H (d)
g.s.
B(GT) = 6.0 ?
Large !
6He
α
6Li
α
g.s.
B(GT) = 4.73
18O
16O
18F
16O
g.s.
B(GT) = 3.09
42Ca
40Ca
42Sc
40Ca
0.611
B(GT) = 2.17
Smaller !
Σ (Sum rule) = 3 x |N-Z| = 6

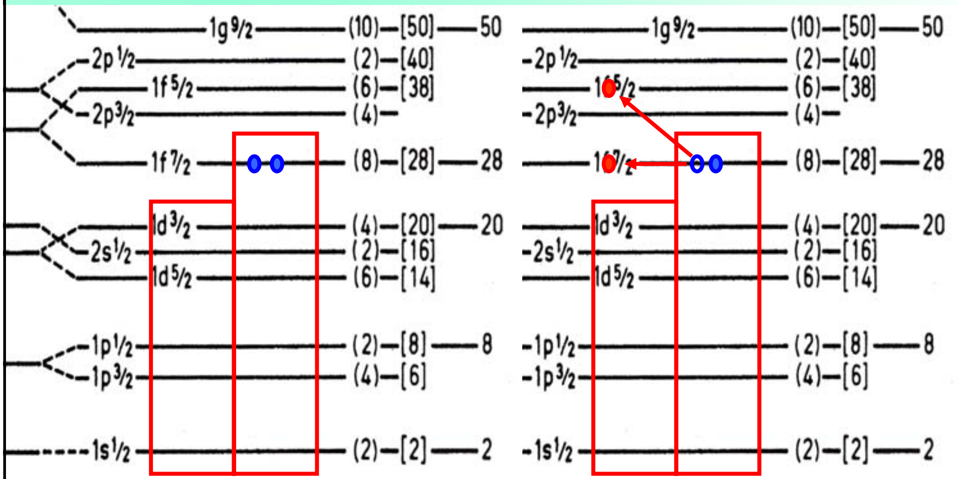

ar Chart
Landscape)
48Ca(3He,t)48Sc
E = 140 MeV/u
Θ = 0°
2.517, 1+
6.678, 0+ (IAS)
16.81, 1+ (T=4)
15000
10000
5000
0
0
4
8
12
16
Ex in 48Sc (MeV)
β+-direction
β--direction
126
82
50
82
28
20
50
8
2
28
20
Protons
Neutrons
rp-process
r-process
Terra
incognita


Nuclear Chart
(Nuclear Landscape)
Stable nuclei
Known nuclei
Proton Z
β+-direction
β--direction
Neutron
Neutrons
82
50
28
20
8
2
42Ca(3He,t)42Sc
E=140 MeV/nucleon
Θ=0°
46Ti(3He,t)46V
50Cr(3He,t)50Mn
54Fe(3He,t)54Co
Counts
Ex (MeV)


Nuclear Chart
(Nuclear Landscape)
Stable nuclei
Known nuclei
Proton Z
Protons
β+-direction
rp-process
r-process
Terra
incognita
126
82
50
28
20
8
2
Neutron N
Neutrons
Neutron stars

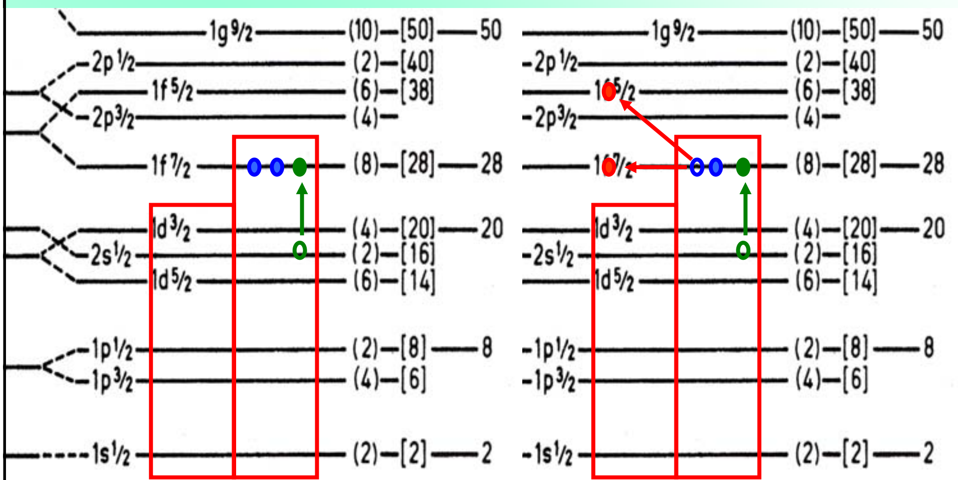
Brink-Axel Hypothesis (I)

^{42}Ca g.s. ^{42}Ca g.s.+ GT Ex.



Brink-Axel Hypothesis (II)

^{42}Ca Ex. ^{42}Ca Ex.+ GT Ex.



The same structure is expected on top of the excited state !

Summary

GT ($\sigma\tau$) operator : a simple operator !

**GT transitions: small number of configurations can participate
**GT transitions: sensitive to the structure of |i> and |f>

High resolution of the (^{3}He,t) reaction

**Fine structures of GT transitions

➔ Fine structure of GT-Resonances

➔ Low-energy Super GT state (LeSGT state)

➔ We started to get the Overview of GT response

We found that the combined understanding of LeSGT state and GTR structure was important !

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Review

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

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