Nuclear Physics Revealed by the study of Gamow-Teller excitations

ガモフ･テラー遷移の研究から見える原子核物理

Yoshitaka FUJITA

RCNP & Dept. Phys., Osaka Univ.

つくば不安定核セミナー January 21, 2016

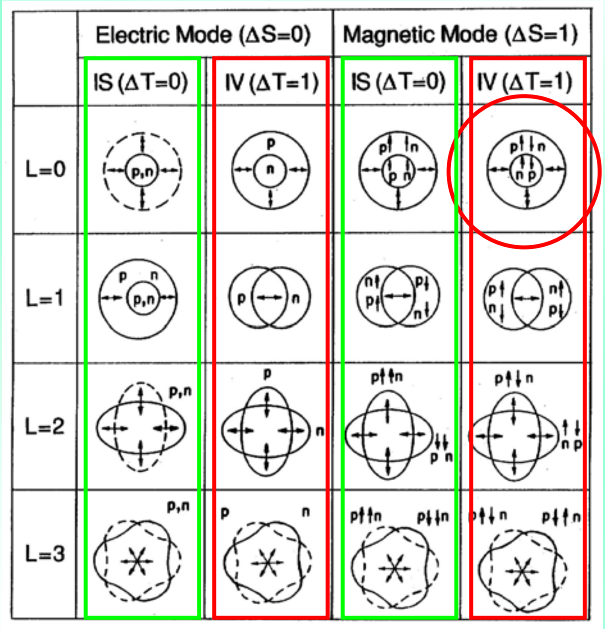
Neptune driving Waves

Neptune = weak interaction

Neptune and the waves, or "steeds," he rides.

_ Walter Crane, 1892

Vibration Modes in Nuclei (Schematic)



Gamow-Teller mode

($\sigma\tau$)

Isovector
&
Spin
excitation

Gamow-Teller transitions

Mediated by $\sigma\tau$ 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 $f_{7/2} \rightarrow f_{7/2}$, $f_{5/2} \rightarrow f_{5/2}$, $f_{7/2} \leftrightarrow f_{5/2}$

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 !

**Basic common understanding of β-decay and Charge-Exchange reaction

β decays :

Absolute B(GT) values,

but usually the study is limited to low-lying states

(p,n), (^{3}He,t) reaction at 0^{o} :

Relative B(GT) values, but Highly Excited States

** Both are important for the study of GT transitions!

β-decay & CE 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 = $|\langle f|\sigma\tau|i\rangle|^2$

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

= reaction mechanism

⊗ operator

⊗ structure

=(matrix element)^2

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 = |<f|στ|i>|^2

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

= reaction mechanism

⊗ operator

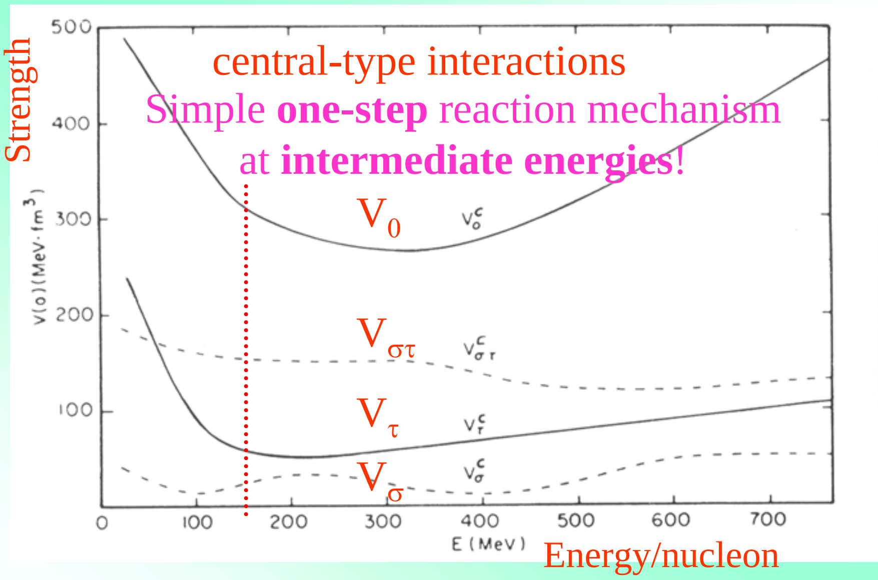
⊗ structure

=(matrix element)^2

*At intermediate energies (100 < E_{in} < 500 MeV)

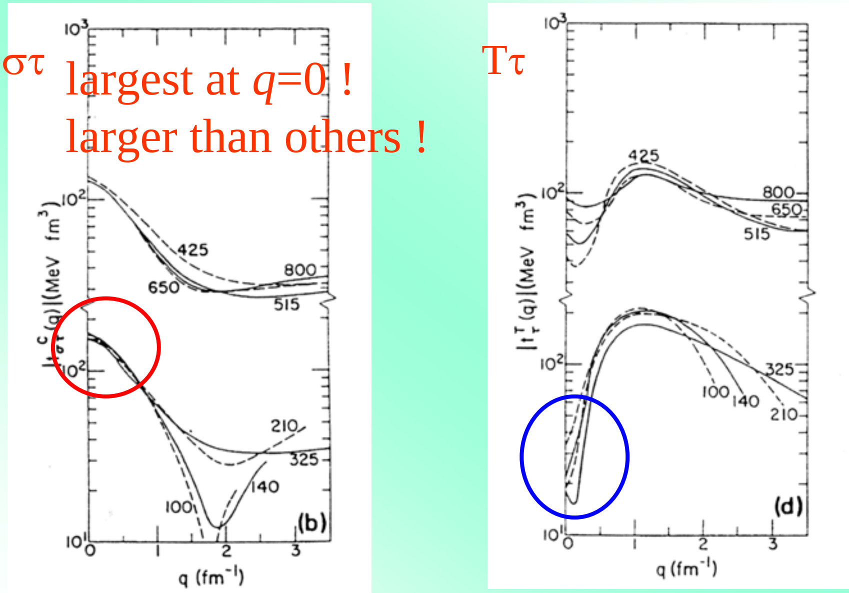
→ dσ/dω(q=0) : proportional to *B*(GT)

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



Love & Franey PRC 24 ('81) 1073

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



Love & Franey PRC 24 ('81) 1073

β-decay & Nuclear Reaction

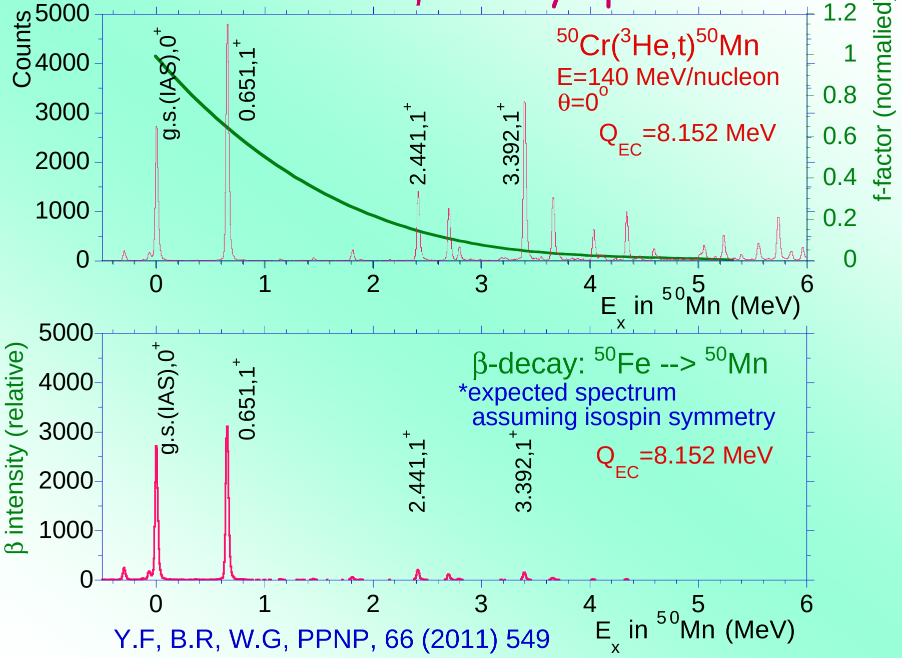
*β-decay GT tra. rate = $\dfrac{1}{t_{1/2}} = f \dfrac{\lambda^2}{K} B(\mathrm{GT})$

B(GT) : reduced GT transition strength
∝ (matrix element)^2 = $|\langle f|\sigma\tau|i\rangle|^2$

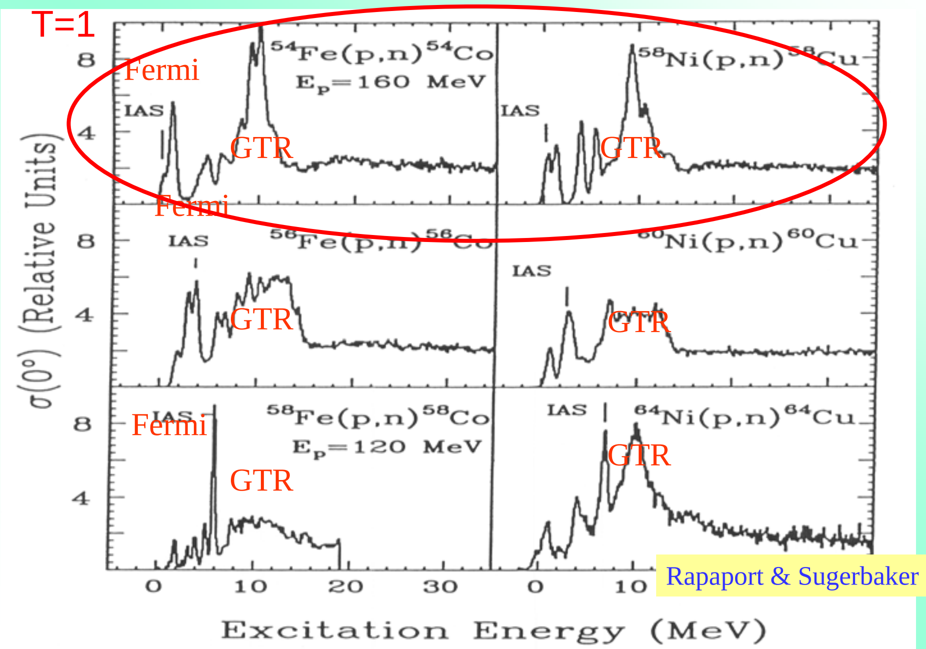
*Nuclear (CE) reaction rate (cross-section)
= reaction mechanism
⊗ operator
⊗ structure
=(matrix element)^2

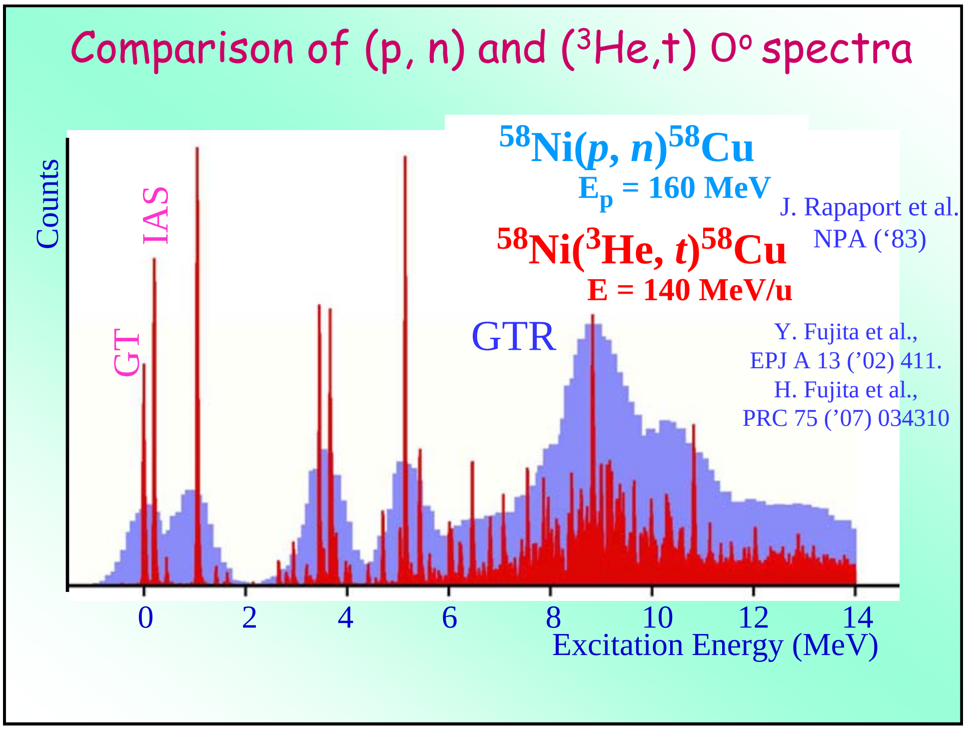
*At intermediate energies (100 < E_{in} < 500 MeV)
➡ dσ/dω(q=0) : proportional to B(GT)

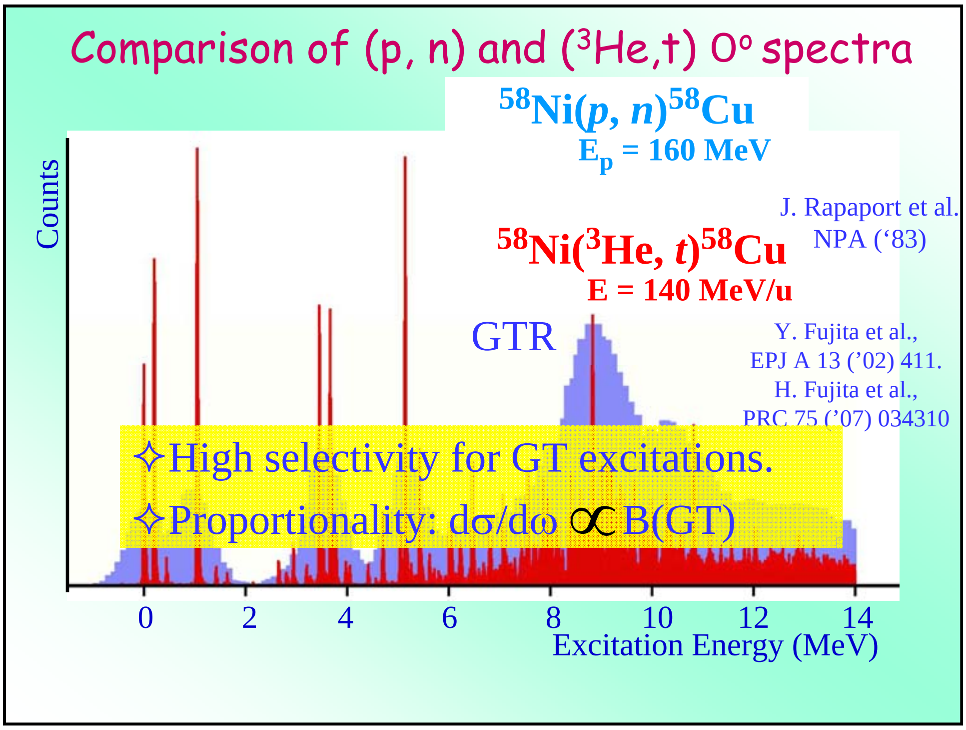
Simulation of β-decay spectrum



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




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
GTR
Y. Fujita et al.,
EPJ A 13 ('02) 411.
H. Fujita et al.,
PRC 75 ('07) 034310
Counts
IAS
GT
0
2
4
6
8
10
12
14
Excitation Energy (MeV)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E = 140 MeV/u
GTR
Y. Fujita et al.,
EPJ A 13 ('02) 411.
H. Fujita et al.,
PRC 75 ('07) 034310
Counts
✧High selectivity for GT excitations.
✧Proportionality: dσ/dω ∝ B(GT)
0
2
4
6
8
10
12
14
Excitation Energy (MeV)

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

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

A simple reaction mechanism should be achieved !

➡ we have to go to high incoming energy

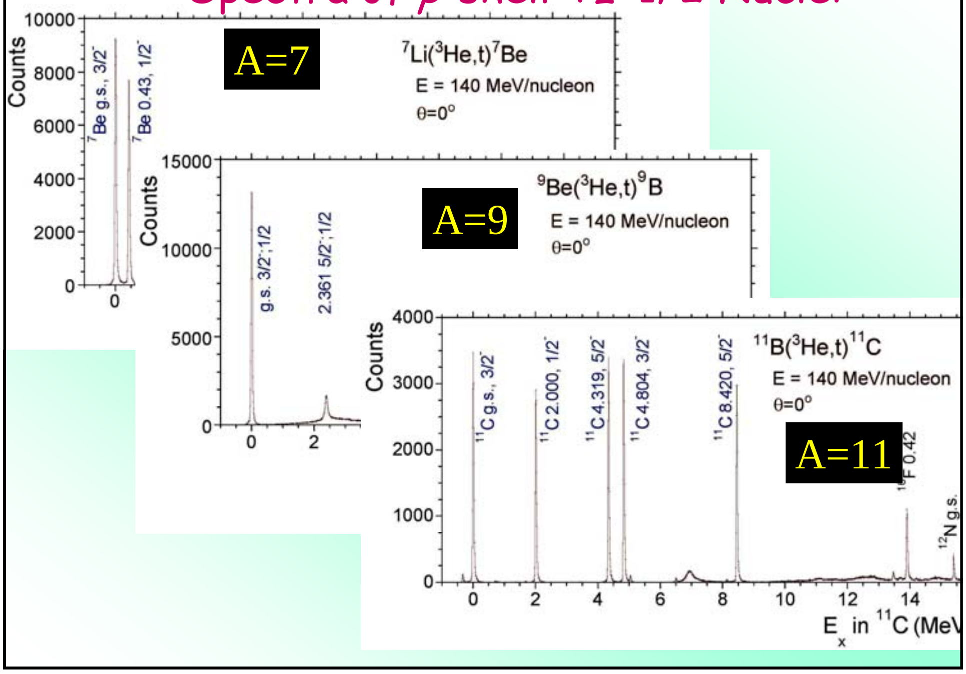
**GT transitions in each nucleus are UNIQUE and INFORMATIVE !

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

**GT transitions in each nucleus are UNIQUE and INFORMATIVE !

- *sd*-shell nuclei -

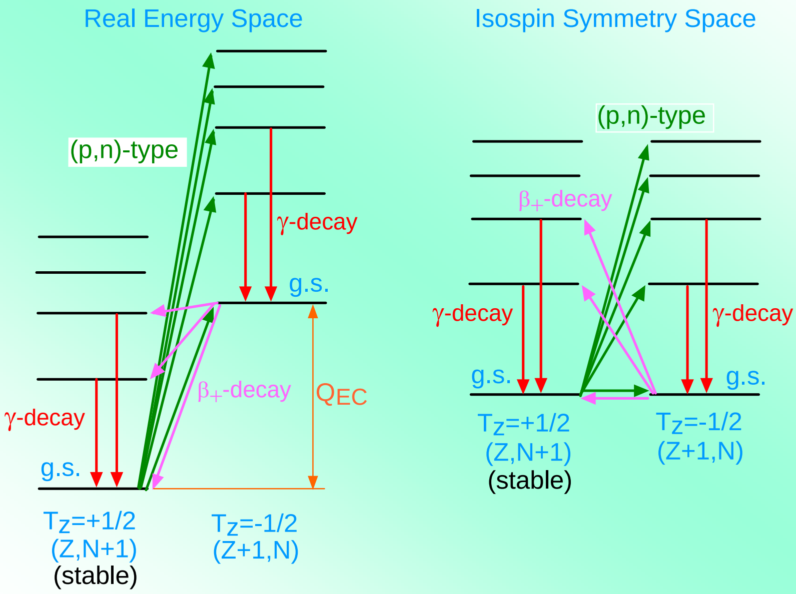
Spectra of *p*-shell Tz=1/2 Nuclei



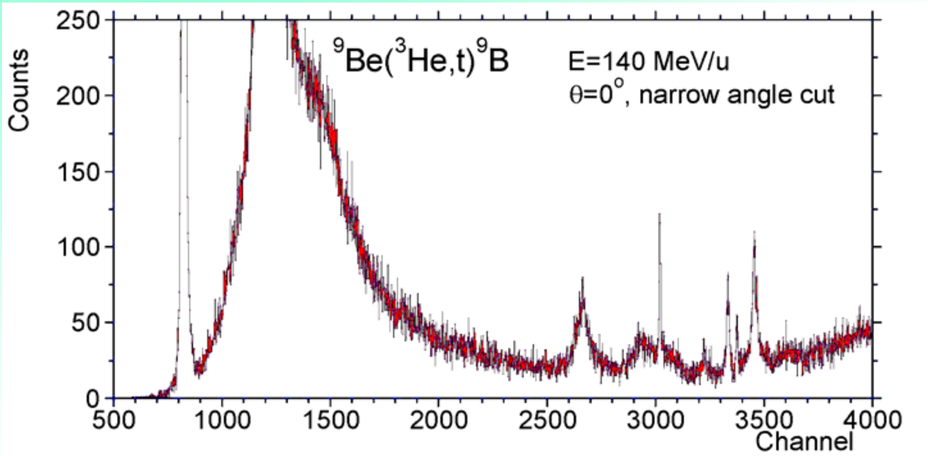
T=1/2 Isospin Symmetry

Koelner Dom
in Germany
(157m high)

Analogous Structures and Transitions in T=1/2 System



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



Relationship: Decay and Width

Heisenberg's Uncertainty Priciple

$$\Delta x \cdot \Delta p \approx \hbar$$

$$\Delta t \cdot \Delta E \approx \hbar$$

Width $\Gamma = \Delta E$

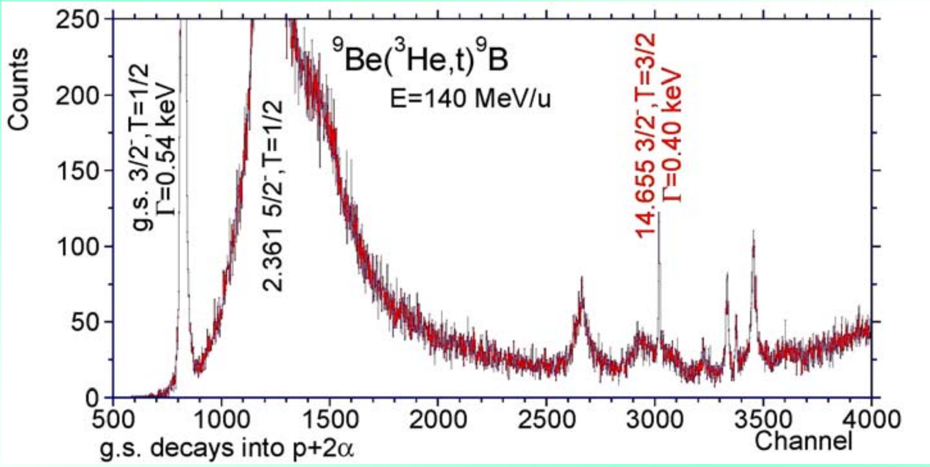
*if: Decay is Fast,

then: Width of a State is Wider !

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

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

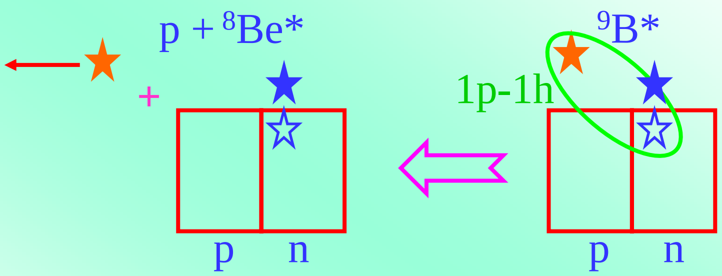
$^9Be(^3He,t)^9B$ spectrum (II)



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

C. Scholl et al, PRC 84, 014308 (2011)

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



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

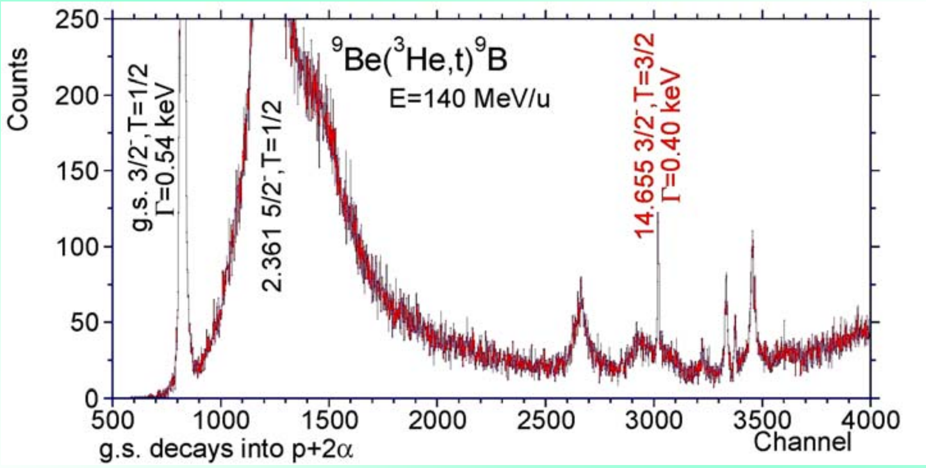
T : 1/2 + 0 (low lying) **= 1/2**

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

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

Therefore, ***p***-decay of T=3/2 states is forbidden!

