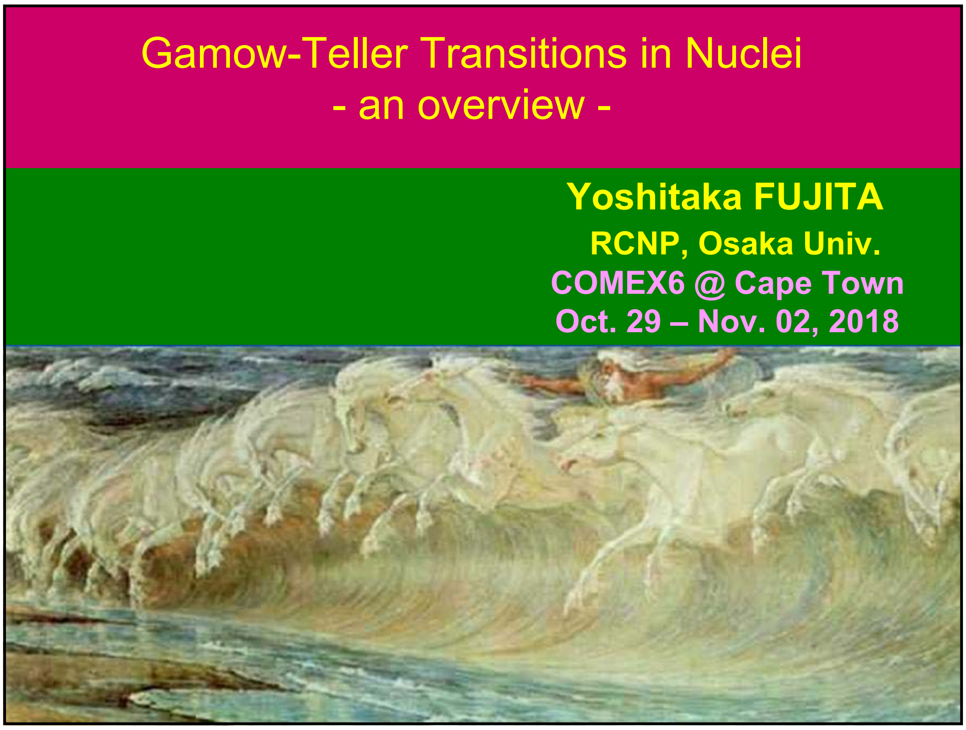


Gamow-Teller Transitions in Nuclei
- an overview -

Yoshitaka FUJITA
RCNP, Osaka Univ.
COMEX6 @ Cape Town
Oct. 29 – Nov. 02, 2018

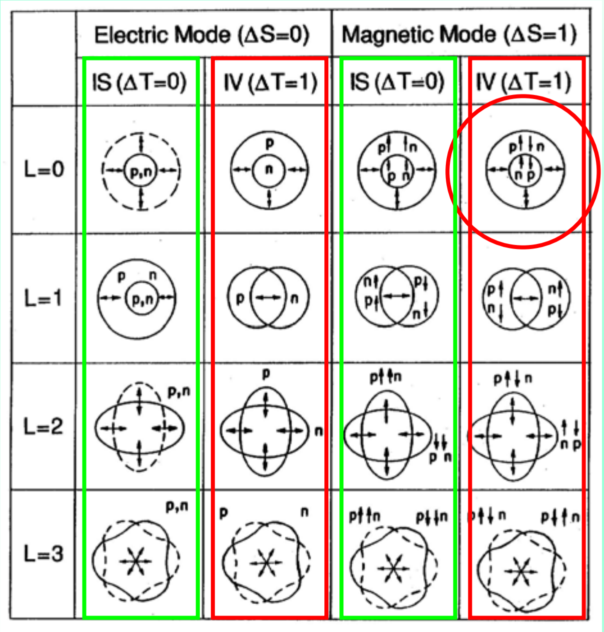
Neptune driving Waves
波を操る海神ネプチューン

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

Vibration Modes in Nuclei (Schematic)