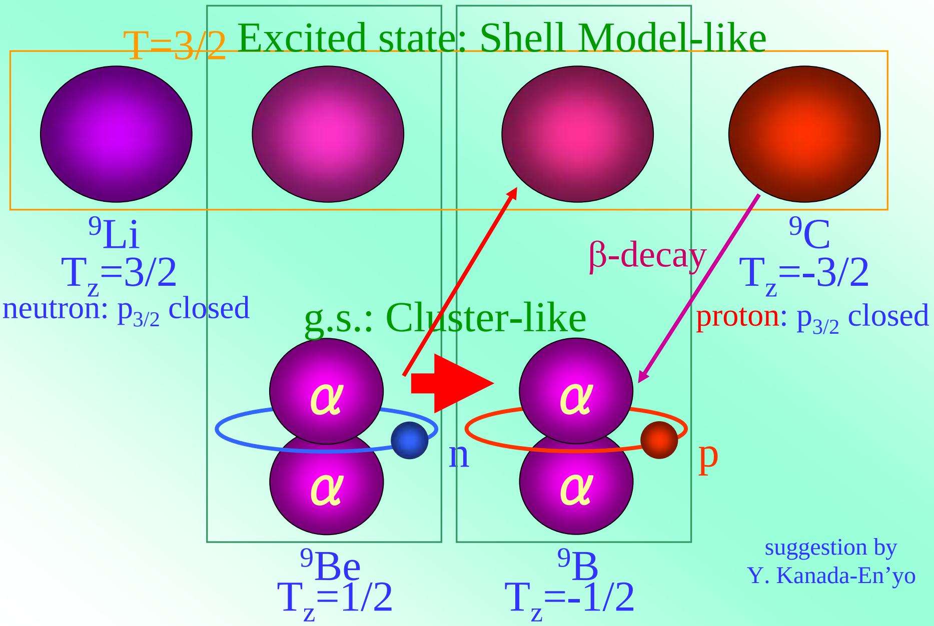
^{9}Be(^{3}He,t)^{9}B spectrum (III)



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

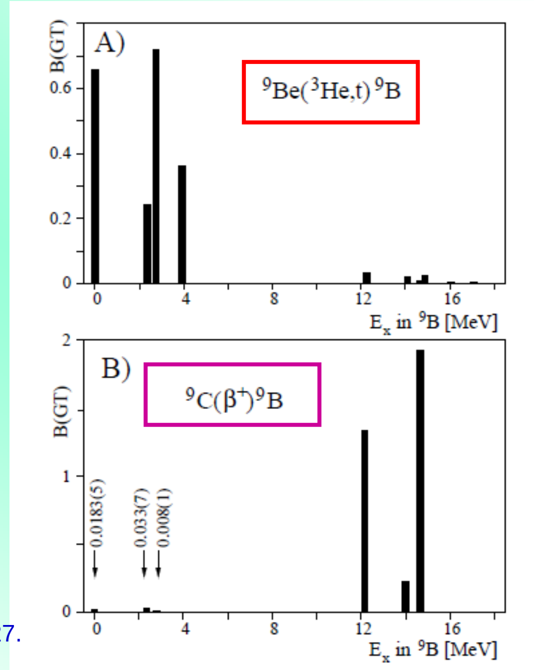
Strength ratio of g.s. & 14.7 MeV 3/2^{-} states: 140:1

Shell Structure and Cluster Structure



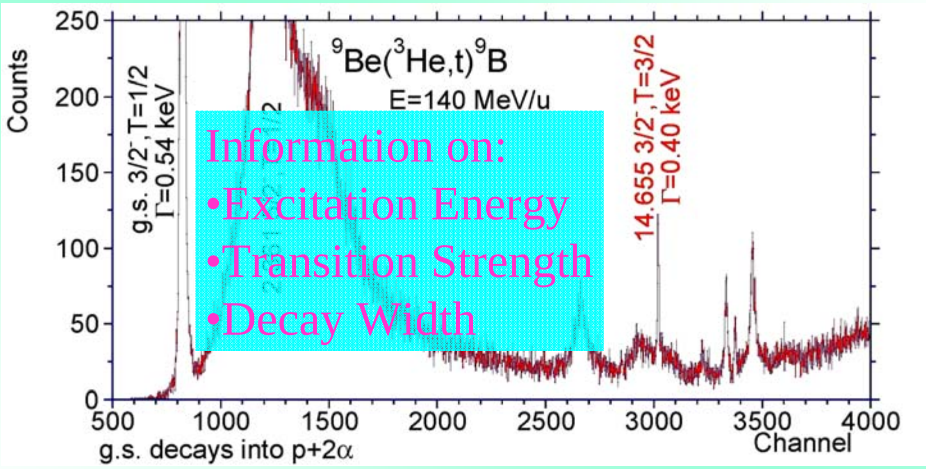
β-decay and (^{3}He,t) results

C. Scholl et al,
PRC 84, 014308 (2011)



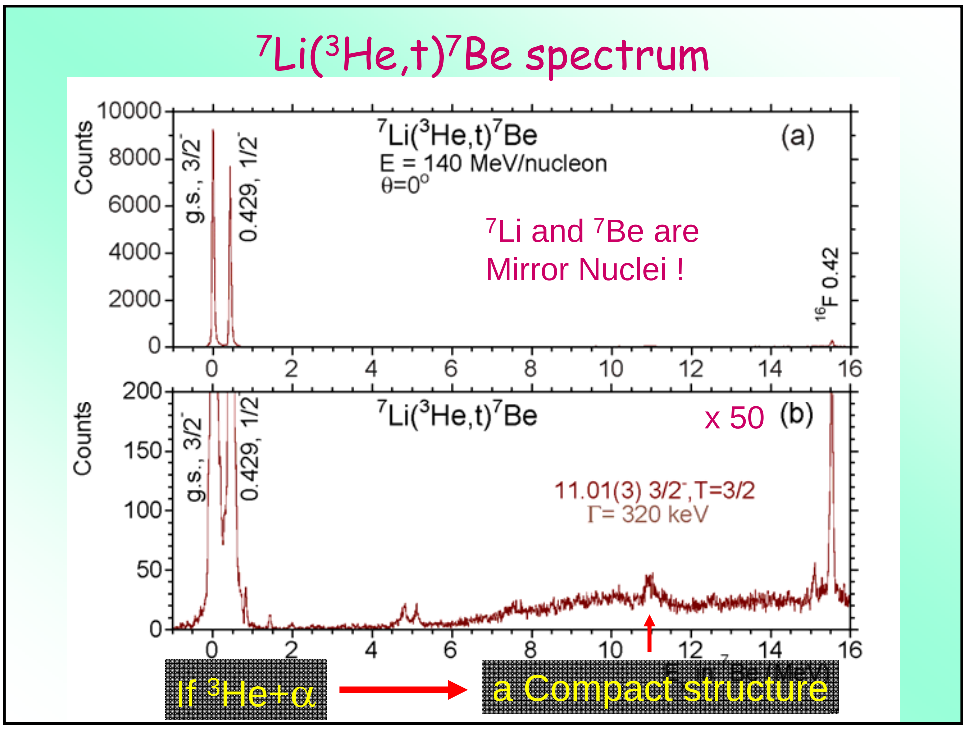
L.Buchmann et al.,
PRC 63 (2001) 034303.
U.C.Bergmann et al.,
Nucl. Phys. A 692 (2001) 427.

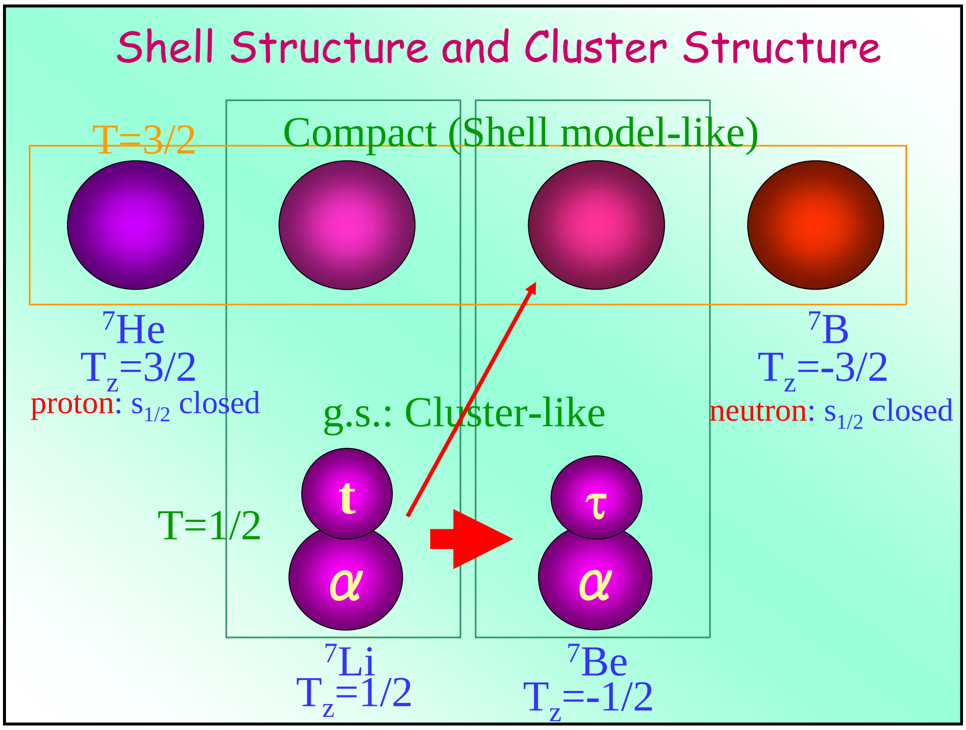
^{9}Be(^{3}He,t)^{9}B spectrum (III)



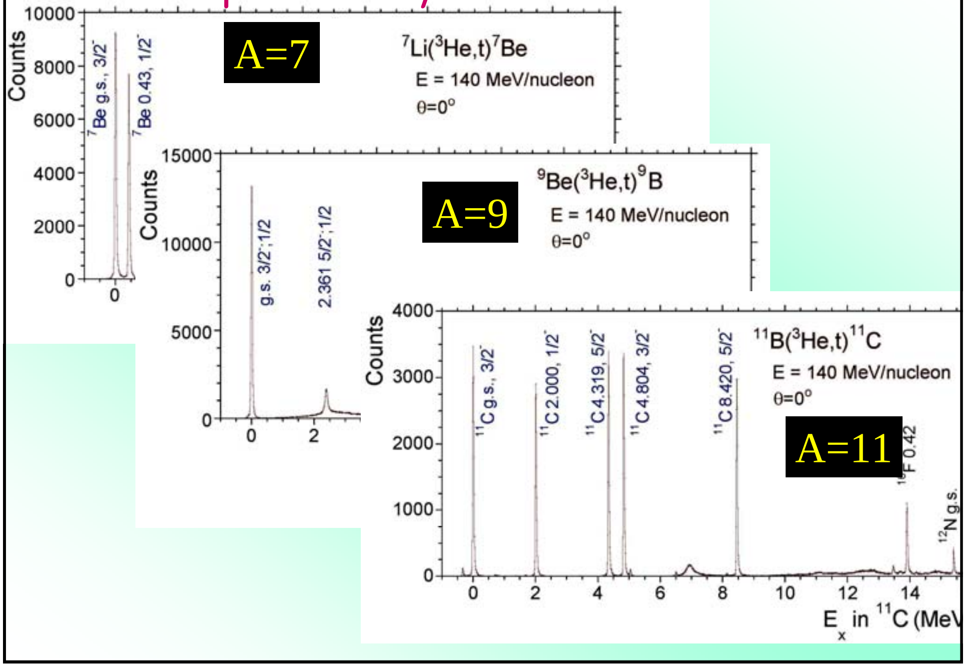
14.7 MeV T=3/2 state is very weak!

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

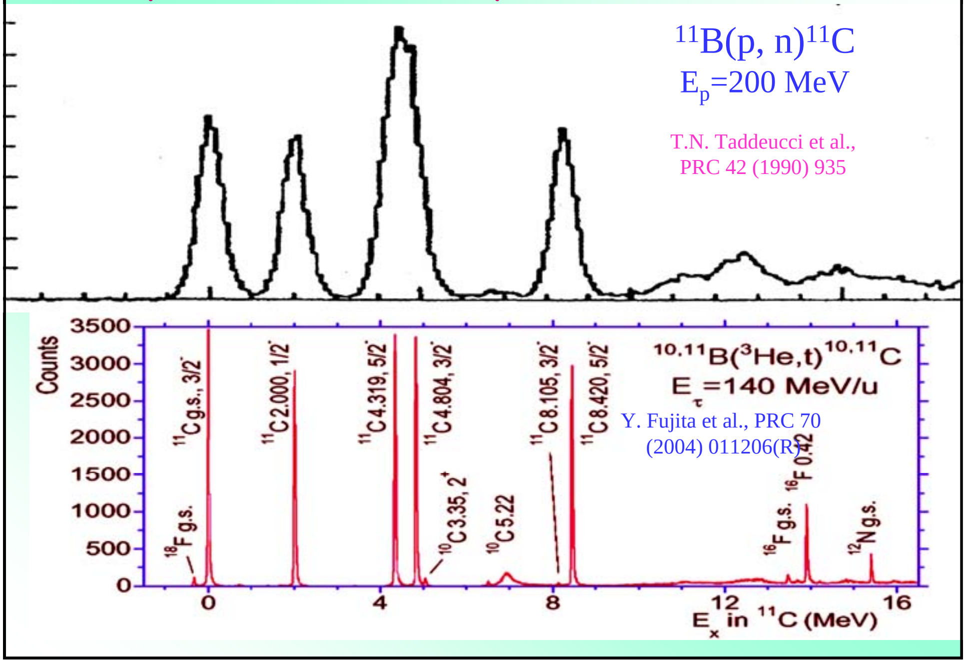

7Li(3He,t)7Be spectrum
Counts
10000
8000
6000
4000
2000
0
g.s., 3/2-
0.429, 1/2-
7Li(3He,t)7Be
E = 140 MeV/nucleon
θ=0°
(a)
7Li and 7Be are
Mirror Nuclei !
16F 0.42
0 2 4 6 8 10 12 14 16
Counts
200
150
100
50
0
7Li(3He,t)7Be
x 50 (b)
11.01(3) 3/2-,T=3/2
Γ= 320 keV
If 3He+α
a Compact structure


Shell Structure and Cluster Structure
T=3/2
Compact (Shell model-like)
7He
Tz=3/2
proton: s1/2 closed
7B
Tz=-3/2
neutron: s1/2 closed
g.s.: Cluster-like
T=1/2
t
α
τ
α
7Li
Tz=1/2
7Be
Tz=-1/2

Spectra of *p*-shell Mirror Nuclei

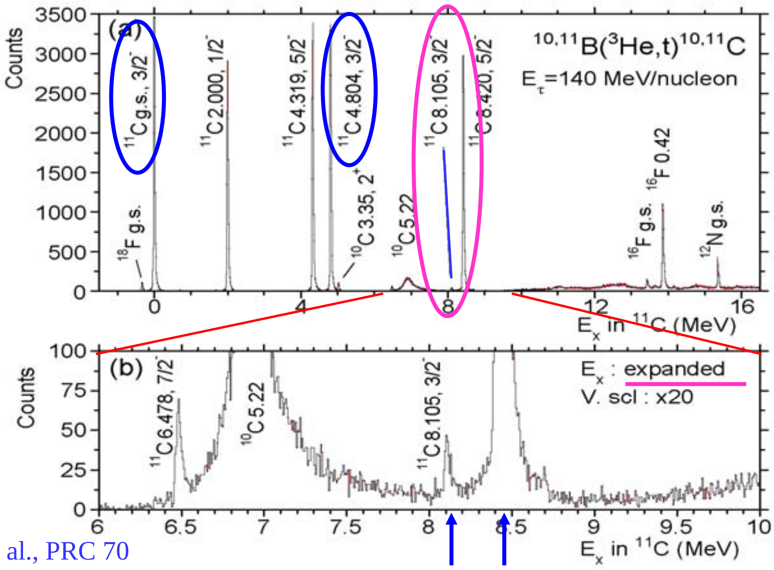


(p,n) and (^{3}He,t) Spectra on ^{11}B



GT transitions to $J^\pi = 3/2^-$ states: J^π allowed

Why $3/2^-_3$ so weak!



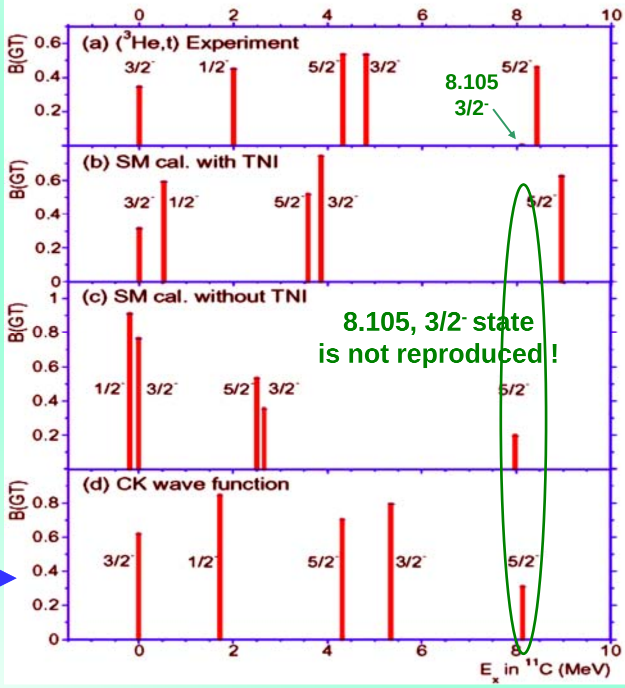
Y. Fujita et al., PRC 70 (2004) 011206(R)

ΔE~300 keV

Comparison: ^{11}B(^{3}He,t)^{11}C & Shell Models

No-core SM-cal: by Navratil & Ormand Phys. Rev. C 68 ('03)034305

"quenching" included



11B→11C: GT transition strengths

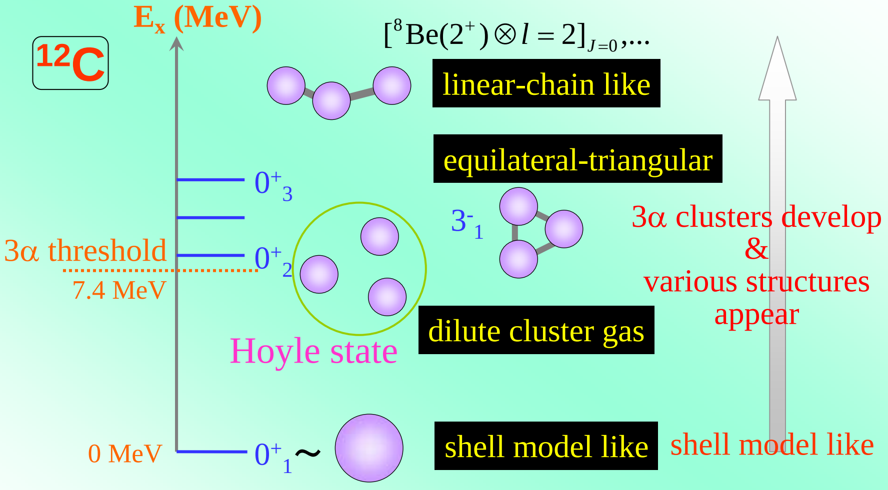
^{11}B(3He,t)^{11}C

Y. Fujita, et al.
PRC 70, 011306(R)(2004).

		Experiment		no-core shell-model With TNI	
		B(GT)			
E_x (MeV)	$2J^\pi$	(p,n)[a]	$(^3\mathrm{He},t)$	E_x (MeV)	B(GT)
0.0	3^-	0.345(8)[b]	0.345(8)[b]	0.0	0.315
2.000	1^-	0.399(32)	0.440(22)	0.525	0.591
4.319	5^-	0.961(60)[c]	0.526(27)	3.584	0.517
4.804	3^-		0.525(27)	3.852	0.741
8.105	3^-	0.444(10)[d]	0.005(2)[e]		
8.420	5^-		0.461(23)	8.943	0.625

small B(GT) :
missing of $3/2^-_3$ in NCSM calculation

Shell-model-like and Cluster structures in ^{12}C

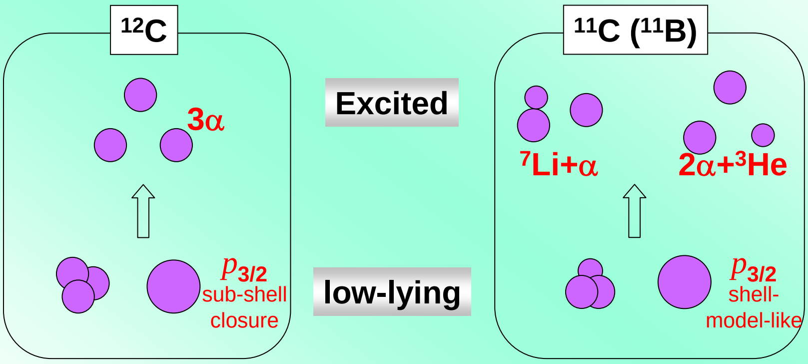


by Suhara & En'yo '08

E. Uegaki, et al. Prog. Theor. Phys. **57**, 1262 (1977)
M. Kamimura, et al. J. Phys. Soc. Jpn. **44** (1978), 225.
A. Tohsaki, et al. Phys. Rev. Lett. **87**, 192501 (2001)
Y. Kanada-En'yo, Prog. Theor. Phys. **117**, 655 (2007) etc

Coexistence of shell-model and cluster states

by Y. Kanada-En'yo
PRC 75 ('07) 024302

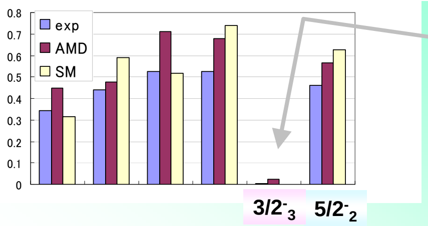


$^{11}B \rightarrow {}^{11}C^{*}$ GT-transition strength

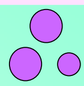
by Y. Kanada-En'yo
PRC 75 ('07) 024302

Y. Fujita, et al. PRC 70, 011306(R)(2004).

^{11}C		Experiment		no-core shell-model		AMD
			B(GT)	With TNI		
E_x (MeV)	$2J^{\pi}$	$(p,n)^{a}$	$(^{3}\mathrm{He},t)$	E_x (MeV)	B(GT)	$B(GT)$
0.0	3^-	$0.345(8)^{b}$	$0.345(8)^{b}$	0.0	0.315	0.45
2.000	1^-	0.399(32)	0.440(22)	0.525	0.591	0.48
4.319	5^-	$0.961(60)^{c}$	0.526(27)	3.584	0.517	0.71
4.804	3^-		0.525(27)	3.852	0.741	0.68
8.105	3^-	$0.444(10)^{d}$	$0.005(2)^{e}$			0.02
8.420	5^-		0.461(23)	8.943	0.625	0.57



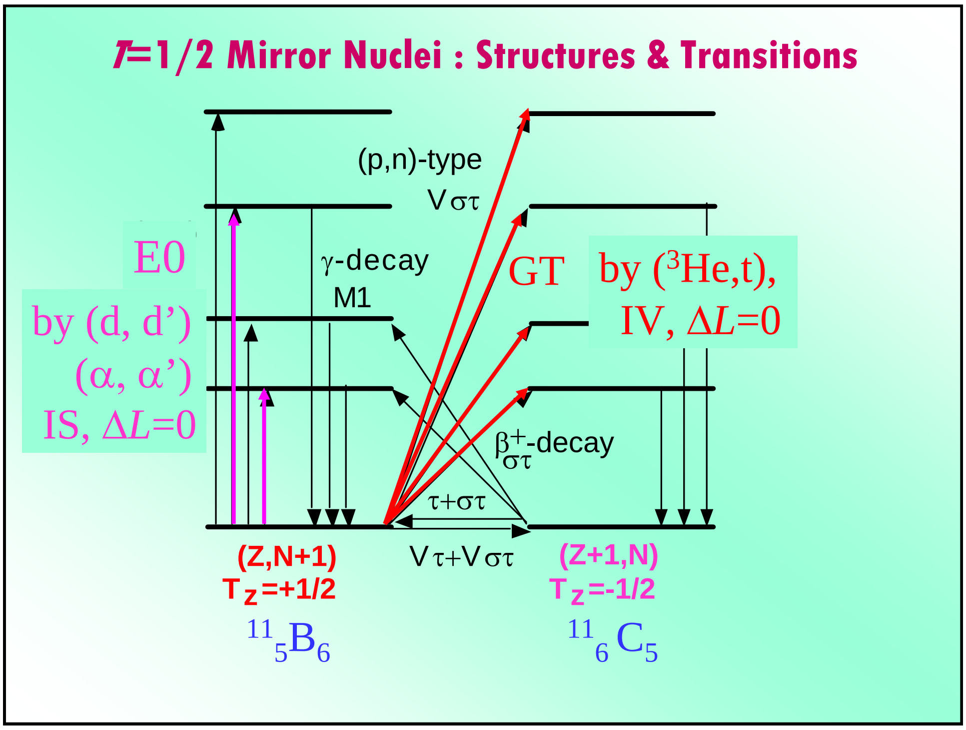
Small B(GT) of $3/2^-_3$: well reproduced

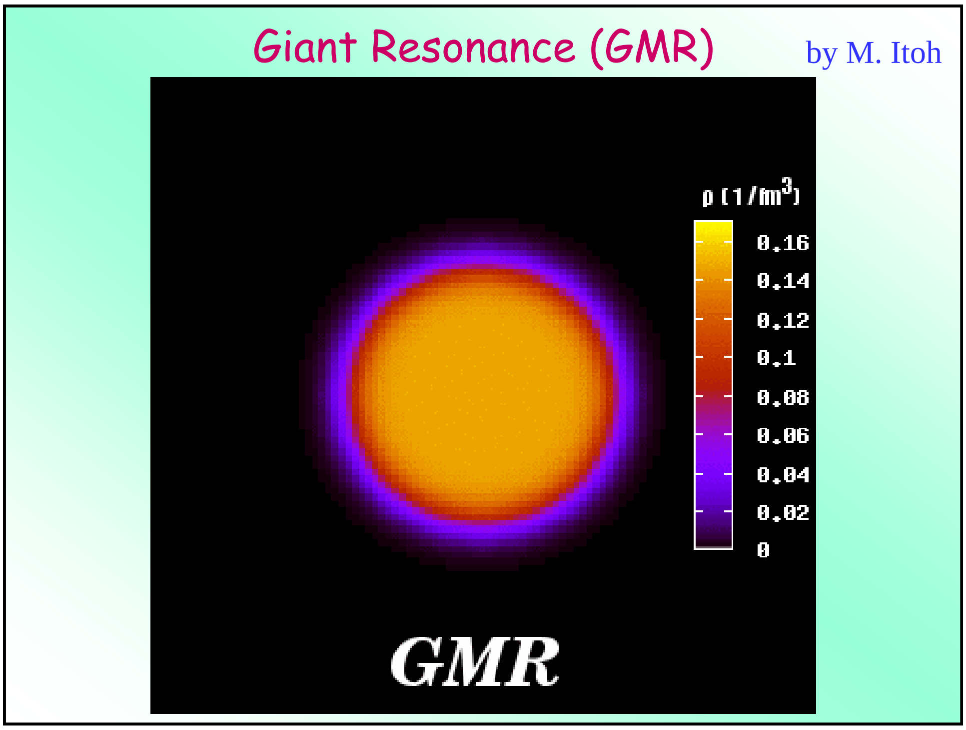


Connection between GT and E0 transitions

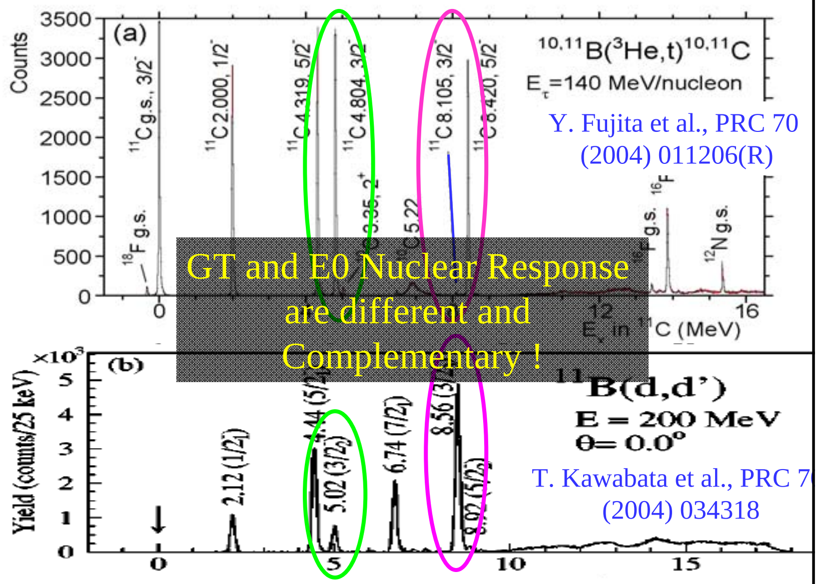
T=1/2 Isospin Symmetry

Koelner Dom
in Germany
(157m high)

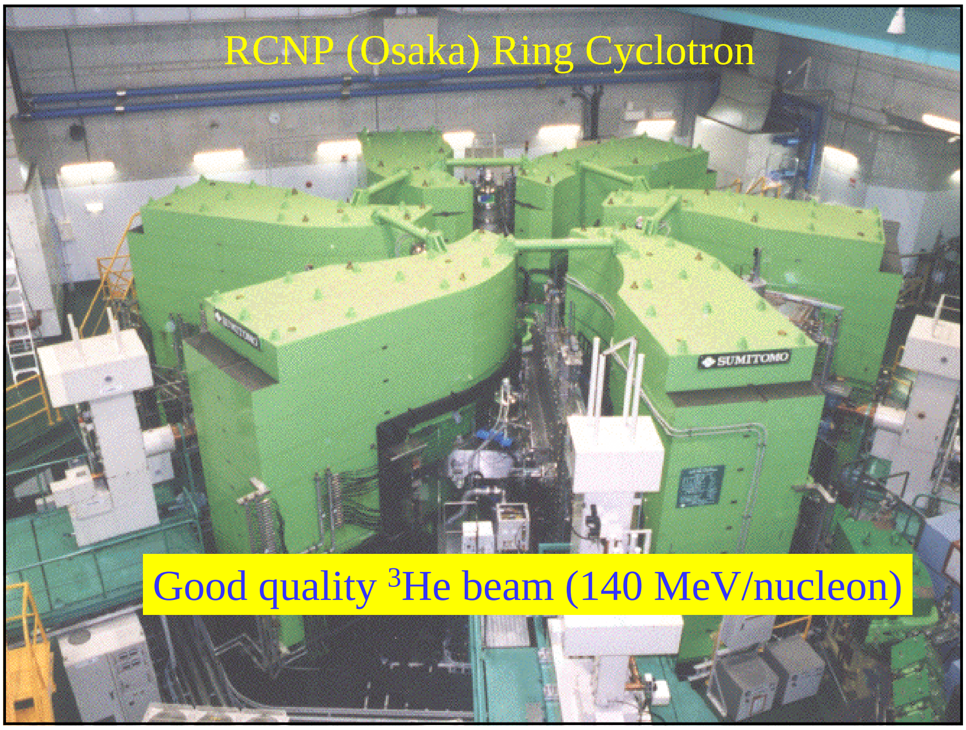

T=1/2 Mirror Nuclei : Structures & Transitions
(p,n)-type
Vστ
γ-decay
M1
E0
by (d, d')
(α, α')
IS, ΔL=0
GT
by (3He,t),
IV, ΔL=0
β+-decay
στ
τ+στ
Vτ+Vστ
(Z,N+1)
Tz=+1/2
11 5 B 6
(Z+1,N)
Tz=-1/2
11 6 C 5

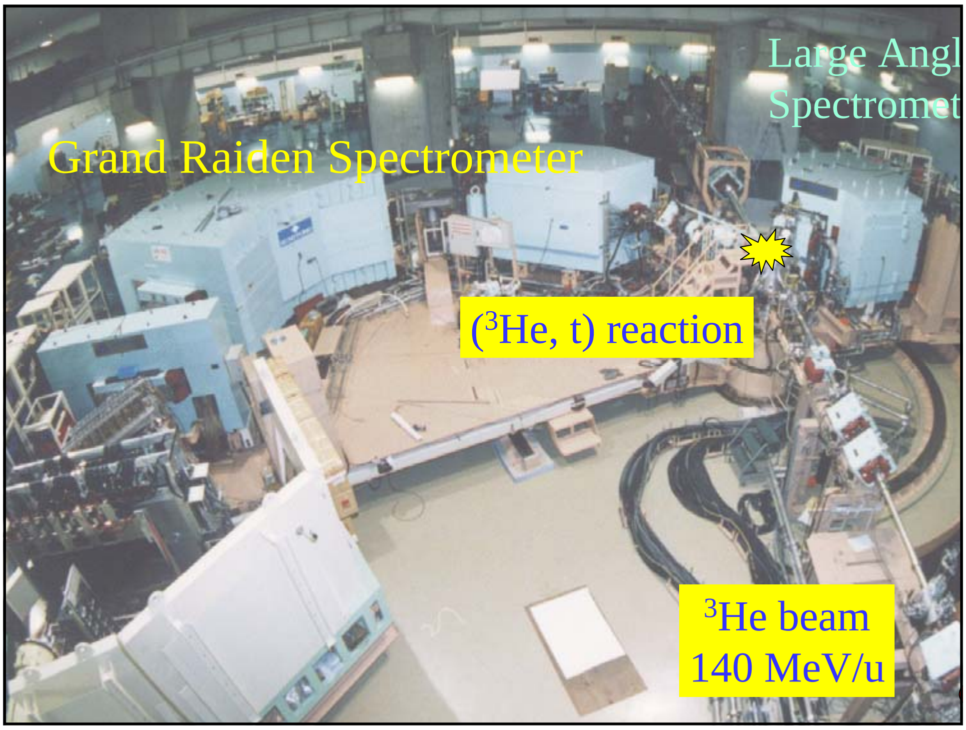

Giant Resonance (GMR)
by M. Itoh
ρ [1/fm3]
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
GMR

Excitation of Mirror $3/2^-_3$ states in (^{3}He,t) and (d,d')

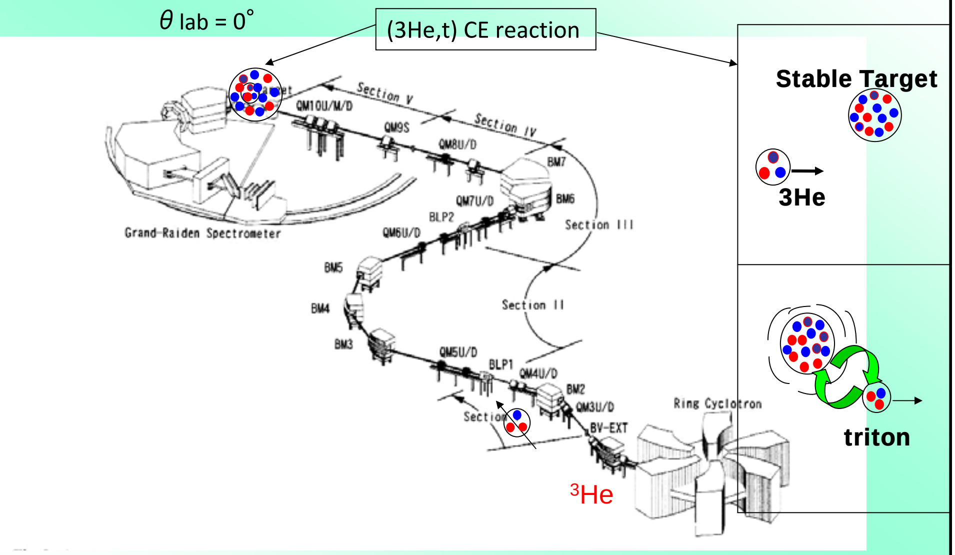


***High Resolution Measurements using Dispersion Matching Technique


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

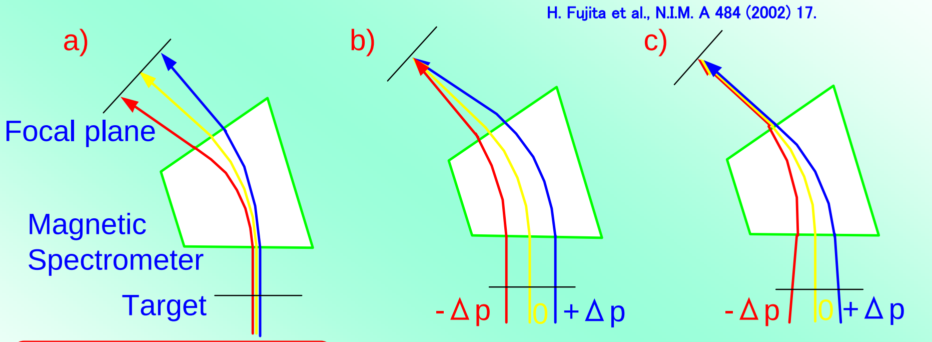

Grand Raiden Spectrometer
(³He, t) reaction
³He beam
140 MeV/u

(^{3}He,t) CE Reactions @ RCNP (Osaka)



Matching Techniques

Y. Fujita et al., N.I.M. B 126 (1997) 274.
H. Fujita et al., N.I.M. A 484 (2002) 17.

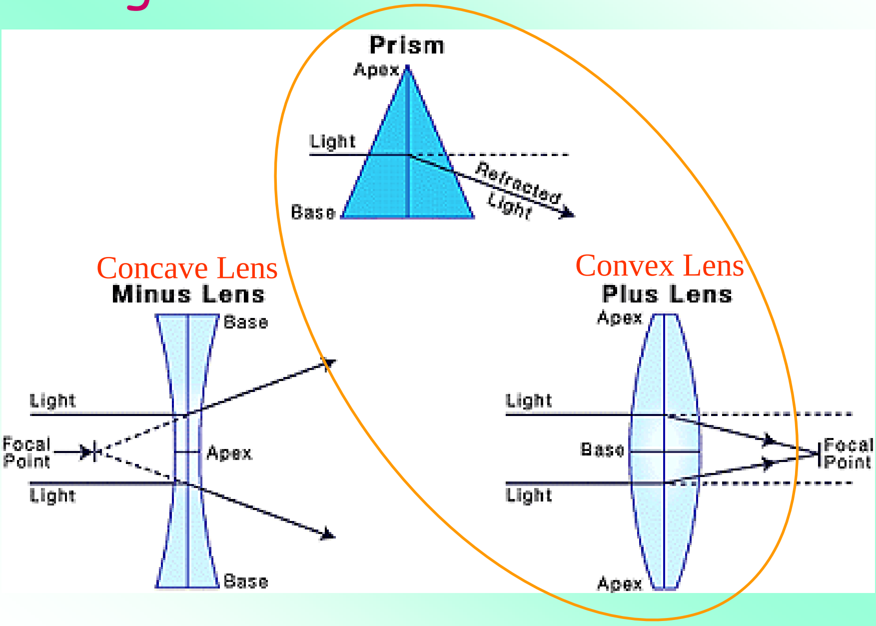


Achromatic beam transportation
ΔE ～200 keV
for 140MeV/u ^{3}He beam

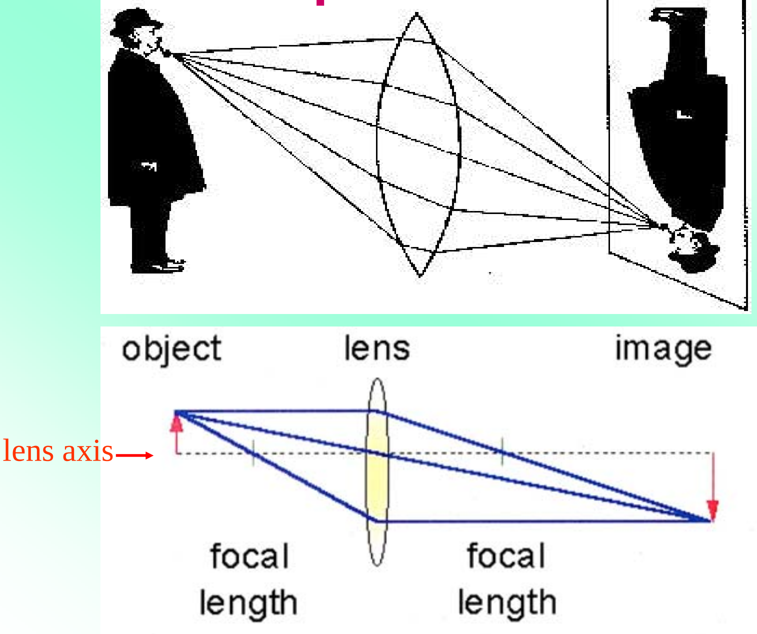
Lateral dispersion matching
ΔE ～ 35 keV
Horiz. angle resolution
$\Delta\theta_{sc}$ > 15mrad

Angular dispersion matching
$\Delta\theta_{sc}$ ～ 5mrad

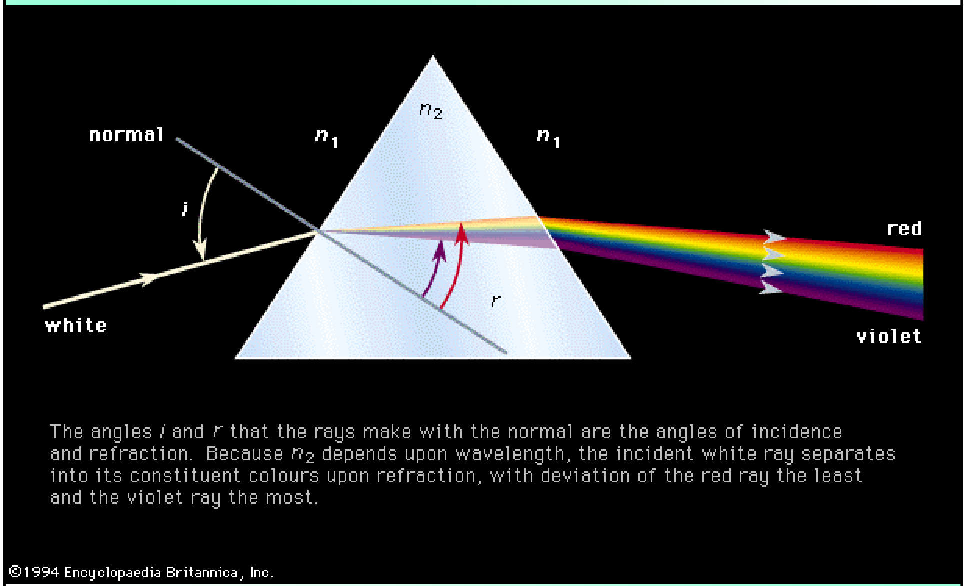
Magnet= Convex Lens + Prism



Optics: focus



Prism



Matching Techniques

Y. Fujita et al., N.I.M. B 126 (1997) 274.
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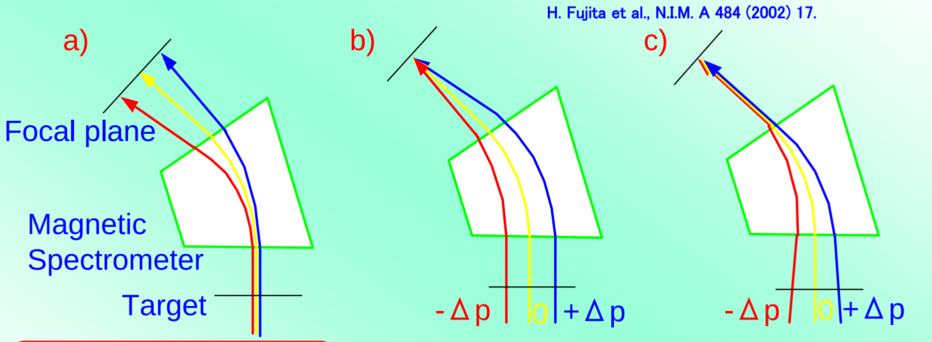
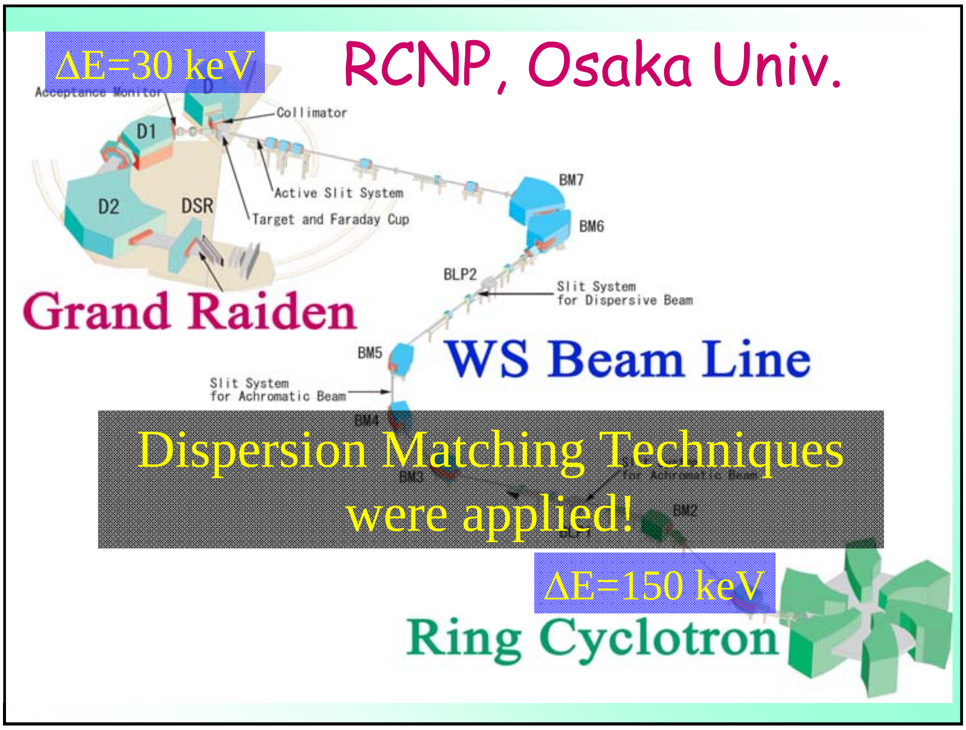
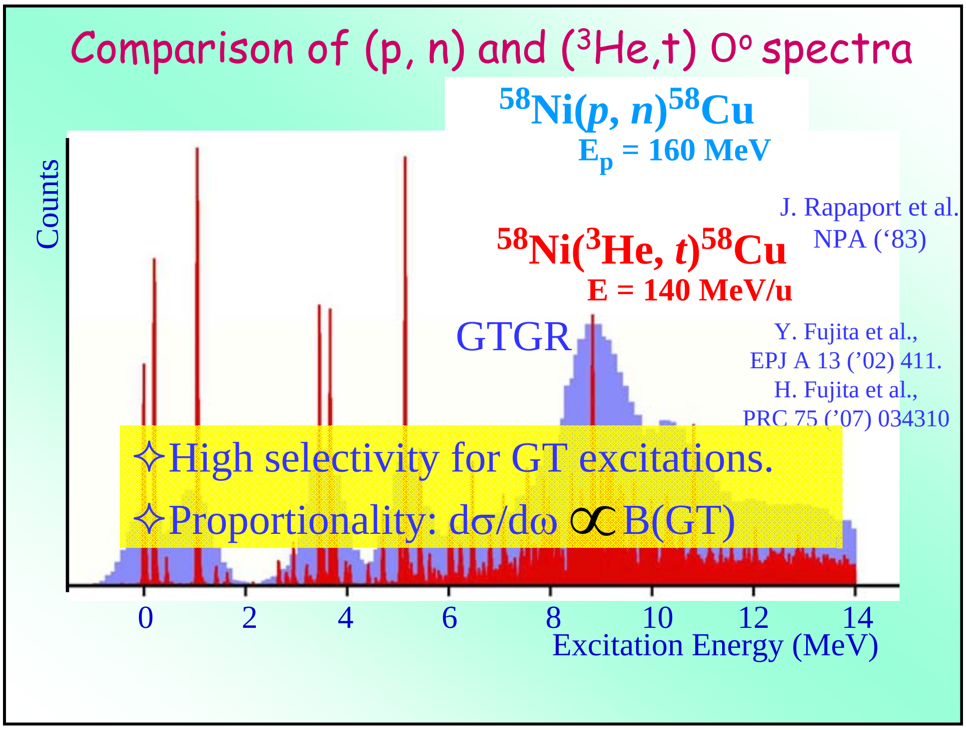


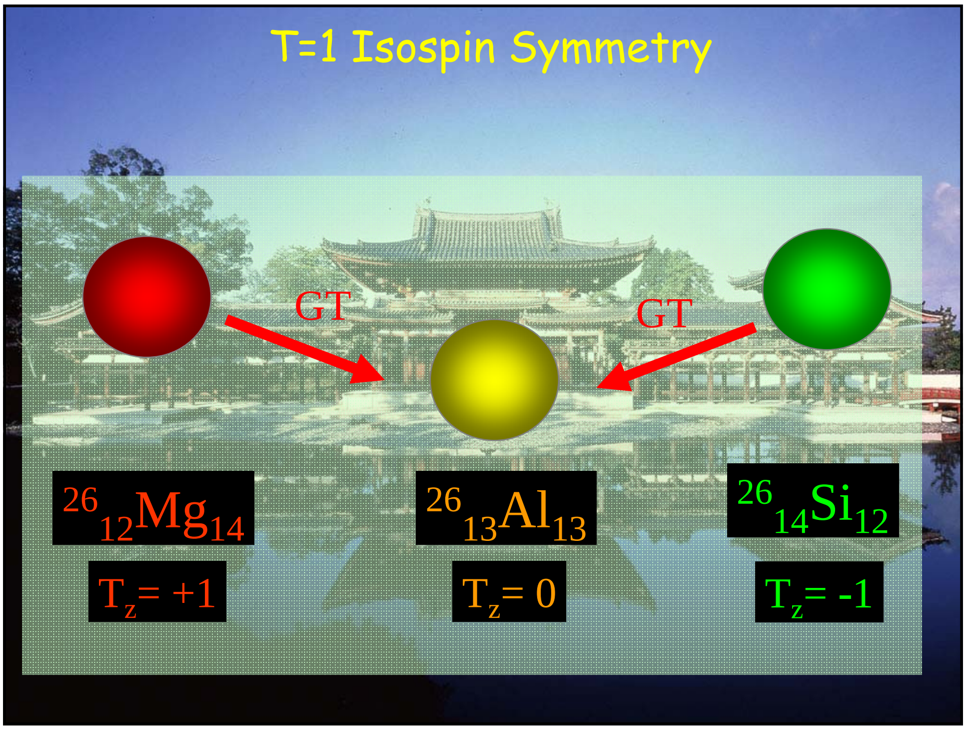
a)	b)	c)
Achromatic beam transportation ΔE ~200 keV for 140MeV/u ^{3}He beam	*Lateral dispersion matching* ΔE ~ 35 keV Horiz. angle resolution $\Delta\theta_{sc}$ > 15mrad	*Angular dispersion matching* $\Delta\theta_{sc}$ ~ 5mrad