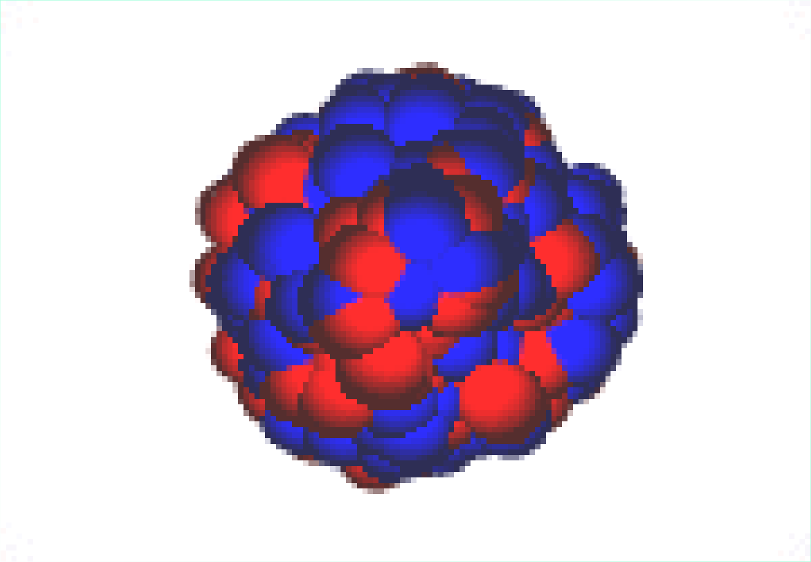


Gamow-
Teller mode
(στ)

Isovector
&
Spin
excitation

IV Giant Monopole Resonance (IVGMR)

by P. Adrich



Properties of Gamow-Teller transitions

Mediated by $\sigma\tau$ op. : Spin & Isospin are Unique Q-numbers

➔ $\Delta S = -1, 0, +1$ and $\Delta T = -1, 0, +1$

(no change in radial w.f. & $\Delta L = 0$)

➔ no change in spatial w.f. ($0\hbar\omega$ excitation)

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

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

example: $f_{7/2} \rightarrow f_{7/2}$, $f_{5/2} \rightarrow f_{5/2}$, $f_{7/2} \leftrightarrow f_{5/2}$

➔ each configuration is a Main Actor !

➔ GT transitions are sensitive to Nuclear Structure !

➔ GT transitions in each nucleus are UNIQUE !

Properties of Gamow-Teller transitions

Mediated by $\sigma\tau$ op. : Spin & Isospin are Unique Q-numbers

➔ $\Delta S = -1, 0, +1$ and $\Delta T = -1, 0, +1$

(no change in radial w.f. & $\Delta L = 0$)

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➔ each configuration is a Main Actor !

➔ G

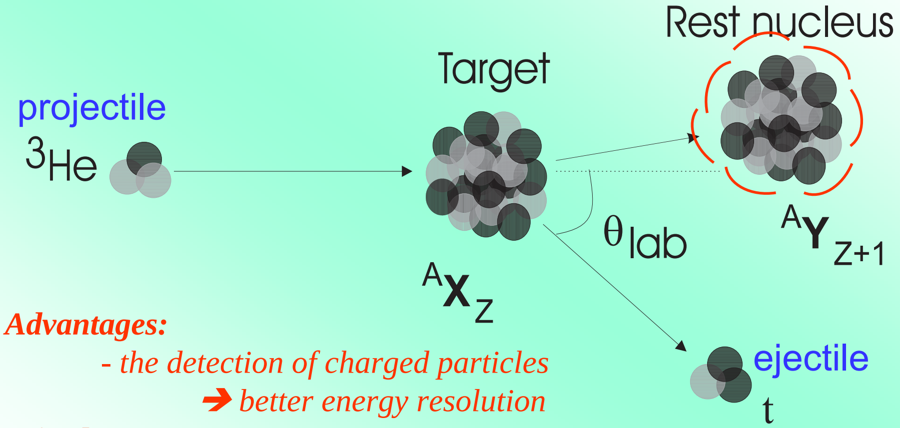
➔ G

In β-decay, GT ($\sigma\tau$) & Fermi (τ) are allowed transitions !

In CE reactions, $\sigma\tau$ operator are active at $\Delta q = 0$!

(^{3}He,t) nuclear reaction

- a **(p,n)**-type charge-exchange reaction -



Advantages:

- the detection of charged particles

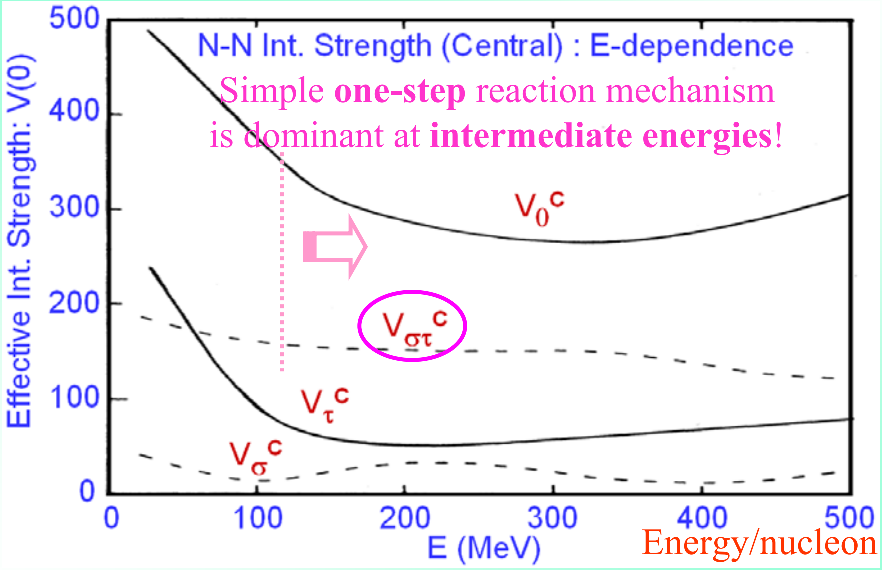
➔ better energy resolution

Disadvantages:

- the structure of the ^{3}He might play a role

from Lucia collection

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



Simple **one-step** reaction mechanism is dominant at **intermediate energies**!