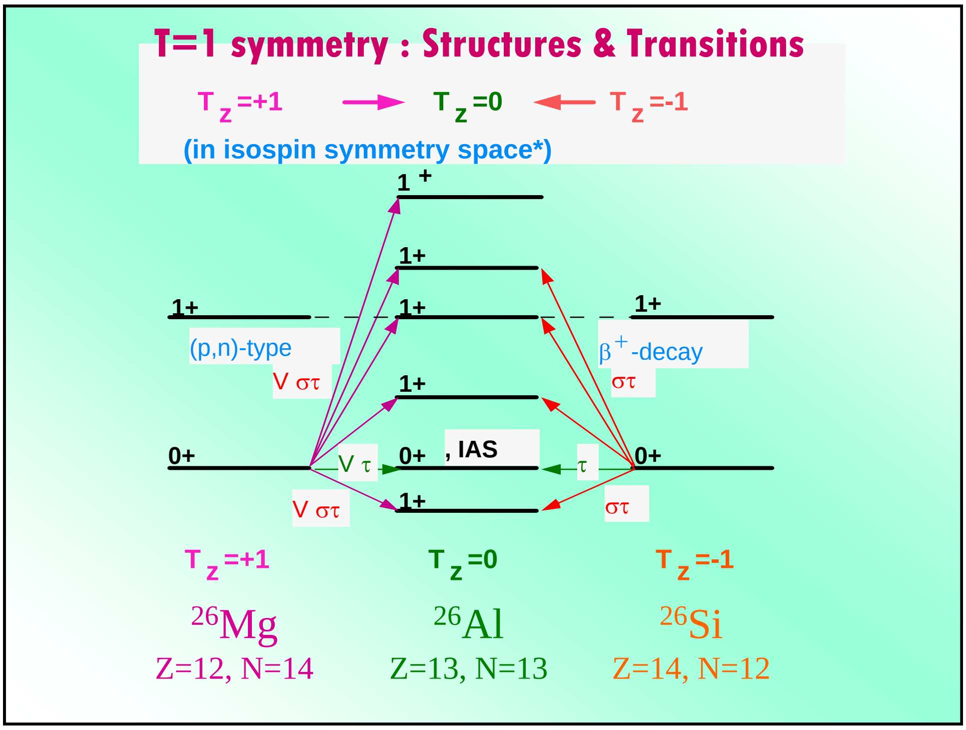

ΔE=30 keV
RCNP, Osaka Univ.
Acceptance Monitor
Collimator
D1
D2
DSR
Active Slit System
Target and Faraday Cup
BM7
BM6
BLP2
Slit System
for Dispersive Beam
Grand Raiden
BM5
WS Beam Line
Slit System
for Achromatic Beam
Dispersion Matching Techniques
were applied!
ΔE=150 keV
Ring Cyclotron

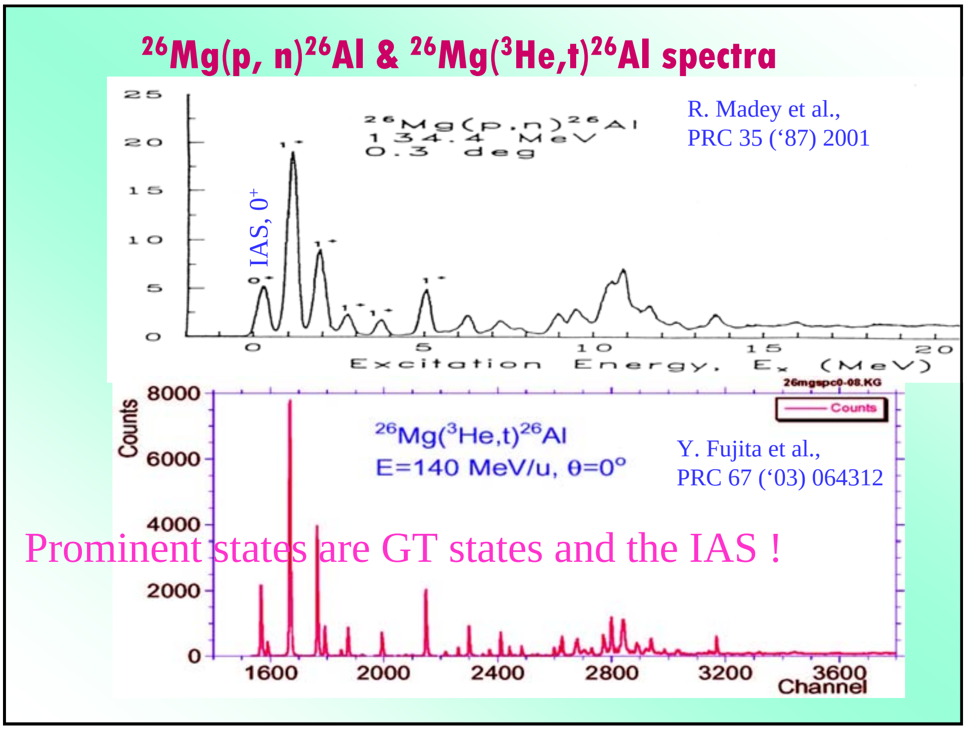

Comparison of (p, n) and (3He,t) 0° spectra
58Ni(p, n)58Cu
Ep = 160 MeV
J. Rapaport et al.
NPA ('83)
58Ni(3He, t)58Cu
E = 140 MeV/u
GTGR
Y. Fujita et al.,
EPJ A 13 ('02) 411.
H. Fujita et al.,
PRC 75 ('07) 034310
✧High selectivity for GT excitations.
✧Proportionality: dσ/dω ∝ B(GT)
Counts
0
2
4
6
8
10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

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

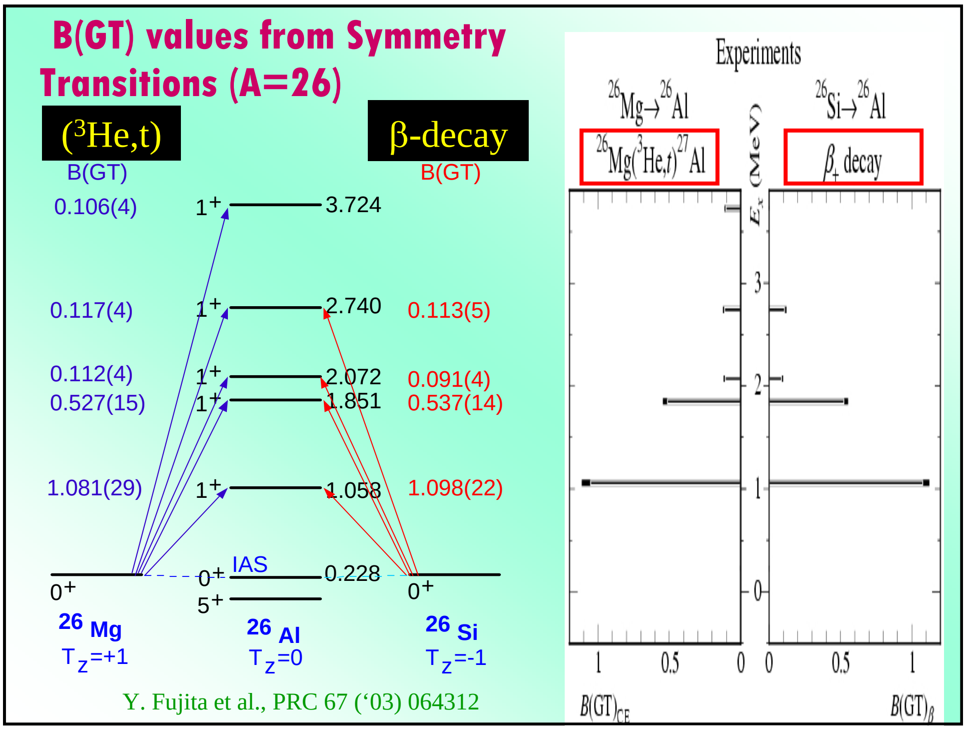
by means of
Isospin Symmetry


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


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



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)
26Mg(3He,t)26Al
E=140 MeV/u, θ=0°
Y. Fujita et al.,
PRC 67 ('03) 064312
Counts
Channel
Prominent states are GT states and the IAS !

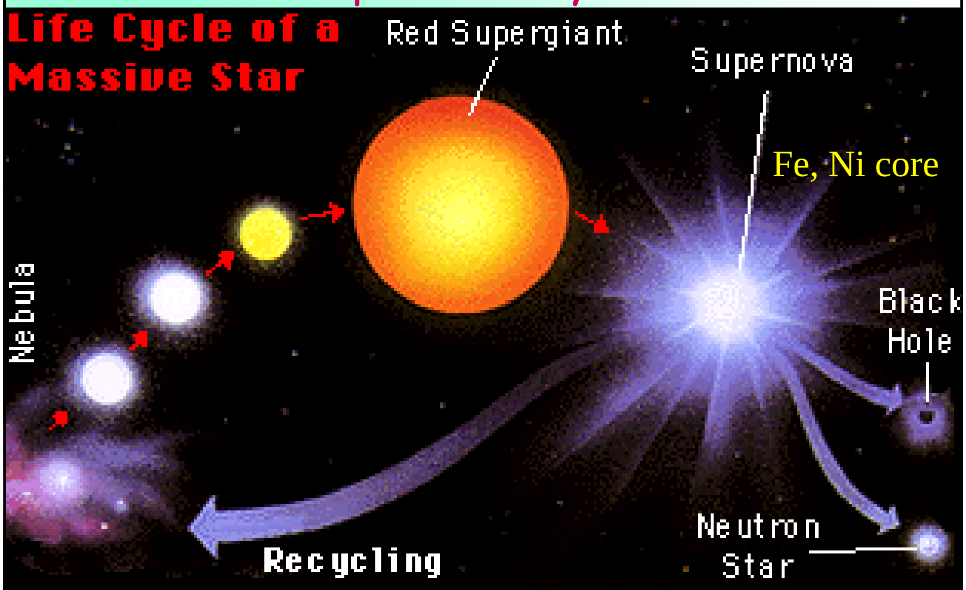


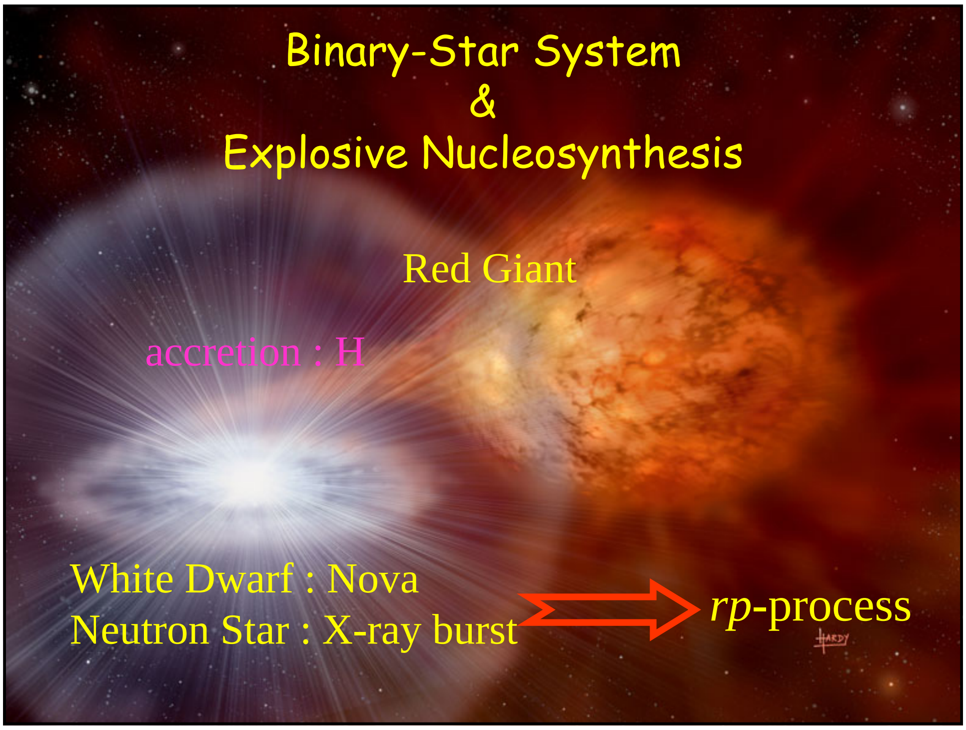
B(GT) values from Symmetry Transitions (A=26)
(3He,t)
B(GT)
β-decay
B(GT)
0.106(4)
1+ 3.724
0.117(4)
1+ 2.740
0.113(5)
0.112(4)
1+ 2.072
0.091(4)
0.527(15)
1+ 1.851
0.537(14)
1.081(29)
1+ 1.058
1.098(22)
0+ IAS 0.228
5+
0+
26 Mg
Tz=+1
26 Al
Tz=0
0+
26 Si
Tz=-1
Y. Fujita et al., PRC 67 ('03) 064312
Experiments
26Mg→26Al
26Si→26Al
26Mg(3He,t)27Al
β+ decay
Ex (MeV)
B(GT)CE
B(GT)β

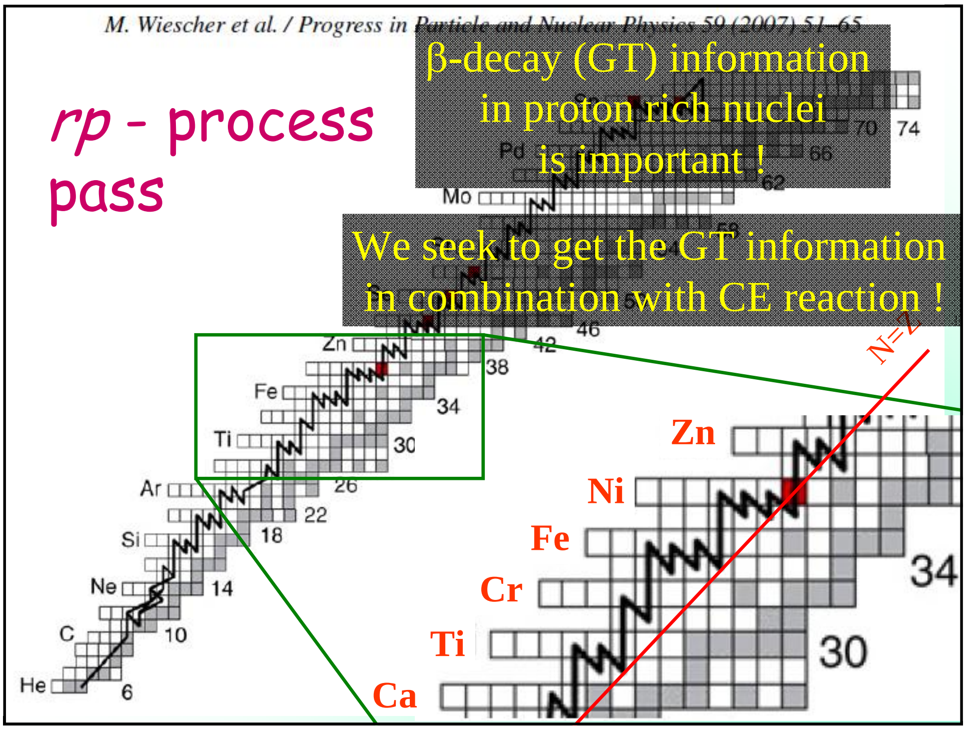
**GT transitions in each nucleus are UNIQUE and INFORMATIVE !

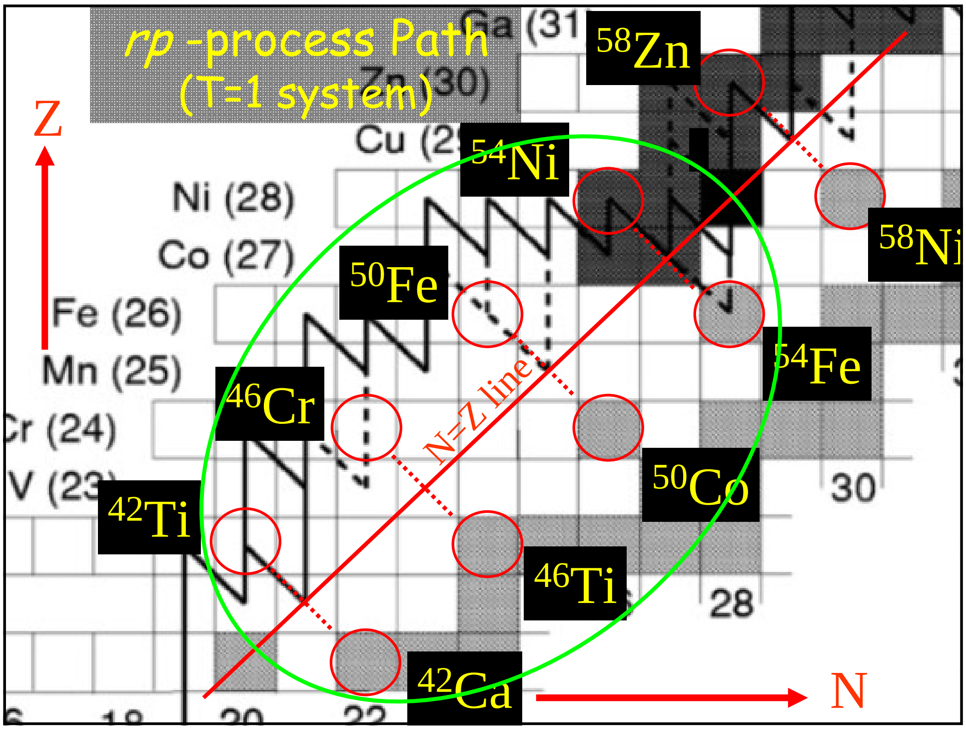
- *pf*-shell nuclei -

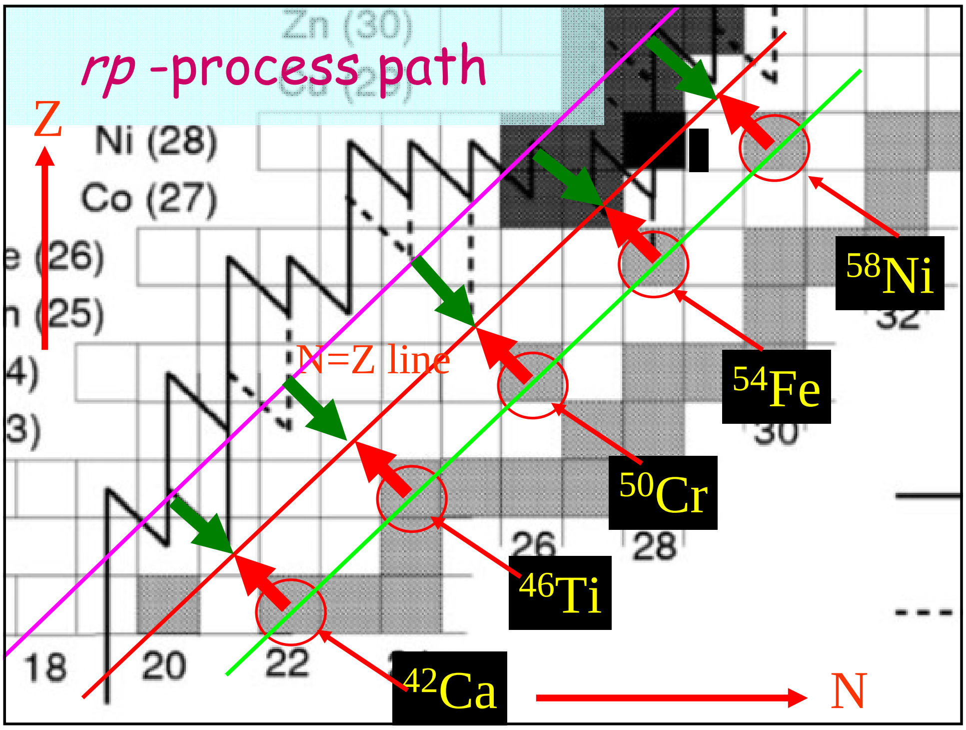
Supernova Cycle



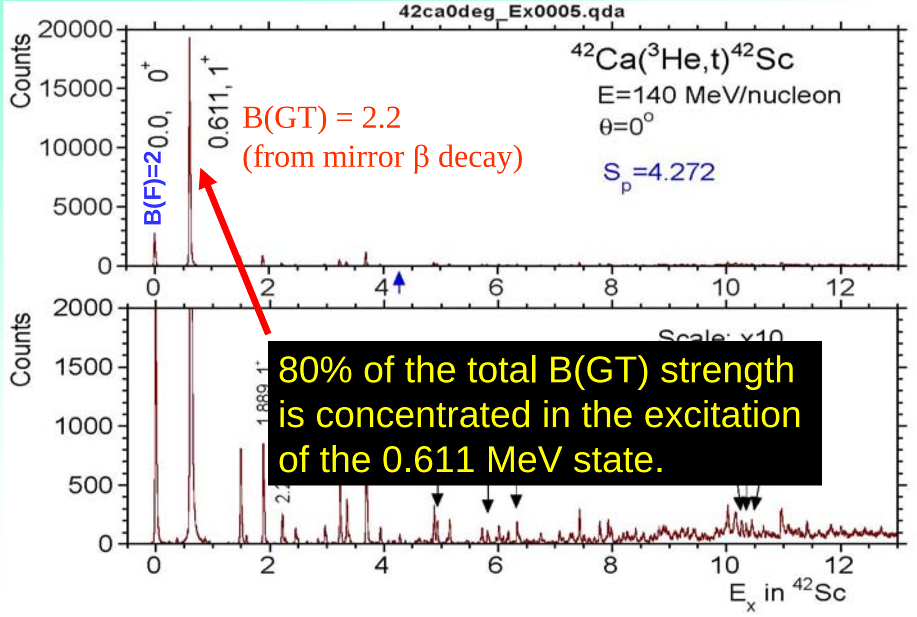

Binary-Star System
&
Explosive Nucleosynthesis
Red Giant
accretion : H
White Dwarf : Nova
Neutron Star : X-ray burst
rp-process


M. Wiescher et al. / Progress in Particle and Nuclear Physics 59 (2007) 51–65
rp - process
pass
β-decay (GT) information
in proton rich nuclei
is important !
We seek to get the GT information
in combination with CE reaction !
N=Z
Zn
Ni
Fe
Cr
Ti
Ca
34
30