Energy/nucleon

Love & Franey PRC 24 ('81) 1073

β-decay & Nuclear Reaction

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

$B(\mathrm{GT})$: reduced GT transition strength

$\propto$ (matrix element)^2 = $|\langle f|\sigma\tau|i\rangle|^2$

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

= reaction mechanism

ⓧ operator

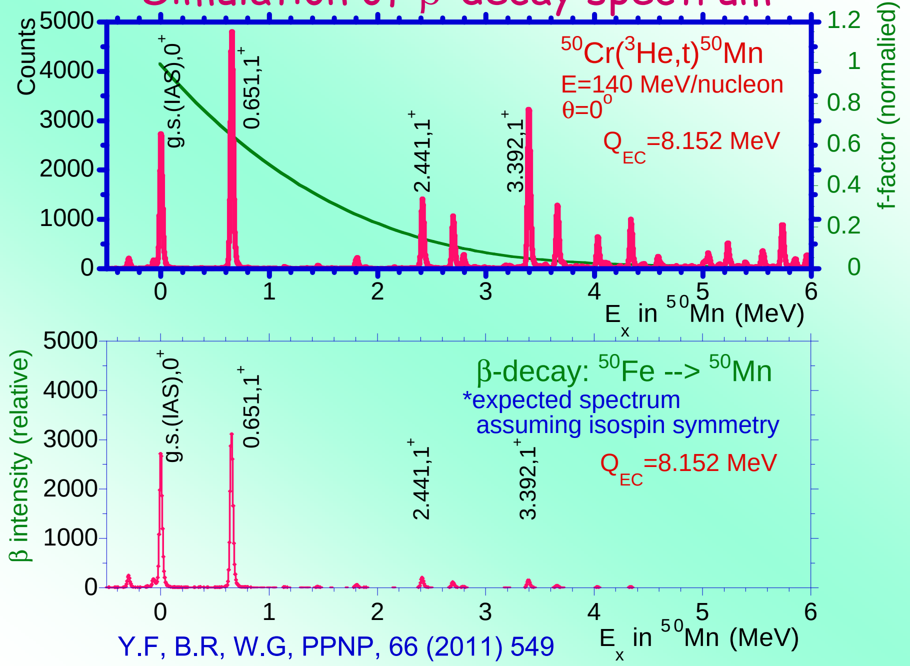
ⓧ structure

=(matrix element)^2

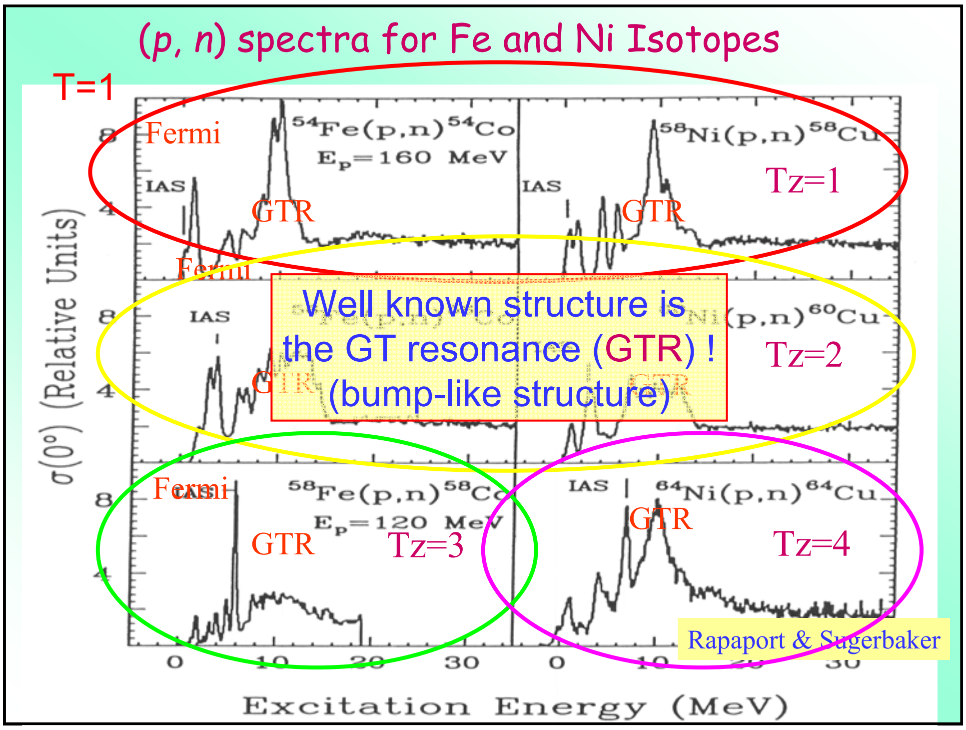
*At intermediate energies ($100 < E_{in} < 500$ MeV)