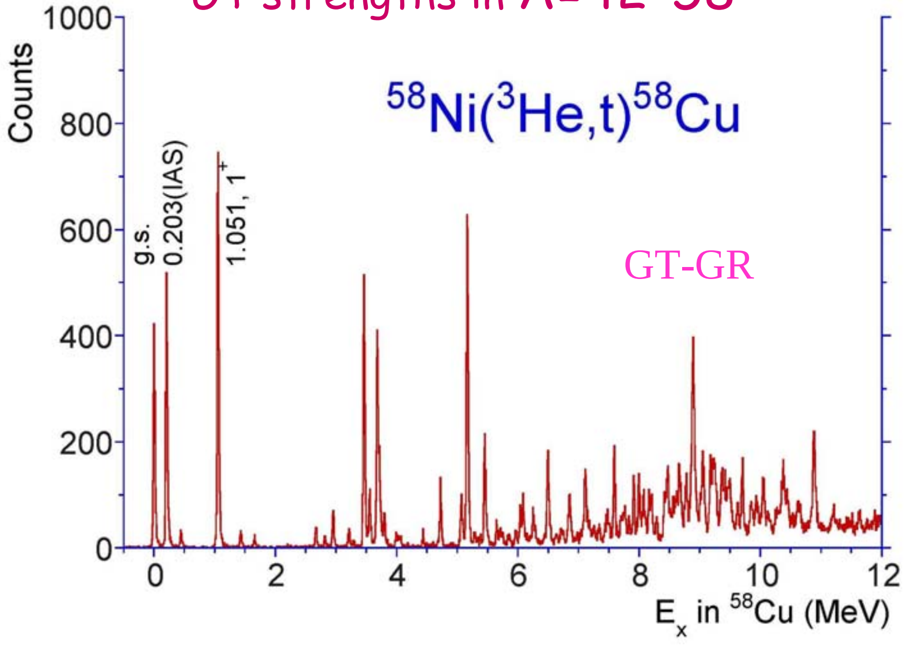

rp -process Path
(T=1 system)
Z
N
58Zn
54Ni
58Ni
50Fe
54Fe
46Cr
50Co
42Ti
46Ti
42Ca
N=Z line
Ni (28)
Co (27)
Fe (26)
Mn (25)
30
28


rp -process path
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



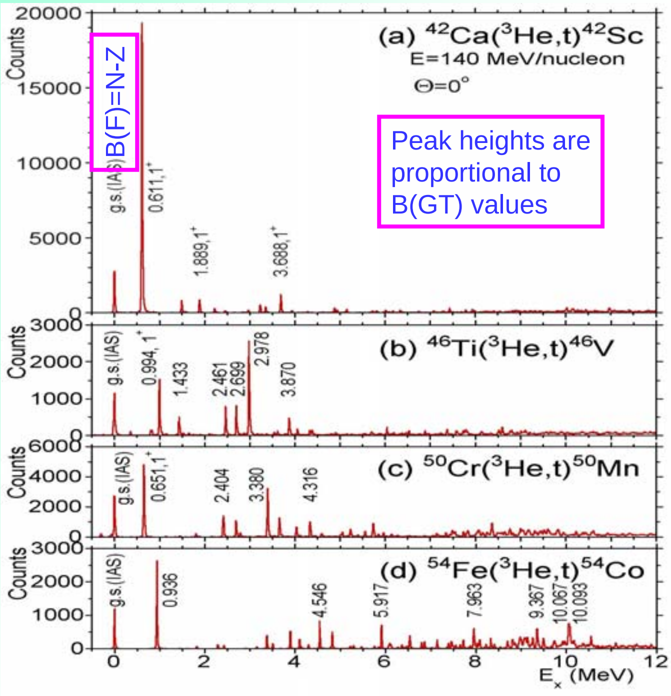
GT states in A=42-54 T_z=0 nuclei

Y. Fujita et al.
PRL 2014
PRC 2015

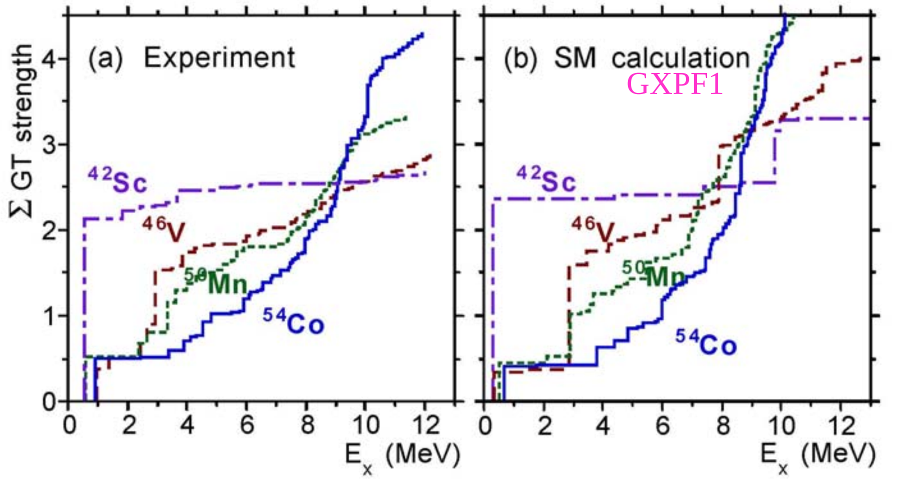
T. Adachi et al.
PRC 2006

Y. Fujita et al.
PRL 2005

T. Adachi et al.
PRC 2012

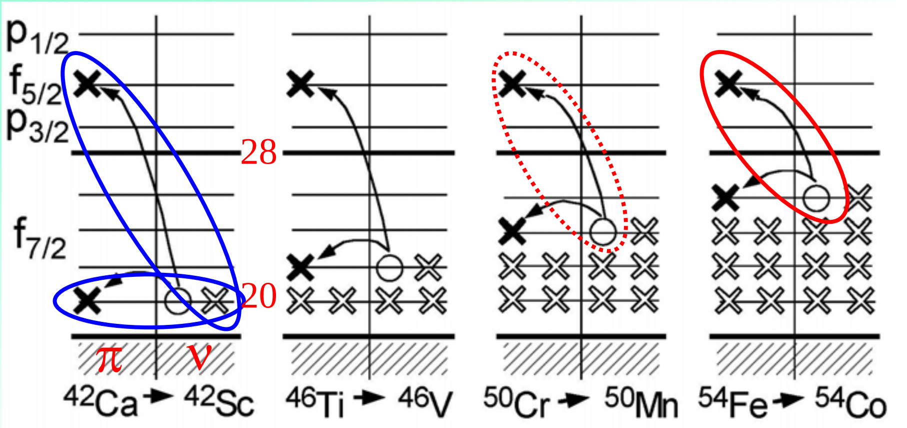


GT-strength: Cumulative Sum

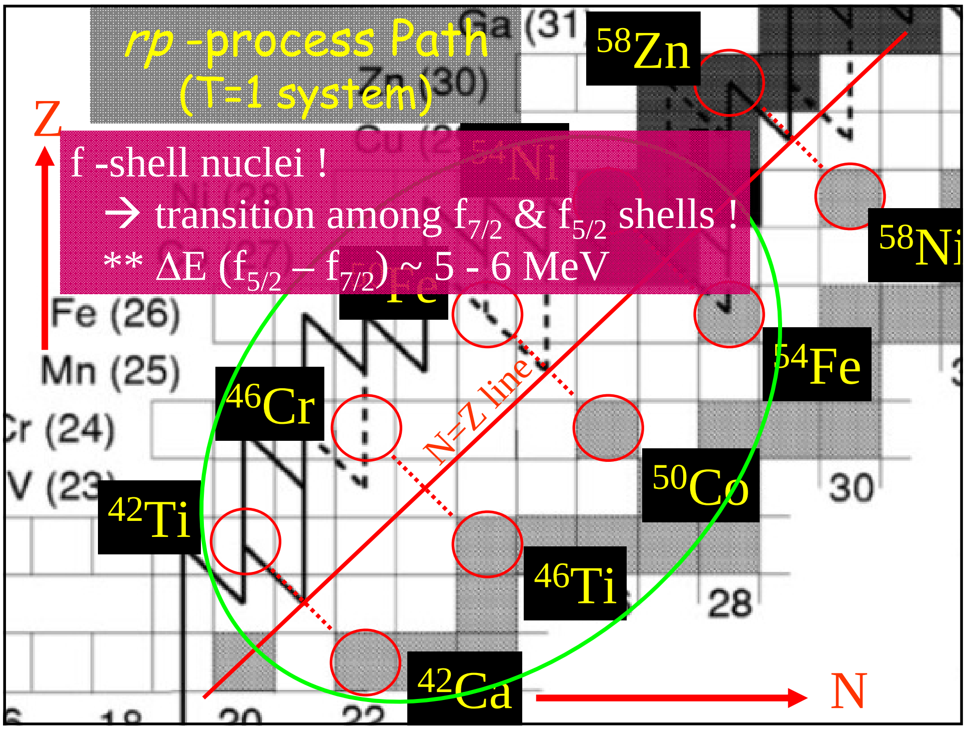


M. Homma et al.

SM Configurations of GT transitions



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



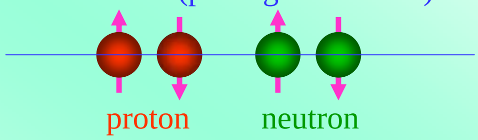
IS & IV pairing and "Residual Interactions"

However, J^π values of even-even nuclei are $J^\pi=0^+$.

➡ We notice the importance of the spin-spin coupling.

(pairing interaction)

ex. $1s_{1/2}$

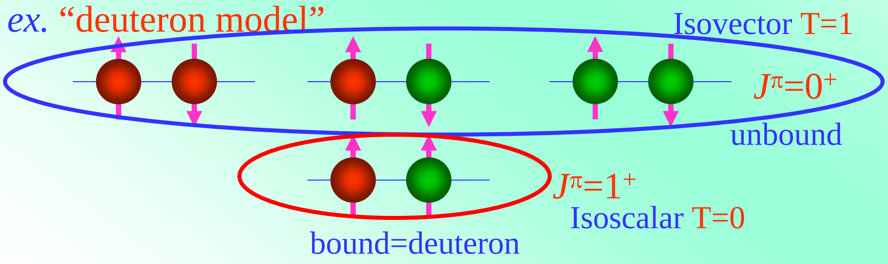


$={}^4He = \alpha$

$J^\pi=0^+$

In general, interactions that are not included in a model are called "residual interactions"

ex. "deuteron model"



Role of Residual Int. (repulsive)

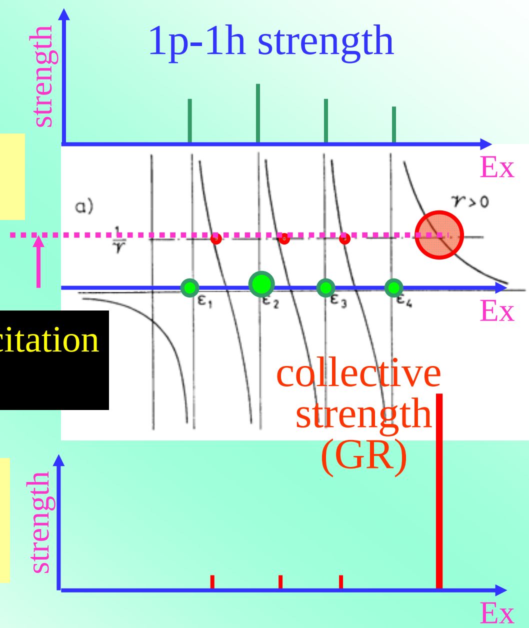
Single particle-hole strength distribution

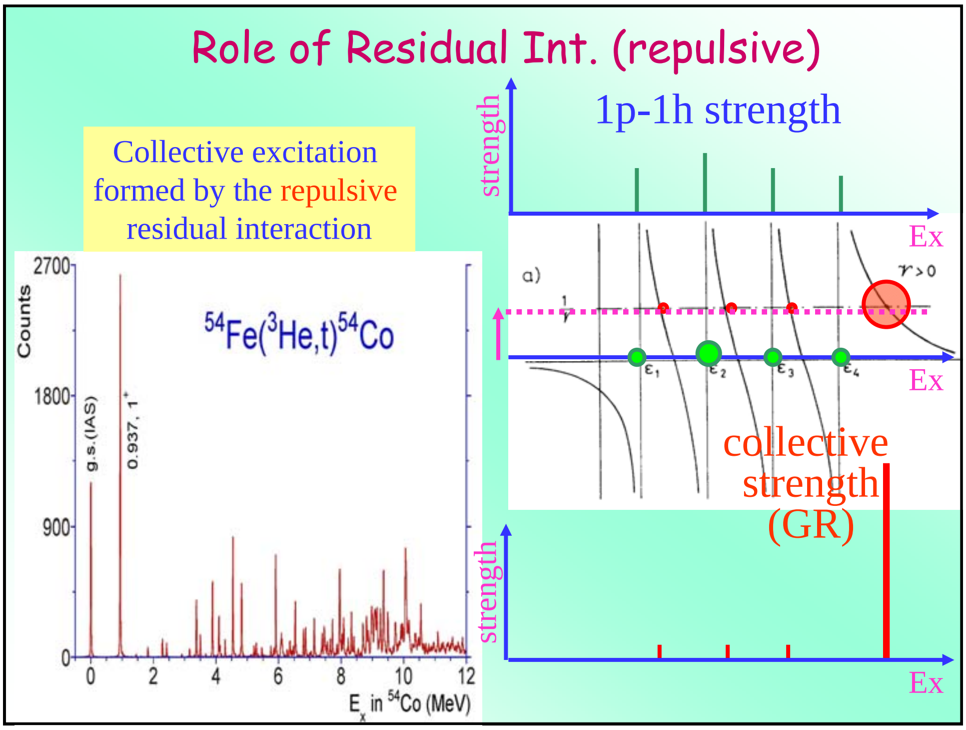
Graphical solution of the RPA dispersive eigen-equation

positive = repulsive

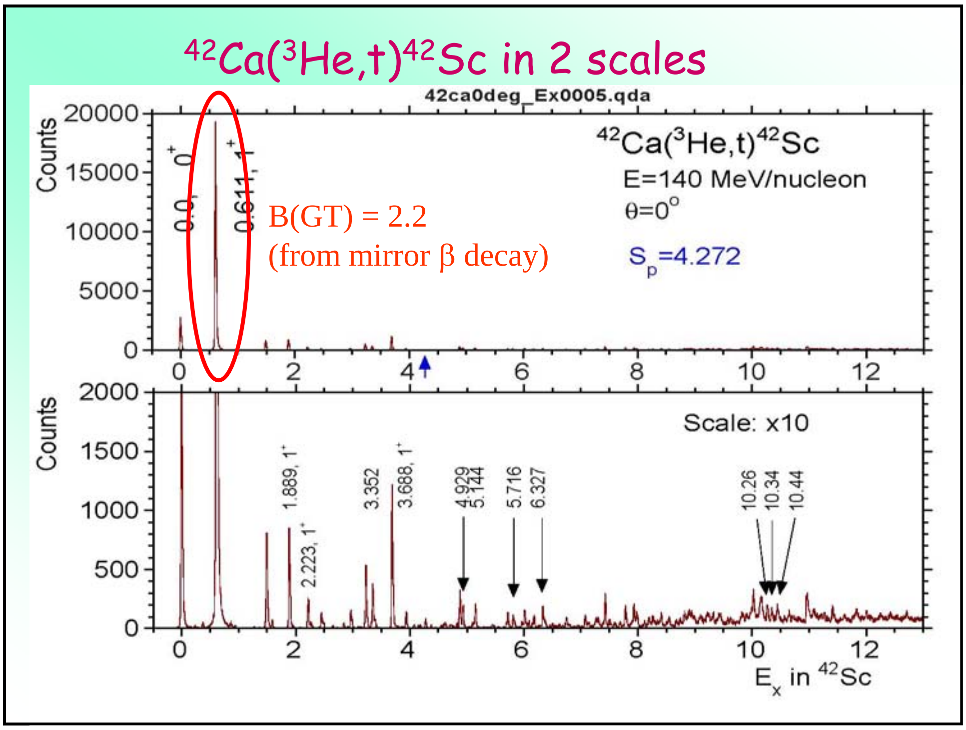
p-h configuration + IV excitation = repulsive

Collective excitation formed by the repulsive residual interaction





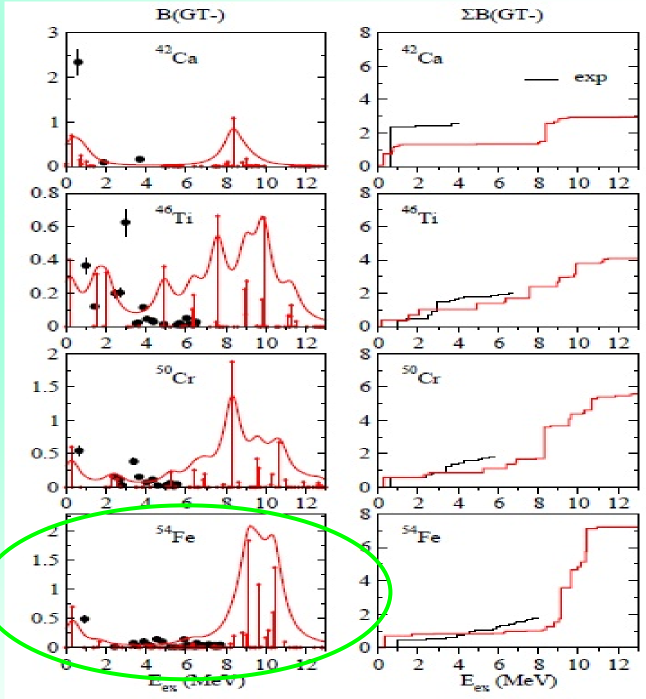
Role of Residual Int. (repulsive)
Collective excitation formed by the repulsive residual interaction
^{54}Fe(^{3}He,t)^{54}Co
Counts
2700
1800
900
0
g.s.(IAS)
0.937, 1+
0
2
4
6
8
10
12
E$_x$ in ^{54}Co (MeV)
1p-1h strength
strength
Ex
a)
Ex
collective strength (GR)
strength
Ex



^{42}Ca(^{3}He,t)^{42}Sc in 2 scales
42ca0deg_Ex0005.qda
^{42}Ca(^{3}He,t)^{42}Sc
E=140 MeV/nucleon
θ=0°
S$_p$=4.272
B(GT) = 2.2
(from mirror β decay)
Counts
20000
15000
10000
5000
0
Scale: x10
2000
1500
1000
500
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
E$_x$ in ^{42}Sc

QRPA calculations

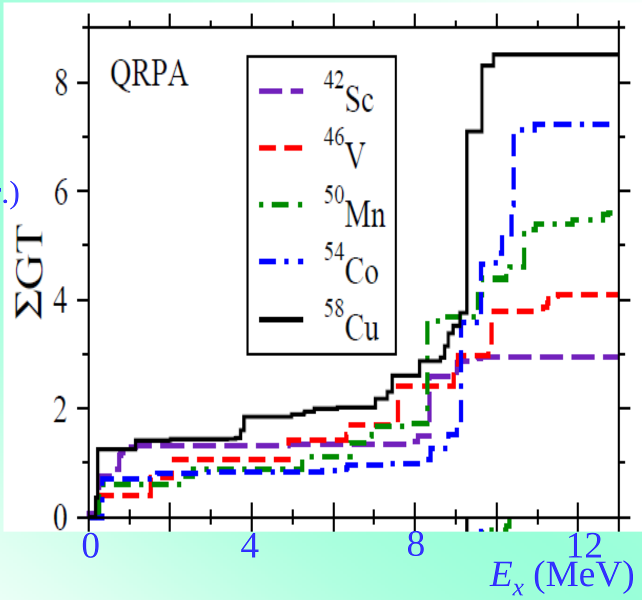
using Skyrme int. SG1
(with IV pairing corr.)



Calculation by
P. Sarrigren,
CSIC, Madrid

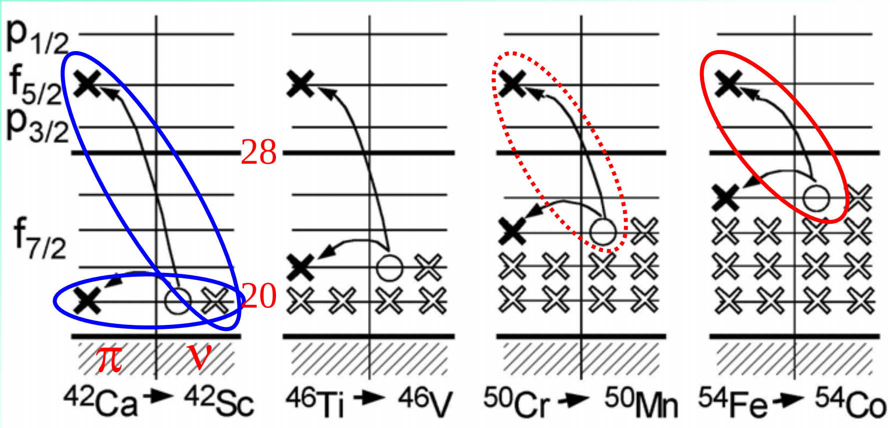
QRPA calculations

using Skyrme int.
(with IV pairing corr.)



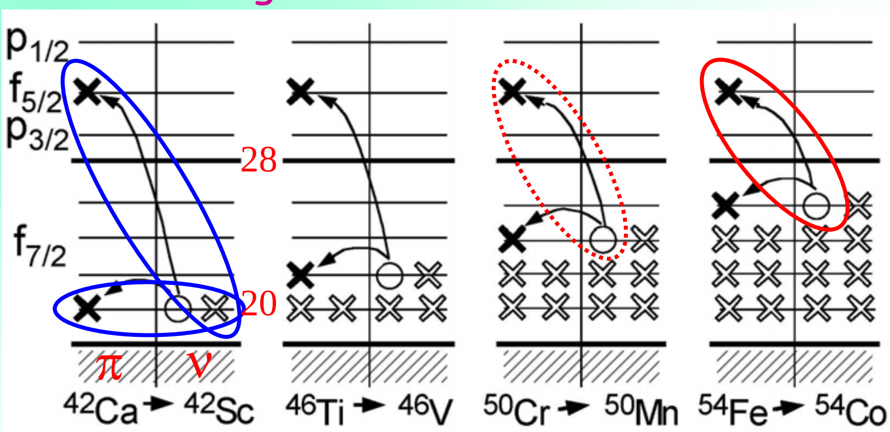
Calculation by
P. Sarrigren,
CSIC, Madrid

SM Configurations of GT transitions



particle-hole configuration
+ IV-type int.
= REPULSIVE

SM Configurations of GT transitions

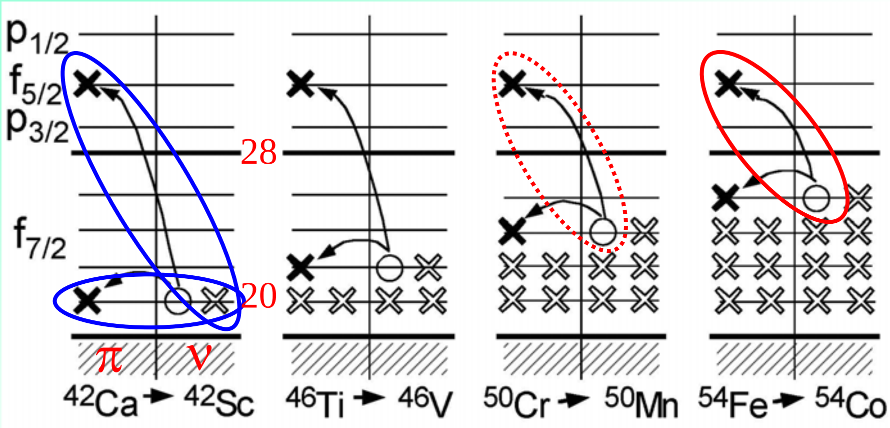


π-p - ν-p configurations
sensitive to IS pairing int.
➔attractive
(spin-triplet, IS int. is stronger
than spin-singlet, IV int.)

particle-hole configurations
+ IV-type excitation (στ)
➔repulsive

by Engel, Bertsch, Macchiavelli

SM Configurations of GT transitions



particle-particle int. (attractive) ⟶ particle-hole int. (repulsive)

(IS p-n int. is attractive)

Isoscalar interaction can play Important roles !

GT strength Calculations: HFB+QRPA + pairing int.

Bai, Sagawa, Colo et al., PL B 719 (2013) 116

The density dependent contact pairing interactions are adopted for both $T=1$ and $T=0$ channels,

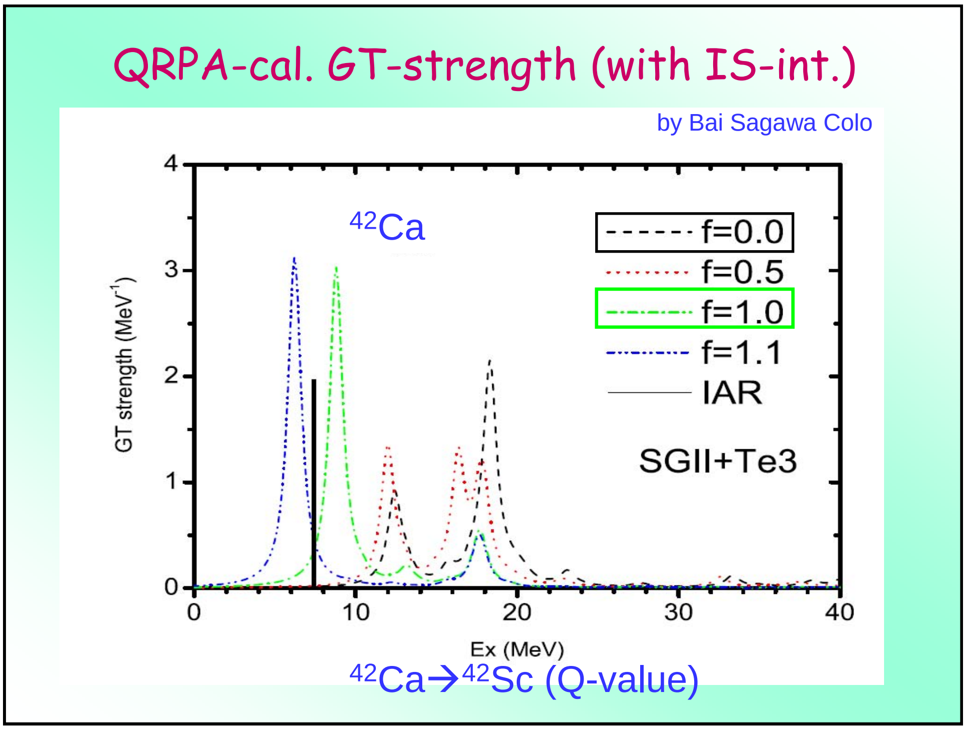
IV $$V_{T=1}(\mathbf{r}_1,\mathbf{r}_2)=V_0\frac{1-P_\sigma}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}_1-\mathbf{r}_2), \quad (1)$$

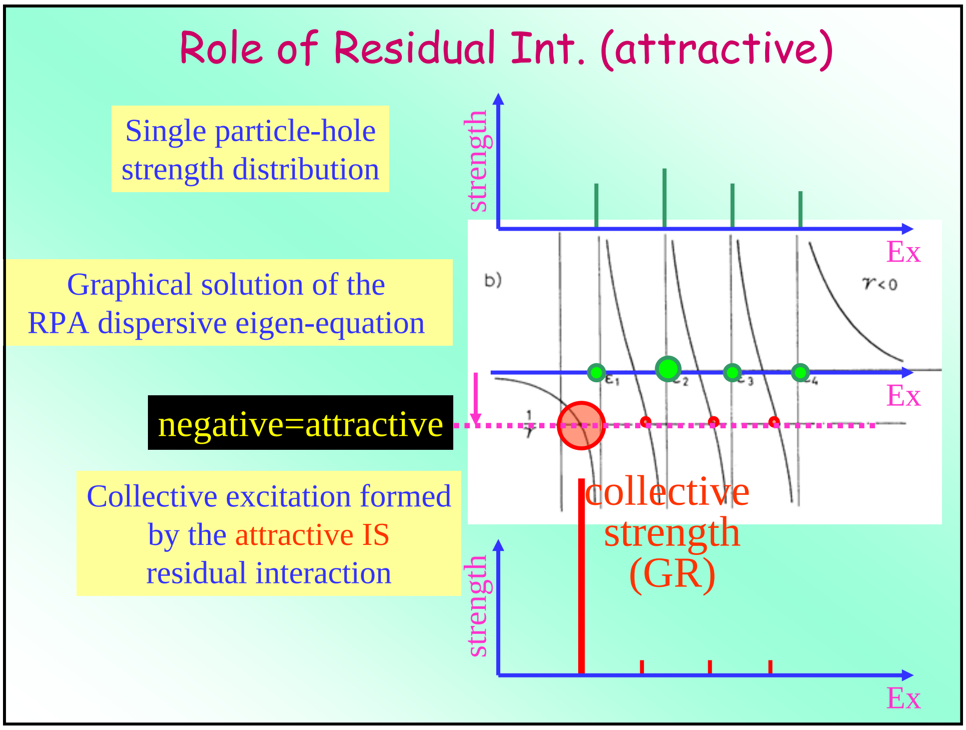
IS $$V_{T=0}(\mathbf{r}_1,\mathbf{r}_2)=fV_0\frac{1+P_\sigma}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}_1-\mathbf{r}_2), \quad (2)$$

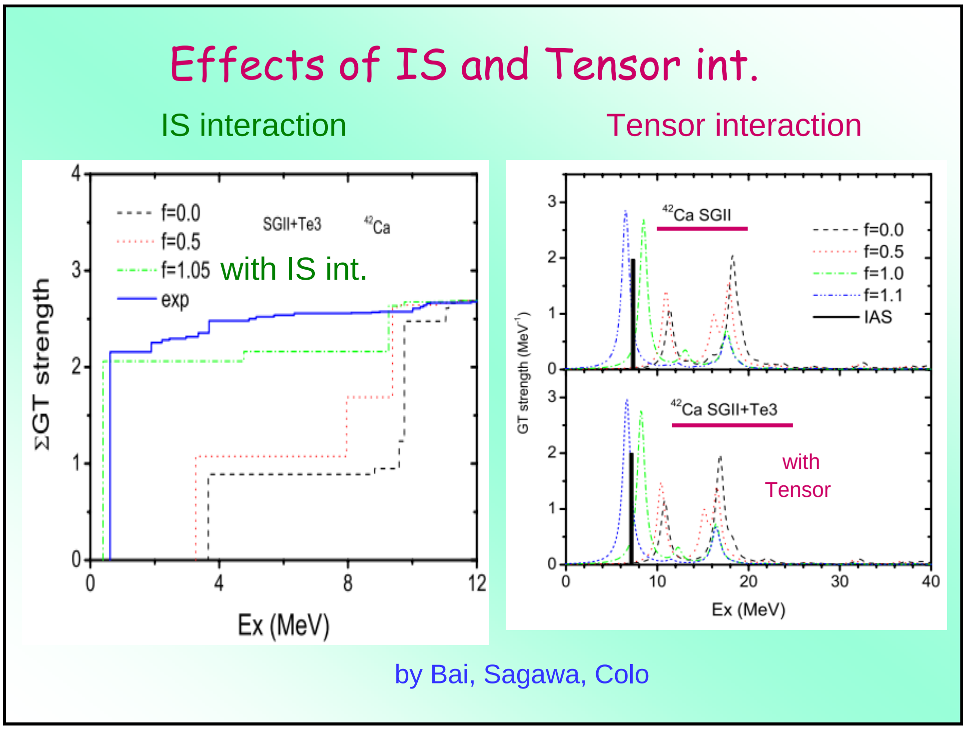
Results (using Skyrme int. SGII)

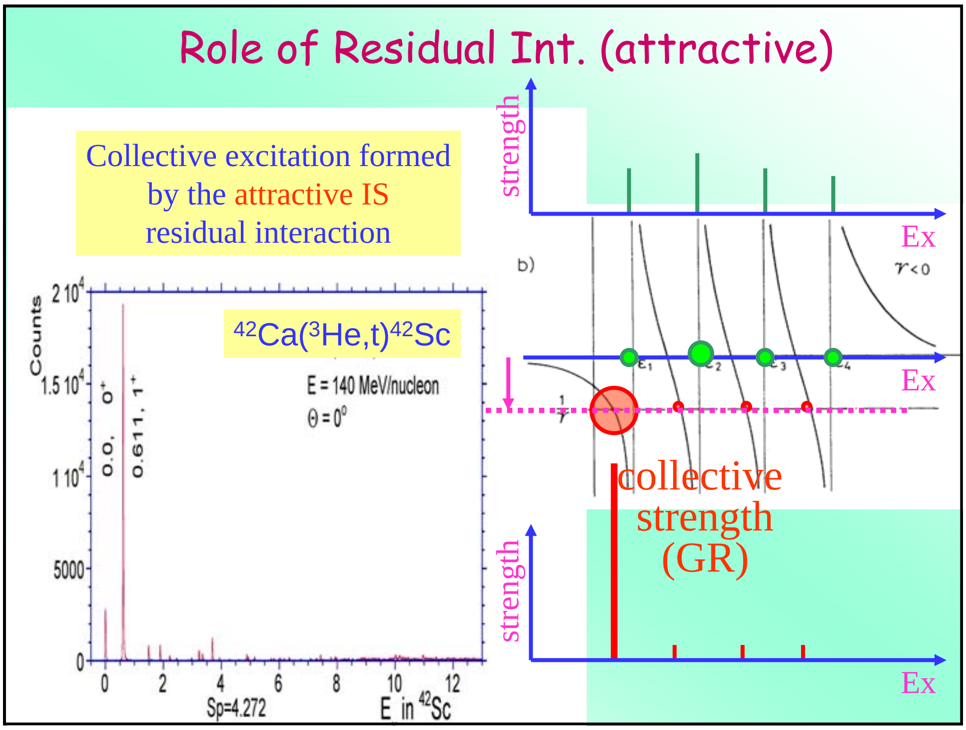
at $f=0$: there is little strength in the lower energy part,

at $f=1.0\sim1.7$: coherent low-energy strength develops!


QRPA-cal. GT-strength (with IS-int.)
by Bai Sagawa Colo
42Ca
f=0.0
f=0.5
f=1.0
f=1.1
IAR
SGII+Te3
GT strength (MeV-1)
Ex (MeV)
42Ca→42Sc (Q-value)


Role of Residual Int. (attractive)
Single particle-hole strength distribution
Graphical solution of the RPA dispersive eigen-equation
negative=attractive
Collective excitation formed by the attractive IS residual interaction
strength
Ex
b)
collective strength (GR)


Effects of IS and Tensor int.
IS interaction
Tensor interaction
ΣGT strength
f=0.0
f=0.5
f=1.05
exp
SGII+Te3
42Ca
with IS int.
Ex (MeV)
GT strength (MeV⁻¹)
42Ca SGII
f=0.0
f=0.5
f=1.0
f=1.1
IAS
42Ca SGII+Te3
with
Tensor
Ex (MeV)
by Bai, Sagawa, Colo


Role of Residual Int. (attractive)
Collective excitation formed
by the attractive IS
residual interaction
42Ca(3He,t)42Sc
E = 140 MeV/nucleon
Θ = 0°
0.0, 0+
0.611, 1+
Counts
Sp=4.272
E in 42Sc
strength
Ex
b)
strength
Ex
collective
strength
(GR)
strength
Ex

QRPA cal. including IS int.

C.L. Bai, H. Sagawa, G. Colo

f	Bnp			
0	1.34			
	neutron	proton	(Xupvn+Yunvp)	(Xupvn+Yunvp)*<p||GT||n>
	1f7/2	1f7/2	0.427	1.3689
0.5	2.051			
	1f7/2	1f7/2	0.432	1.384
1	4.75			
	1f5/2	1f7/2	0.053	0.2158
	1f7/2	1f5/2	0.129	0.474
	1f7/2	1f7/2	0.33	1.059

Configurations are in phase!

42Ca→42Sc: Shell Model Cal.: Transition Matrix Elements

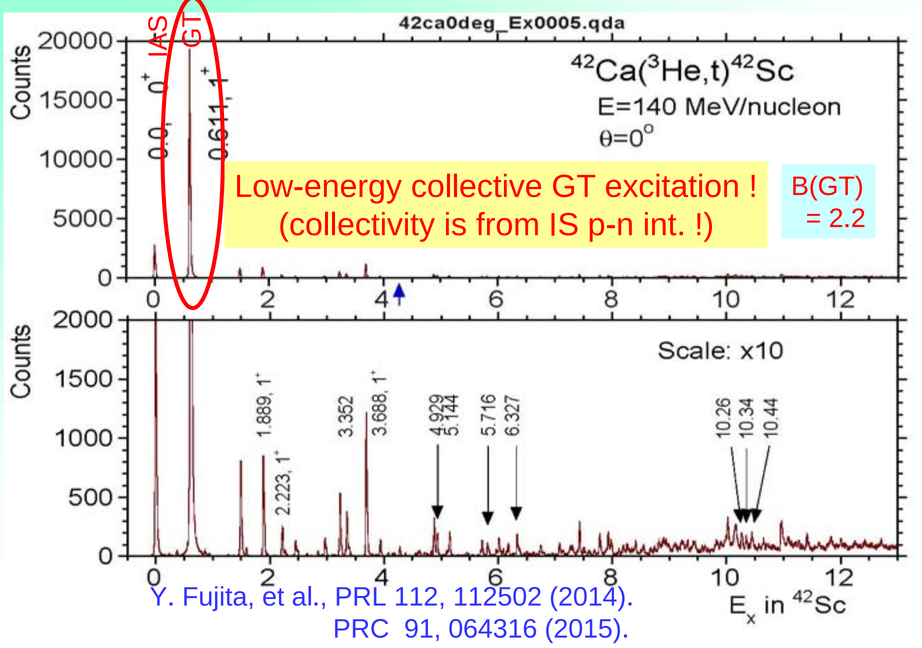
TABLE VI. Results of the *pf*-shell SM calculation using the GXPF1J interaction. The matrix elements M(GT) of GT transitions exciting individual $J^\pi = 1^+$ GT states in ^{42}Sc from the g.s. of ^{42}Ca are shown for each configuration. The results are shown for all excited GT states predicted in the region up to 9.82 MeV. The notation $f7 \to f7$, for example, stands for the transition with the $\nu f_{7/2} \to \pi f_{7/2}$ type and $p3 \to p3$ the $\nu p_{3/2} \to \pi p_{3/2}$. The summed value of the matrix elements is denoted by ΣM(GT) and its squared value is the B(GT), where the B(GT) values do not include the quenching factor of the SM calculation.

SM cal: M. Honma

States in ^{42}Sc		Configurations						Transition strengths	
E_x (MeV)	T	$f7 \to f7$	$f7 \to f5$	$f5 \to f7$	$p3 \to p3$	$p3 \to p1$	$p1 \to p3$	ΣM(GT)	B(GT)
0.33 1^+_1	0	1.383	0.548	0.063	0.031	0.024	0.016	2.07	4.28
4.41	0	0.719	−0.742	−0.085	−0.079	−0.073	−0.048	−0.31	0.09
7.41	0	0.193	−0.788	−0.090	0.142	0.060	0.040	−0.44	0.19
8.62	0	−0.151	0.385	0.044	0.109	−0.071	−0.047	0.30	0.09
9.82	1	0.0	1.196	−0.137	0.0	−0.053	0.035	1.04	1.08

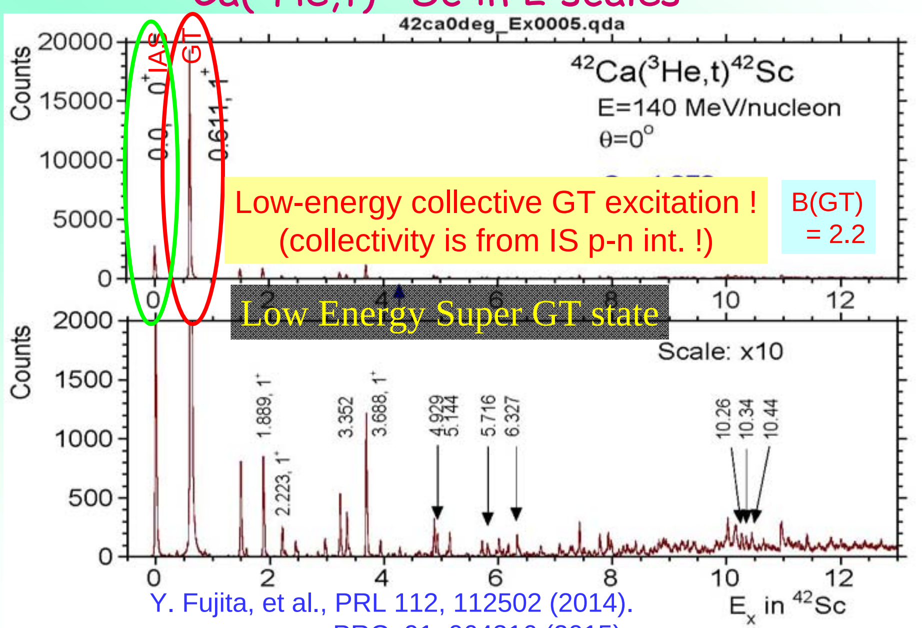
Matrix Elements are **in-phase** !

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



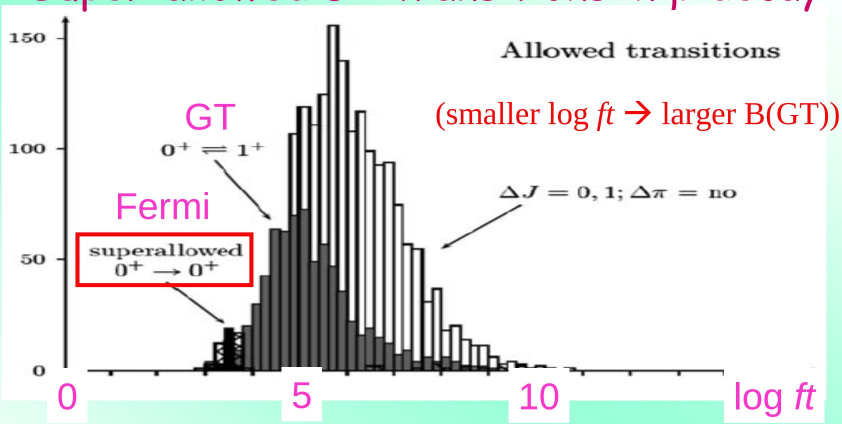
Y. Fujita, et al., PRL 112, 112502 (2014).
PRC 91, 064316 (2015).

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



Y. Fujita, et al., PRL 112, 112502 (2014).
PRC 91, 064316 (2015).

Super-allowed GT transitions in β decay



$^{6}He, 0^+ \to {}^{6}Li, 1^+$ log *ft* = 2.9
$^{18}Ne, 0^+ \to {}^{18}F, 1^+$ log *ft* = 3.1
$^{42}Ti, 0^+ \to {}^{42}Sc, 1^+$ log *ft* = 3.2

Super-allowed GT transitions

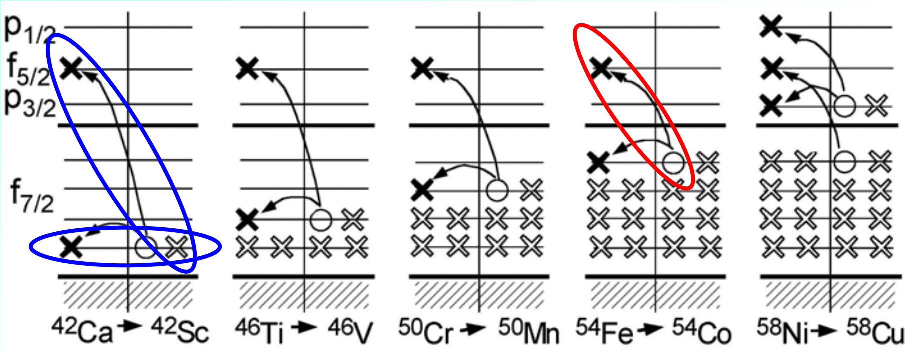
Super-Multiplet State

*proposed by Wigner (1937)

In the limit of null *L·S* force, SU(4) symmetry exists.
We expect:
a) GT excitation strength is concentrated in a low-energy GT state.
b) excitation energies of both the IAS and the GT state are identical.
→ *Super-Multiplet State*

In ^{54}Co, we see a broken SU(4) symmetry.
In ^{42}Sc, we see a good SU(4) symmetry.
→ attractive IS residual int. restores the symmetry !
→ 0.611 MeV state in ^{42}Sc has a character close to *Super-Multiplet State* !
We call this state the *Low-energy Super GT state* !

SM Configurations of GT transitions



particle-particle int. (attractive)
(T=0, IS p-n int. is attractive)

particle-hole int. (repulsive)

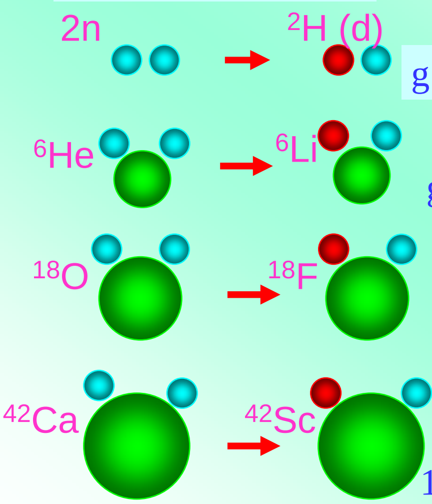
Isoscalar interaction can play Important roles !

← *N=Z* LS-closed Core + 2 nucleon system !

GT transitions forming Low-Energy Super GT state

$J^{\pi} = 0^{+}$ → 1^{+}

Σ (Sum rule) = 3 x |N-Z| = 6



g.s. B(GT) = 6.0 ? Large !

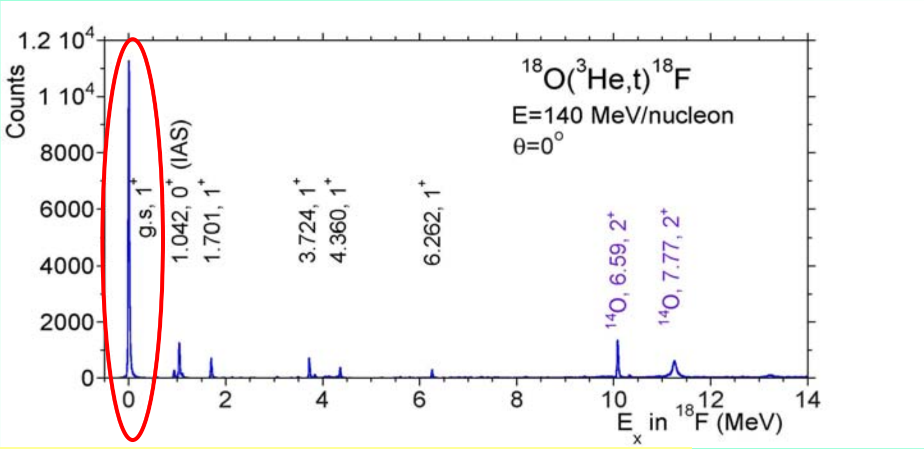
g.s. B(GT) = 4.73

g.s. B(GT) = 3.09

B(GT) = 2.17 Smaller !

1st E_x state (IAS is the g.s.)

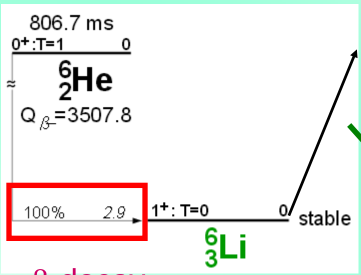
$^{18}O(^{3}He,t)^{18}F$ at 0°

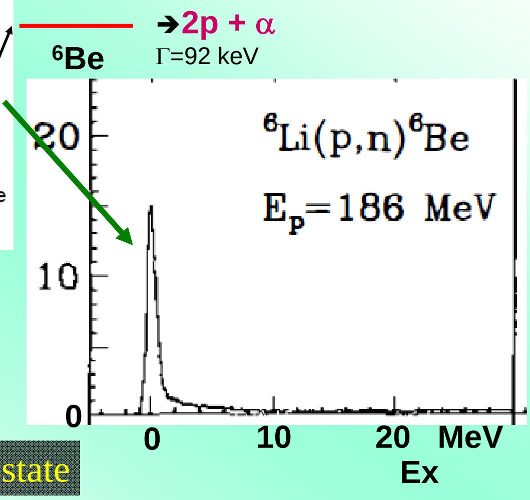


Low-energy collective GT excitation: B(GT)=3.1

Low Energy Super GT state

^{6}He β^{-}-decay & $^{6}Li(p,n)^{6}Be$



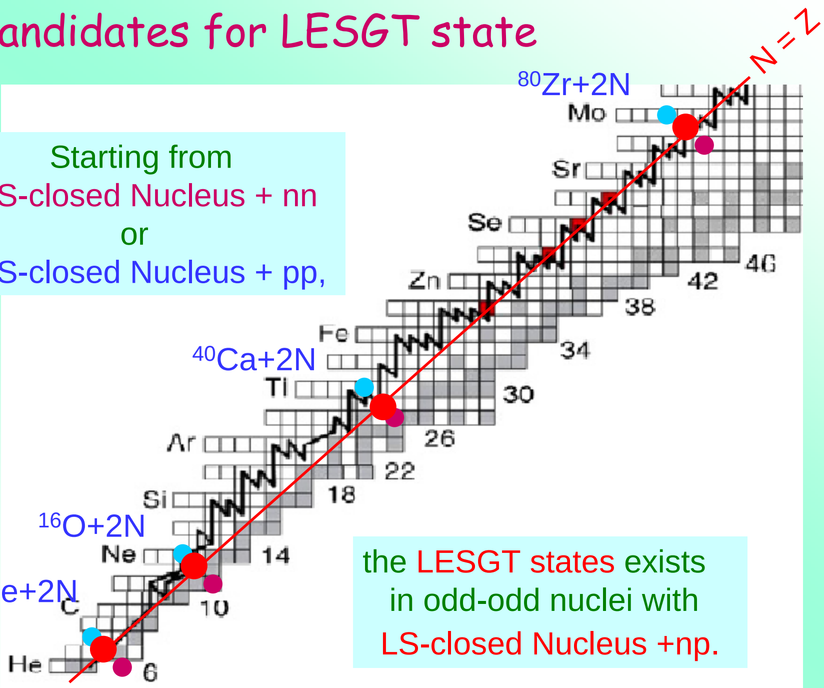


β-decay
log *ft* = 2.9
[B(GT) = 4.7]

Low Energy Super GT state

Candidates for LESGT state

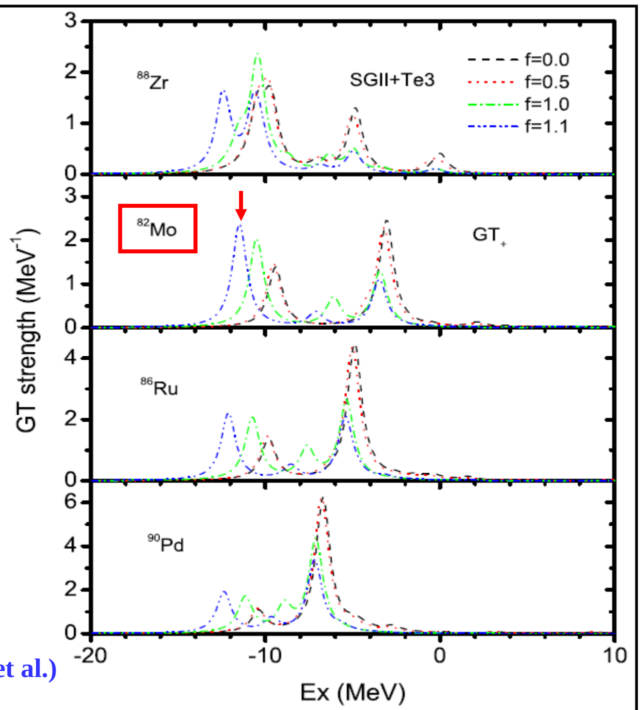
Starting from
LS-closed Nucleus + nn
or
LS-closed Nucleus + pp,



the LESGT states exists
in odd-odd nuclei with
LS-closed Nucleus +np.