→ $d\sigma/d\omega(q=0)$: proportional to $B(\mathrm{GT})$

Simulation of β-decay spectrum



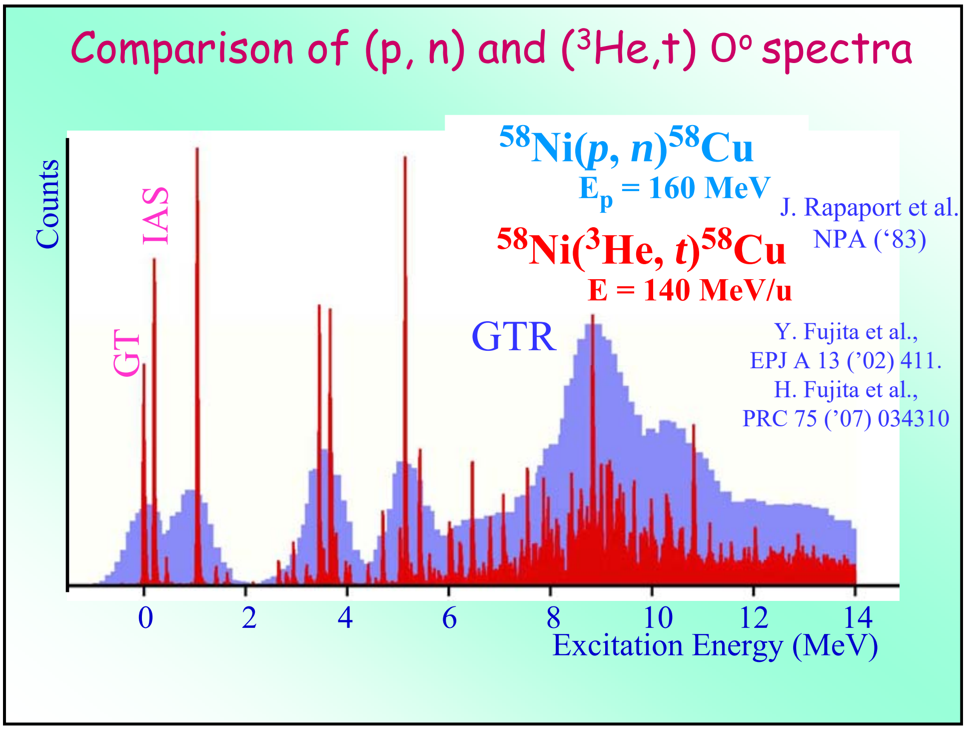
Y.F, B.R, W.G, PPNP, 66 (2011) 549



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

Well known structure is the GT resonance (GTR) ! (bump-like structure)

Rapaport & Sugerbaker



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

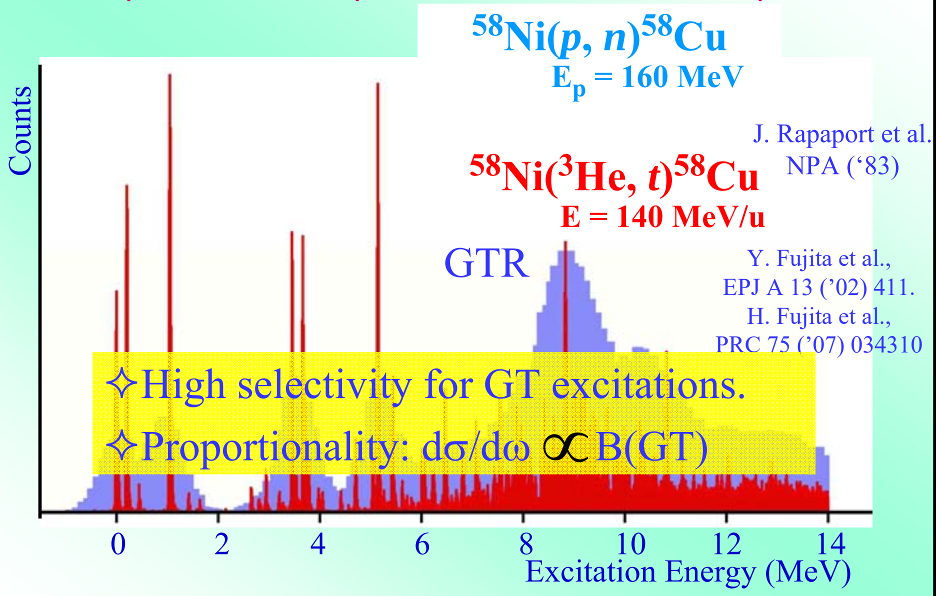
^{58}Ni(*p*, *n*)^{58}Cu
E$_p$ = 160 MeV