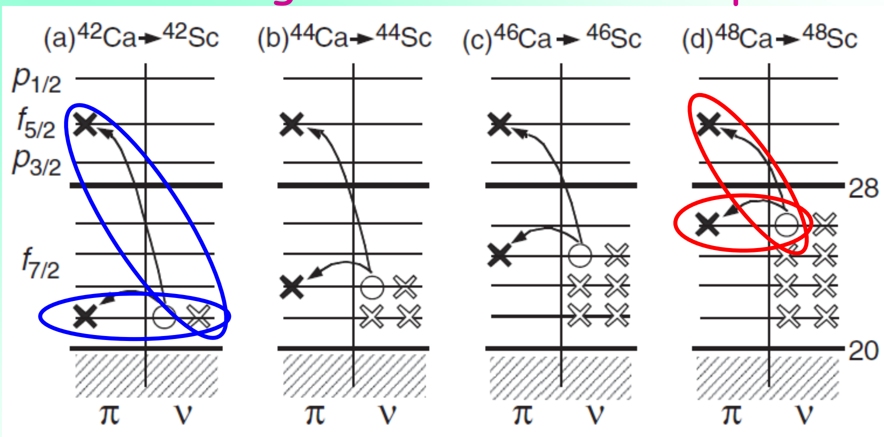
^{82}Mo β^+-decay or ^{82}Zr(p,n)^{82}Sb

Concentration of the GT strength to the lowest 1^+ state is expected only in ^{80}Zr + 2N Initial nuclei.



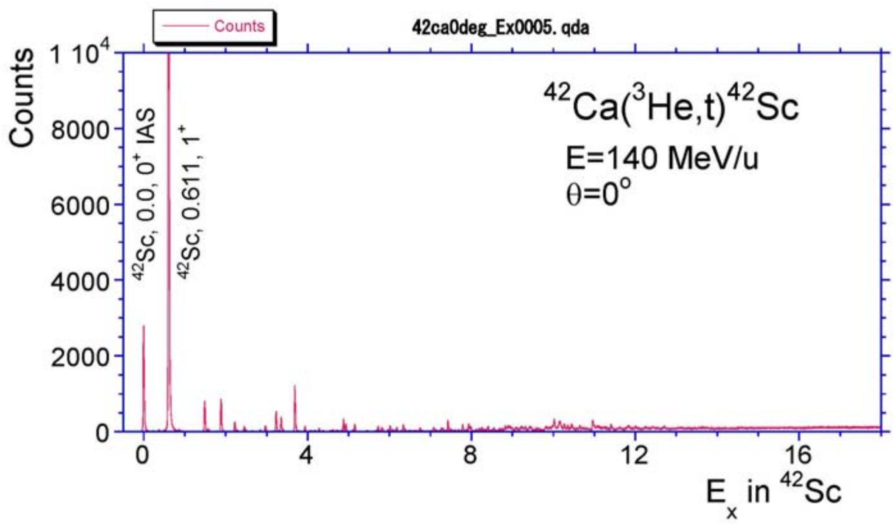
Spherical QRPA Cal.
(by C.L. Bai et al.)

GT Configurations in Sc isotopes

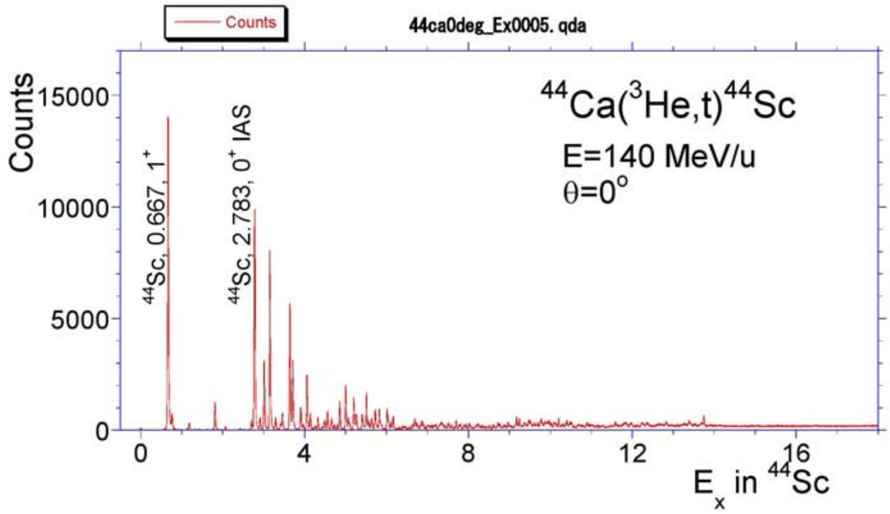


particle-particle int. (attractive) ⟶ particle-hole int. (repulsive)

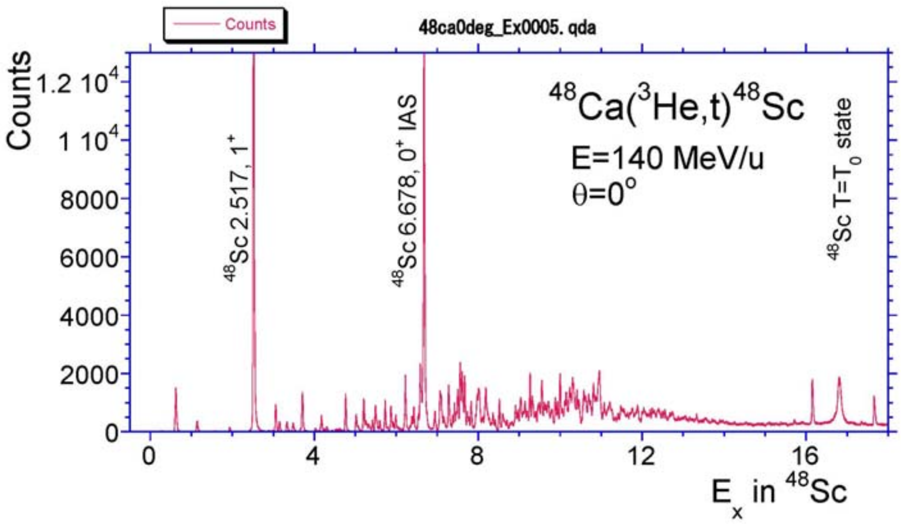
$^{42}Ca(^3He,t)^{42}Sc$



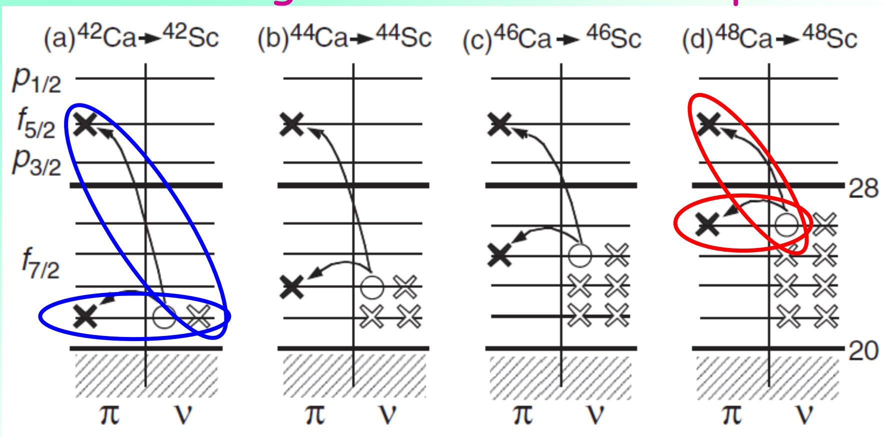
$^{44}Ca(^{3}He,t)^{44}Sc$



$^{48}Ca(^{3}He,t)^{48}Sc$



GT Configurations in Sc isotopes

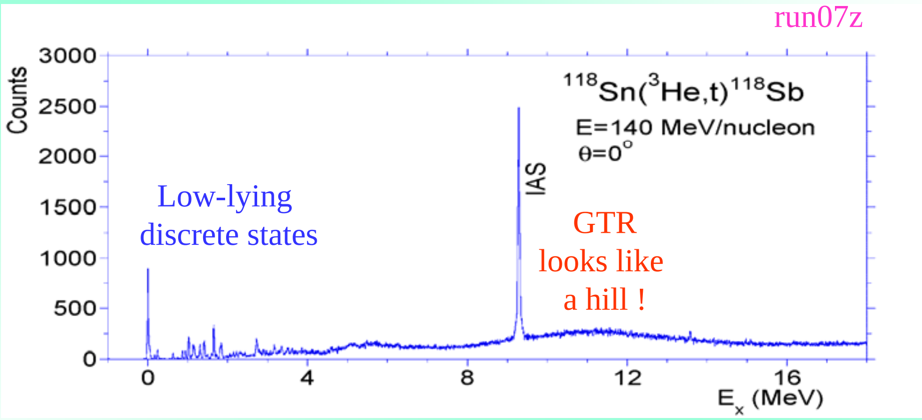


particle-particle int. (attractive) → particle-hole int. (repulsive)

Low-Energy Super GT state Is formed !

Gamow-Teller Resonance Is formed !

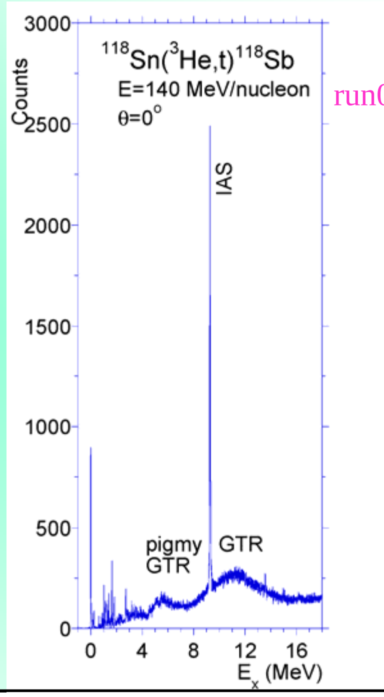
^{120}Sn(^{3}He,t)^{120}Sb spectrum (I)



Energy Resolution=30 keV

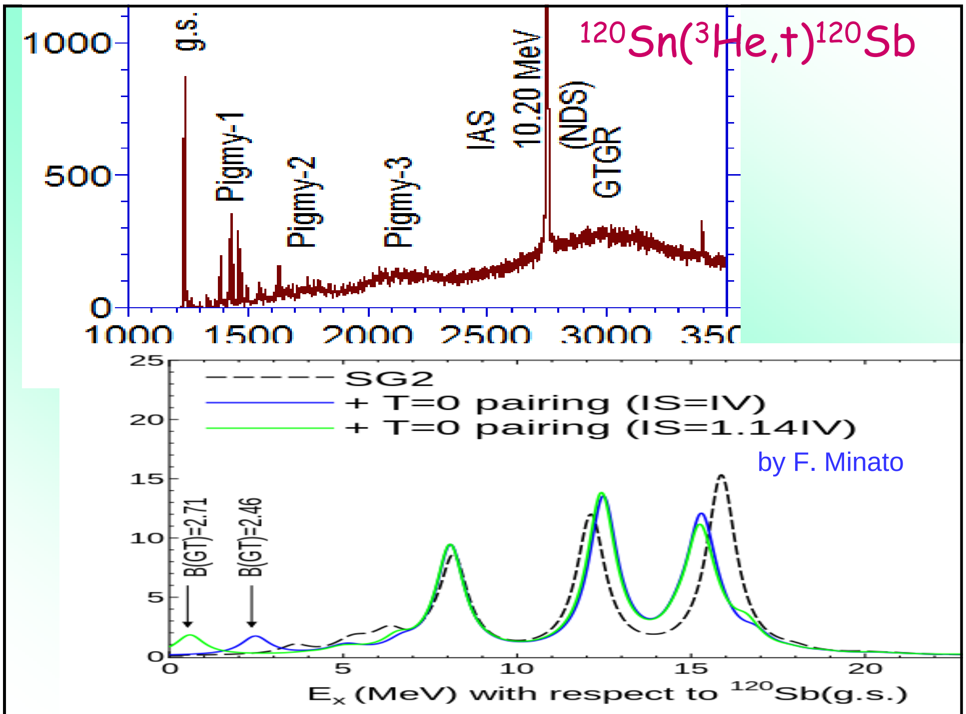
^{120}Sn(^{3}He,t)^{120}Sb spectrum (II)

height x2
width /2.5



run07z

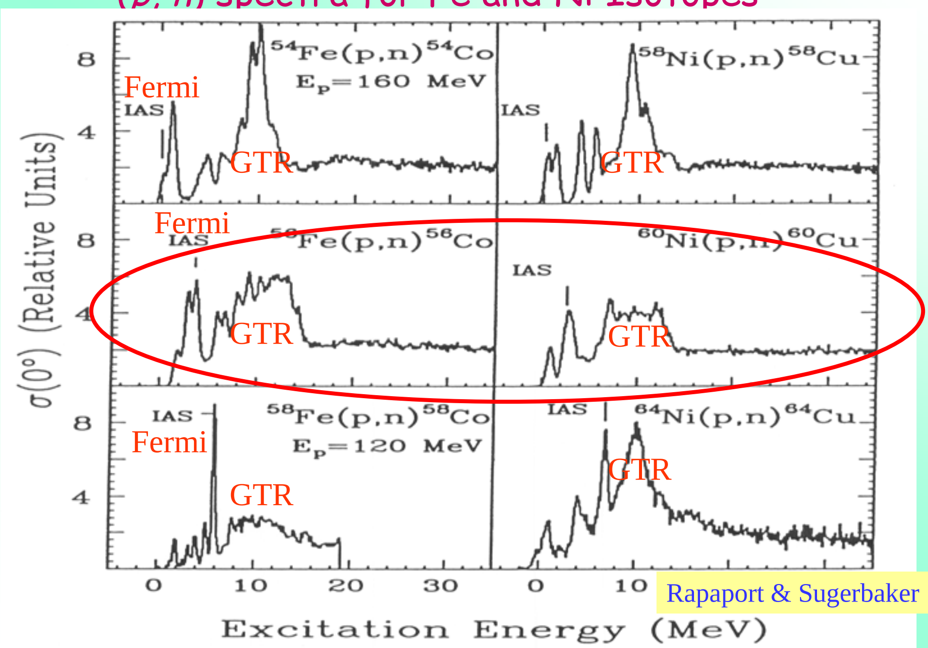
^{120}Sn(^{3}He,t)^{120}Sb

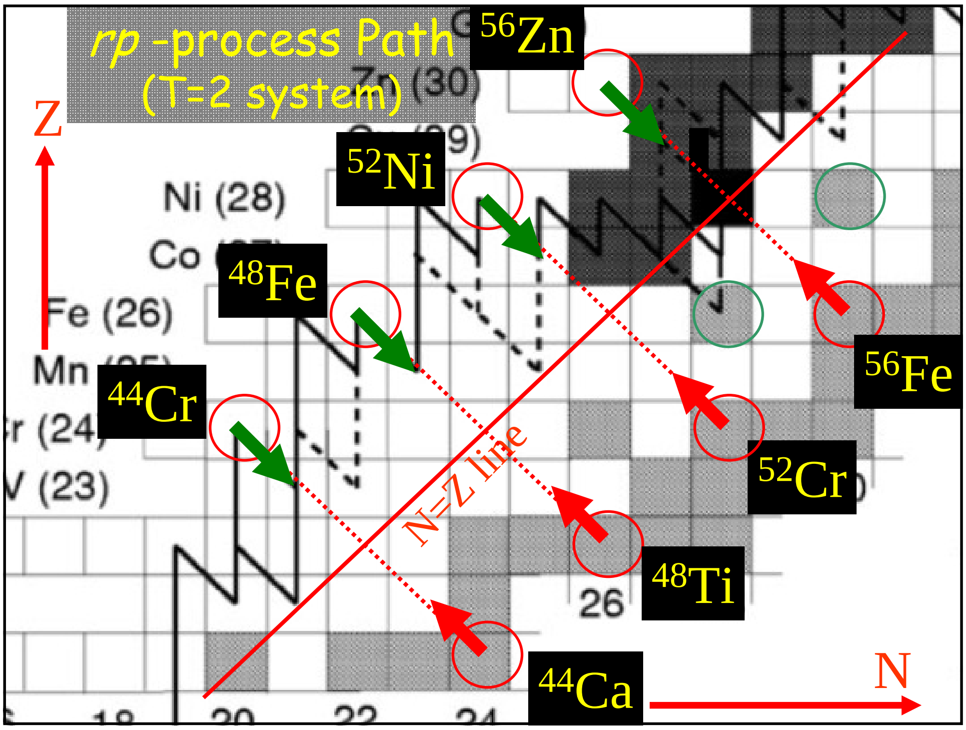


**T_z= +-2 to +-1 GT tra. in *pf*-shell nuclei

(GT transitions of *pf*-shell are unique!)

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

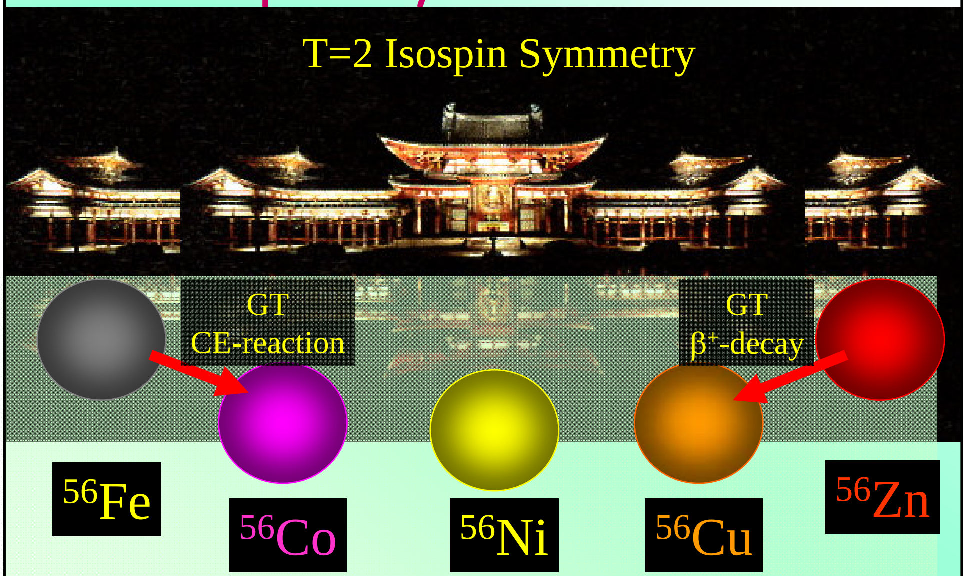



rp -process Path
(T=2 system)
Z
N
^{56}Zn
^{52}Ni
^{48}Fe
^{44}Cr
^{56}Fe
^{52}Cr
^{48}Ti
^{44}Ca
N=Z line
Ni (28)
Fe (26)
V (23)
26
20
22

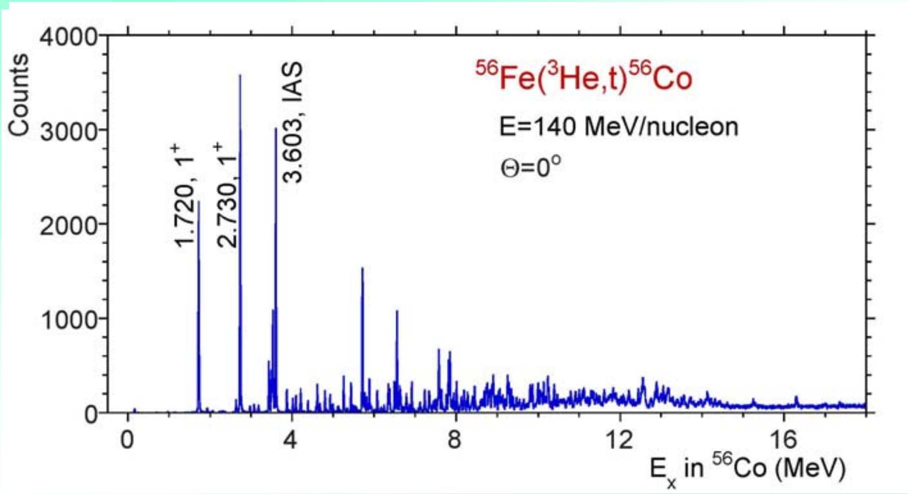

T=1 Isospin Symmetry
Byodoin-temple,
Uji, Kyoto

Super-Byodoin 平等院

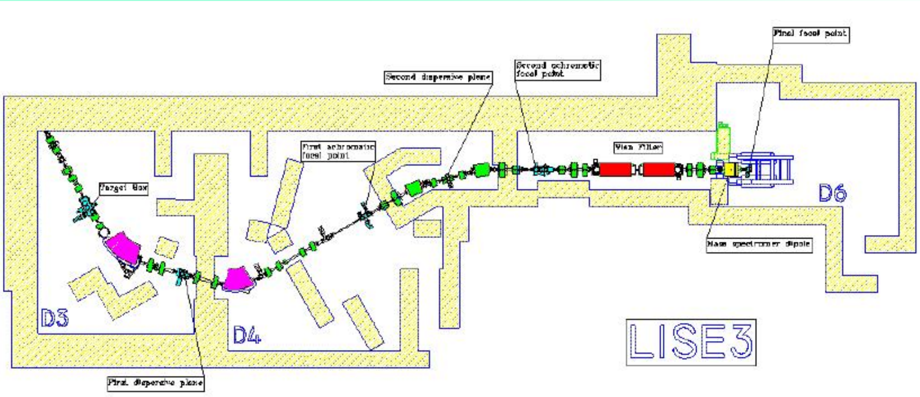
Super-Byodoin 平等院



Tz= +2→ +1 GT strengths in A=44-56

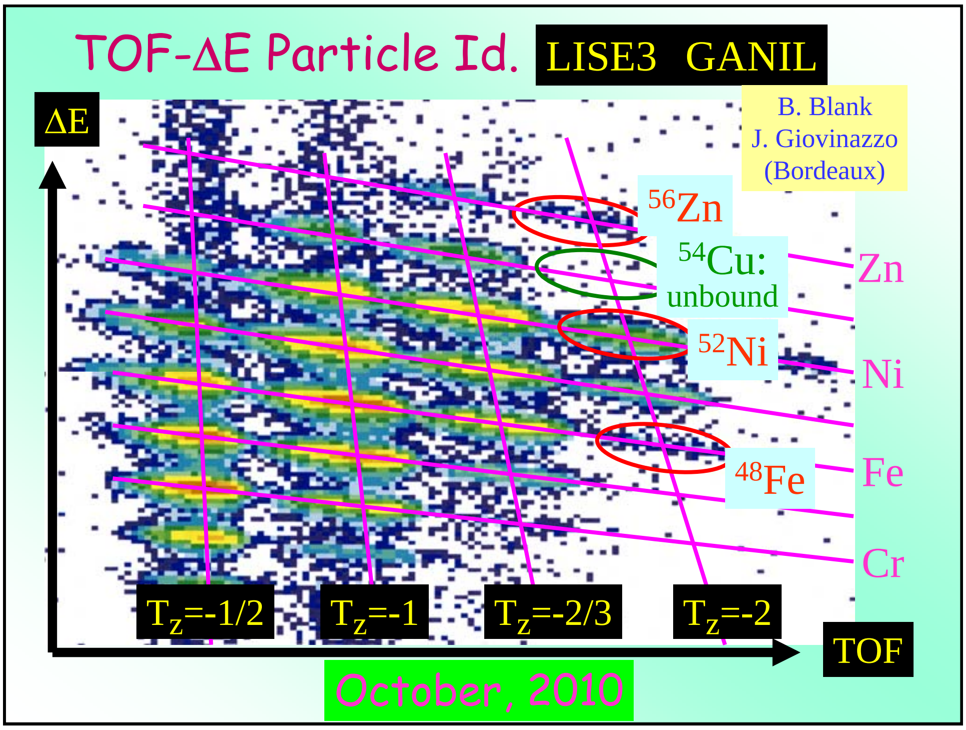


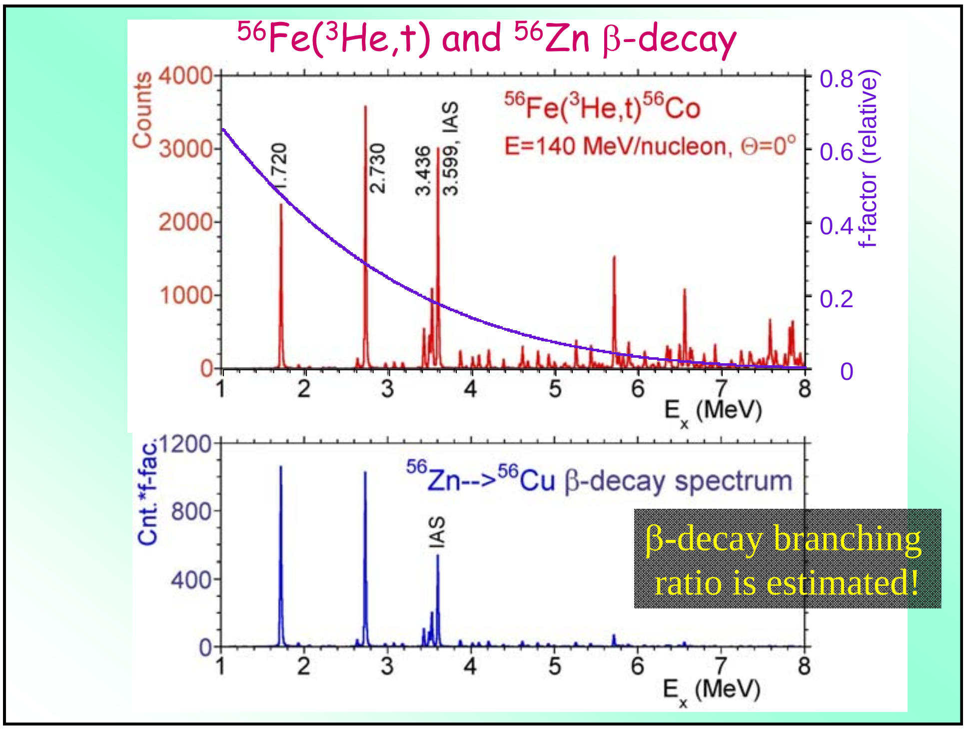
GANIL LISE3 fragment separator



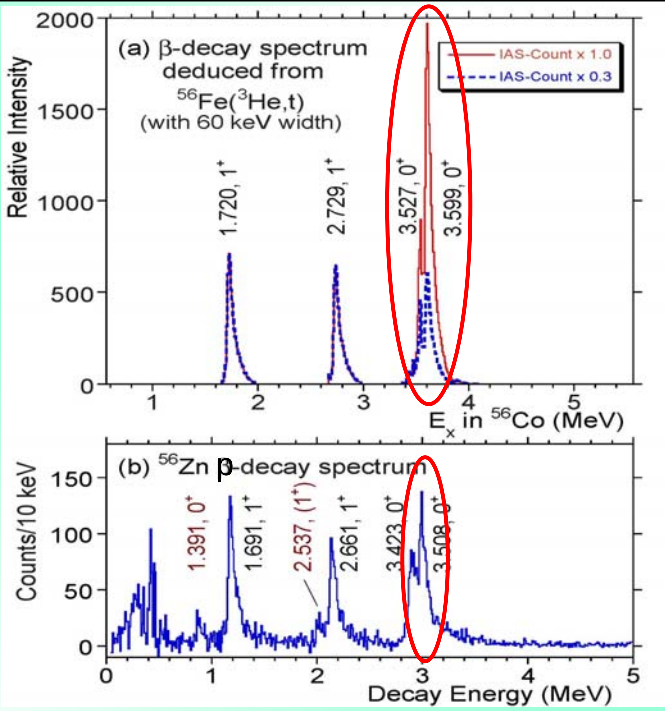
^{58}Ni beam: ~ 79MeV/u, 3.5 eμA, production target: Ni

p-decay: by DSSD, γ-decay: by Ge detectors

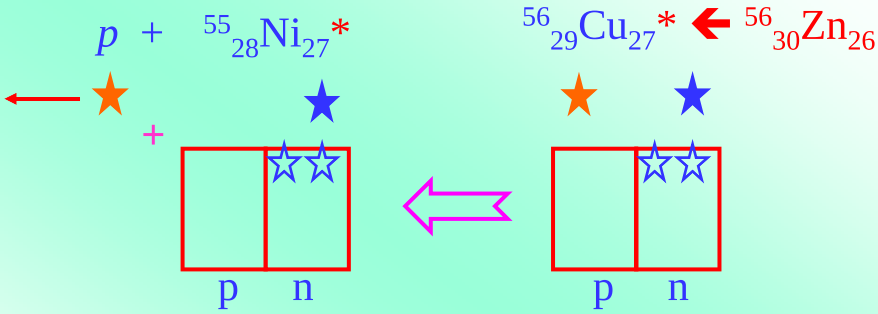

TOF-ΔE Particle Id.
LISE3 GANIL
ΔE
B. Blank
J. Giovinazzo
(Bordeaux)
56Zn
54Cu:
unbound
52Ni
48Fe
Zn
Ni
Fe
Cr
Tz=-1/2
Tz=-1
Tz=-2/3
Tz=-2
TOF
October, 2010


56Fe(3He,t) and 56Zn β-decay
56Fe(3He,t)56Co
E=140 MeV/nucleon, Θ=0°
Counts
f-factor (relative)
1.720
2.730
3.436
3.599, IAS
Ex (MeV)
Cnt.*f-fac.
56Zn-->56Cu β-decay spectrum
IAS
β-decay branching ratio is estimated!

Comparison: modified $^{56}Fe(^3He,t)$ & ^{56}Zn β-decay



Isospin Selection Rules : in *p*-decay of ^{56}Cu



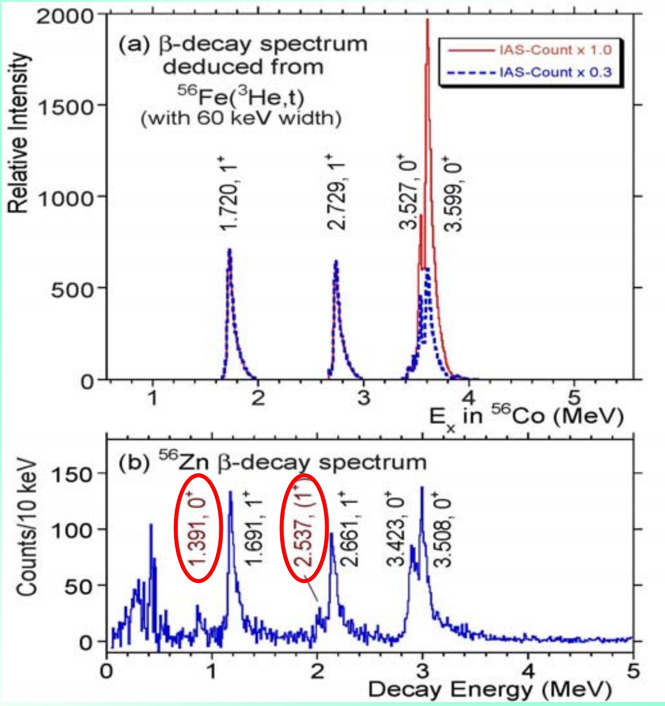
T_z : -1/2 + (-1/2) = -1

T : 1/2 + 1/2 (low lying) = 0 & 1

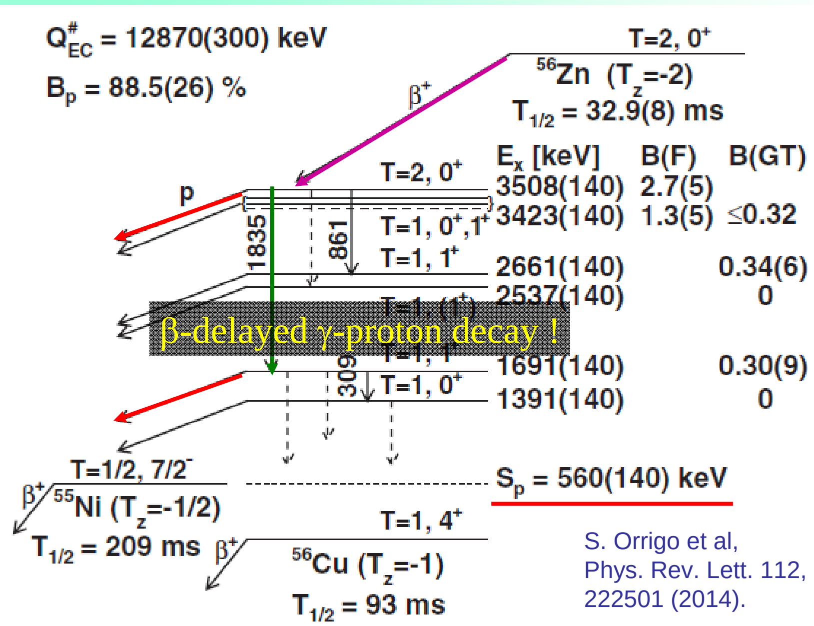
T : 1/2 + 3/2 (higher Ex) = 1 & 2

*T=3/2 state in ^{55}Ni is only in high Ex region

Comparison: modified $^{56}Fe(^{3}He,t)$ & ^{56}Zn β-decay



^{56}Zn decay scheme

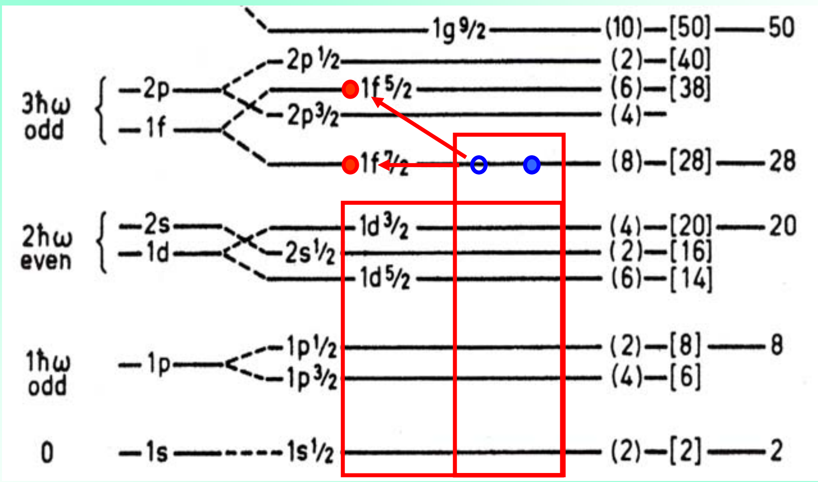


B(GT)⁻ & B(GT)⁺ strengths from Ca isotopes

Ikeda Sum Rule

$$\Sigma\, B(GT)\beta^- - \Sigma\, B(GT)\beta^+ = 3(N-Z)$$

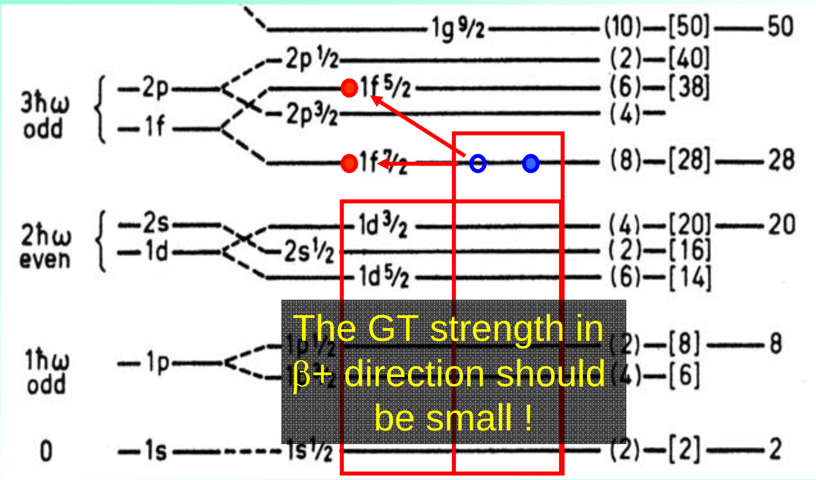
B(GT)⁻ & B(GT)⁺ strengths from Ca isotopes



neutron: $f_{7/2}$ → proton $f_{7/2}$

neutron: $f_{7/2}$ → proton $f_{5/2}$

B(GT)$^-$ & B(GT)$^+$ strengths from Ca isotopes

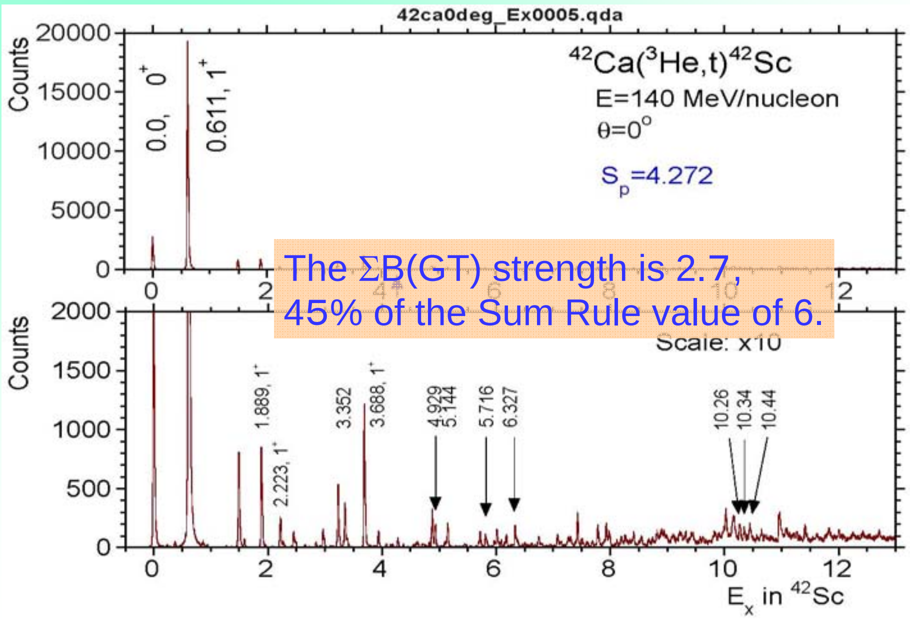


The GT strength in β+ direction should be small !

neutron: $f_{7/2}$ → proton $f_{7/2}$

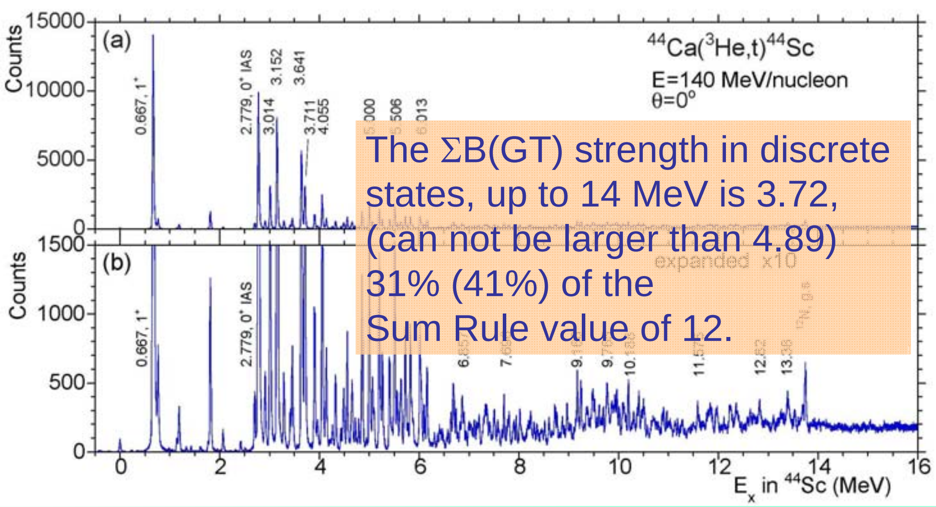
neutron: $f_{7/2}$ → proton $f_{5/2}$

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



The ΣB(GT) strength is 2.7, 45% of the Sum Rule value of 6.

$^{44}Ca(^{3}He,t)^{44}Sc$ in 2 scales



The ΣB(GT) strength in discrete states, up to 14 MeV is 3.72, (can not be larger than 4.89) 31% (41%) of the Sum Rule value of 12.

Y. Fujita et al., PRC in press

ΣB(GT) in $^{48}Ca(p,n)^{48}Sc$

In E_x < 30 MeV, ΣB(GT+IVSD =ΔL=0) is 15.3, which is 64(9)% of the Ikeda Sum Rule value of 3(N-Z) =24

K. Yako et al., PRL103 (2009)

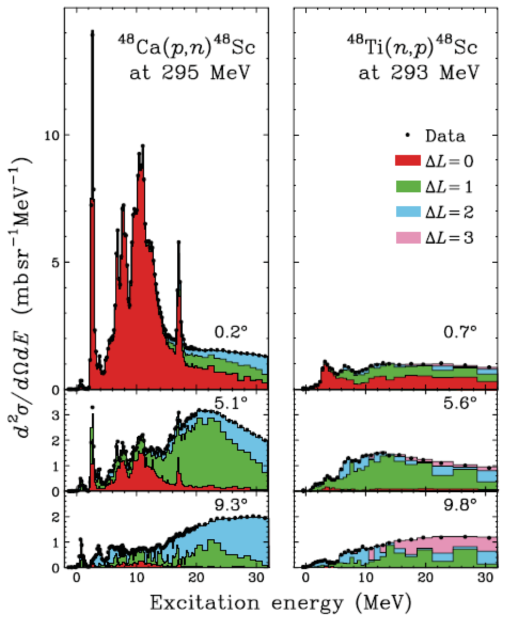
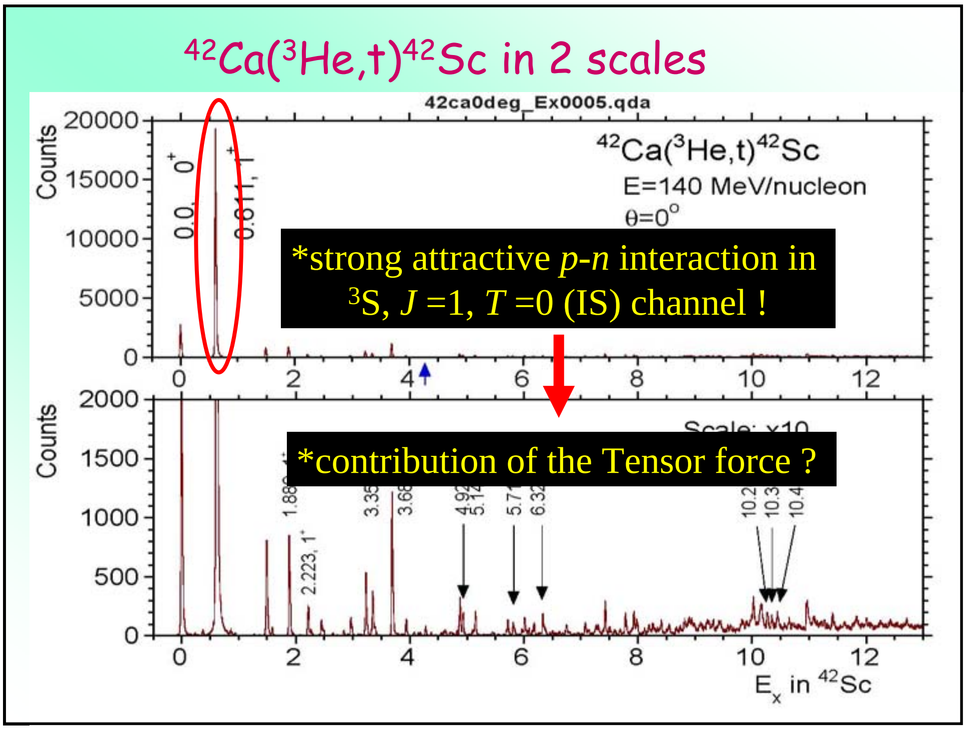
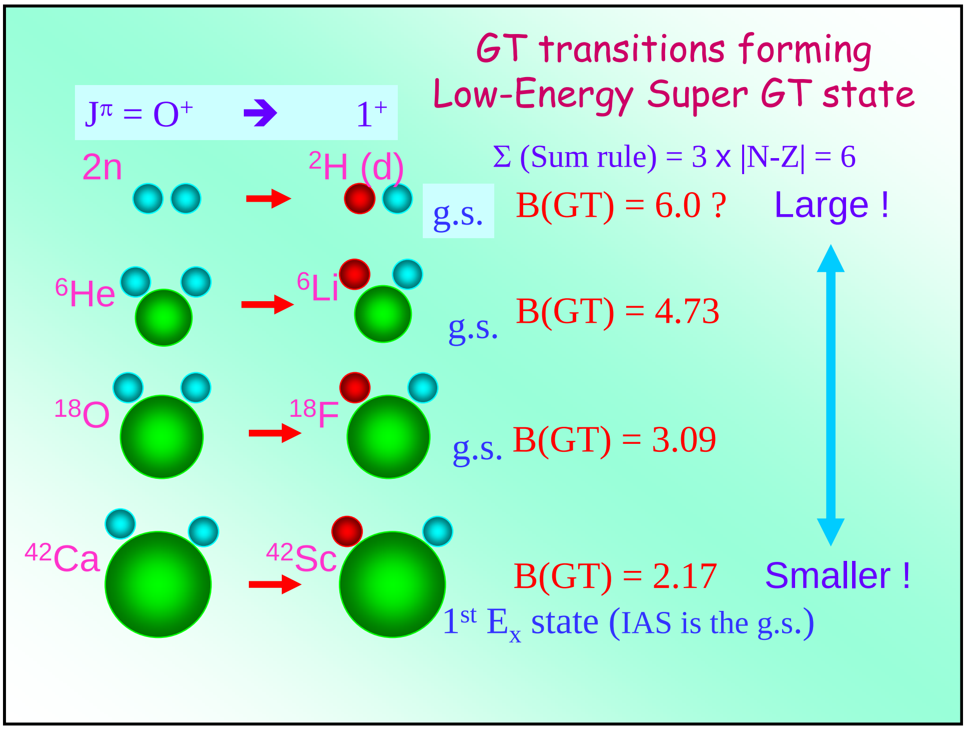


FIG. 1 (color). Double-differential cross sections for the $^{48}Ca(p,n)^{48}Sc$ (left-hand panel) and $^{48}Ti(n,p)^{48}Sc$ (right-hand panel) reactions. The histograms show the MD analysis results.

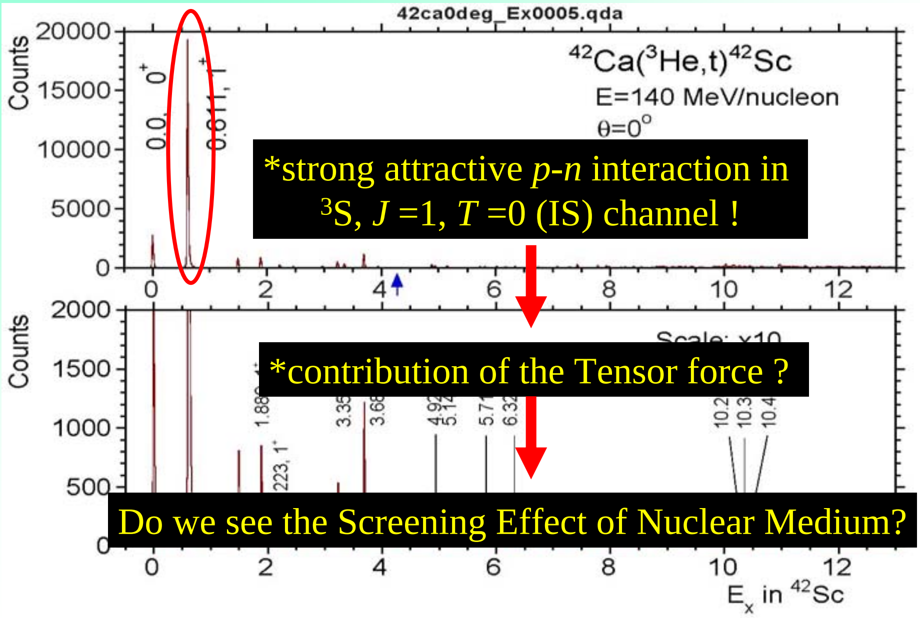


$^{42}Ca(^{3}He,t)^{42}Sc$ in 2 scales
42ca0deg_Ex0005.qda
$^{42}Ca(^{3}He,t)^{42}Sc$
E=140 MeV/nucleon
θ=0°
0.0, 0+
0.611, 1+
*strong attractive *p-n* interaction in ^{3}S, *J* =1, *T* =0 (IS) channel !
*contribution of the Tensor force ?
2.223, 1+
Counts
E_x in ^{42}Sc



GT transitions forming
Low-Energy Super GT state
J^{π} = O+ → 1+
Σ (Sum rule) = 3 x |N-Z| = 6
2n
^{2}H (d)
g.s.
B(GT) = 6.0 ?
Large !
^{6}He
^{6}Li
g.s.
B(GT) = 4.73
^{18}O
^{18}F
g.s.
B(GT) = 3.09
^{42}Ca
^{42}Sc
B(GT) = 2.17
Smaller !
1st E_x state (IAS is the g.s.)

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



Summary

GT (στ) operator : a simple operator !

* GT transitions: sensitive to the structure of |i> and |f>

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

* Fine structures of GT transitions

(Precise comparison with mirror β-decay results)

➔ Cluster structures in *sd*-shell nuclei

➔ Low-energy Super GT state (LESGT state)

GT transitions are talented in detecting "key issues" of Nuclear Structure and Nuclear Interactions

GT-study Collaborations

Bordeaux (France) : β decay
GANIL (France) : β decay
Gent (Belgium) : (^{3}He, t), (d, ^{2}He), (γ, γ'), theory
GSI, Darmstadt (Germany) : β decay, theory
ISOLDE, CERN (Switzerland) : β decay
iThemba LABS. (South Africa) : (p, p'), (^{3}He, t)
Istanbul (Turkey): (^{3}He, t), β decay
Jyvaskyla (Finland) : β decay
Koeln (Germany) : γ decay, (^{3}He, t), theory
KVI, Groningen (The Netherlands) : (d, ^{2}He)
Leuven (Belgium) : β decay
LTH, Lund (Sweden) : theory
Osaka University (Japan) : (p, p'), (^{3}He, t), theory
Surrey (GB) : β decay
Tokyo Science University : β decay
TU Darmstadt (Germany) : (e, e'), (^{3}He, t)
Valencia (Spain) : β decay
Michigan State University (USA) : theory, (t, ^{3}He)
Muenster (Germany) : (d, ^{2}He), (^{3}He,t)
Univ. Tokyo and CNS (Japan) : theory, β decay

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Review

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

Y. Fujita[a,*], B. Rubio[b], W. Gelletly[c]

[a] Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
[b] IFIC, CSIC-University of Valencia, E-46071 Valencia, Spain
[c] Department of Physics, University of Surrey, Guildford GU2 7XH, Surrey, UK

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