J. Rapaport et al.
NPA (‘83)

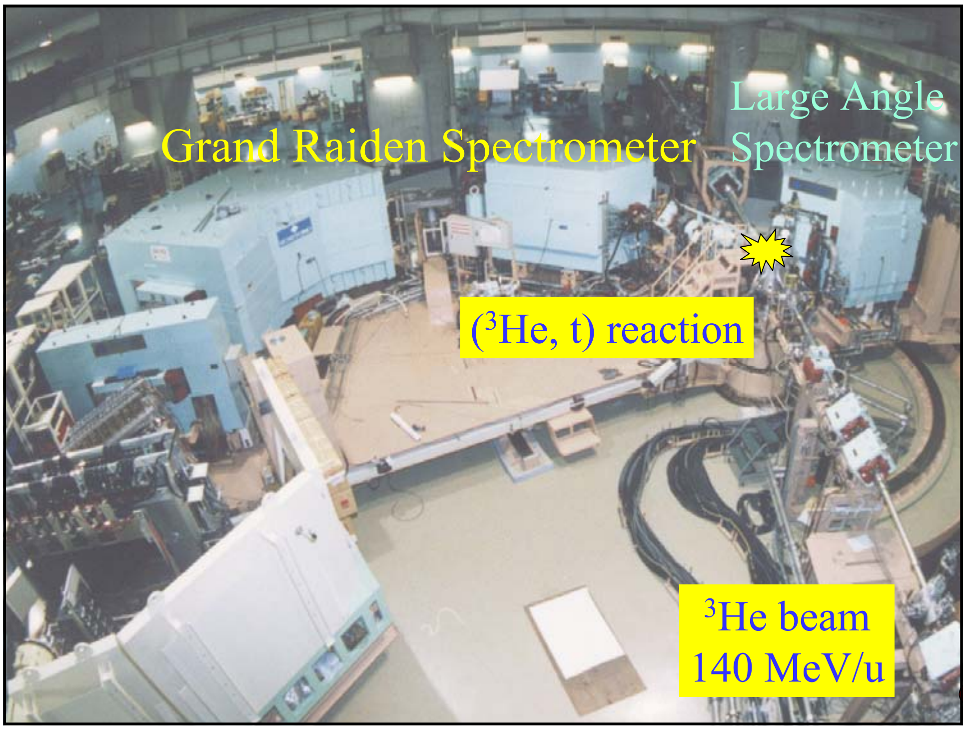
^{58}Ni(^{3}He, *t*)^{58}Cu
E = 140 MeV/u

Y. Fujita et al.,
EPJ A 13 (’02) 411.
H. Fujita et al.,
PRC 75 (’07) 034310

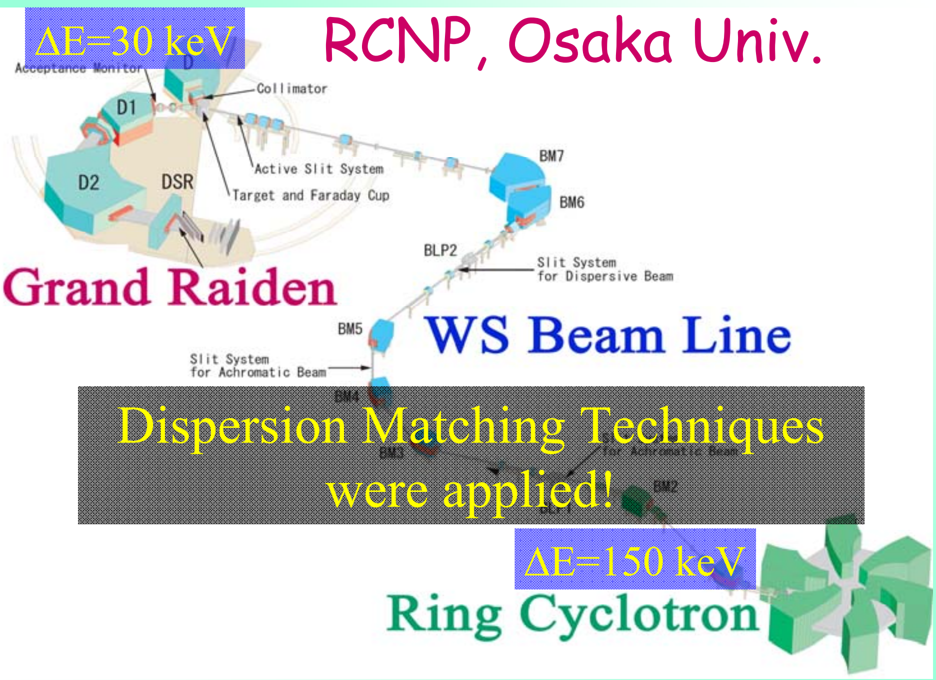
Comparison of (p, n) and (^{3}He,t) 0° spectra



- ✧High selectivity for GT excitations.
- ✧Proportionality: $d\sigma/d\omega \propto B(GT)$



RCNP, Osaka Univ.



ΔE=30 keV

Grand Raiden

WS Beam Line

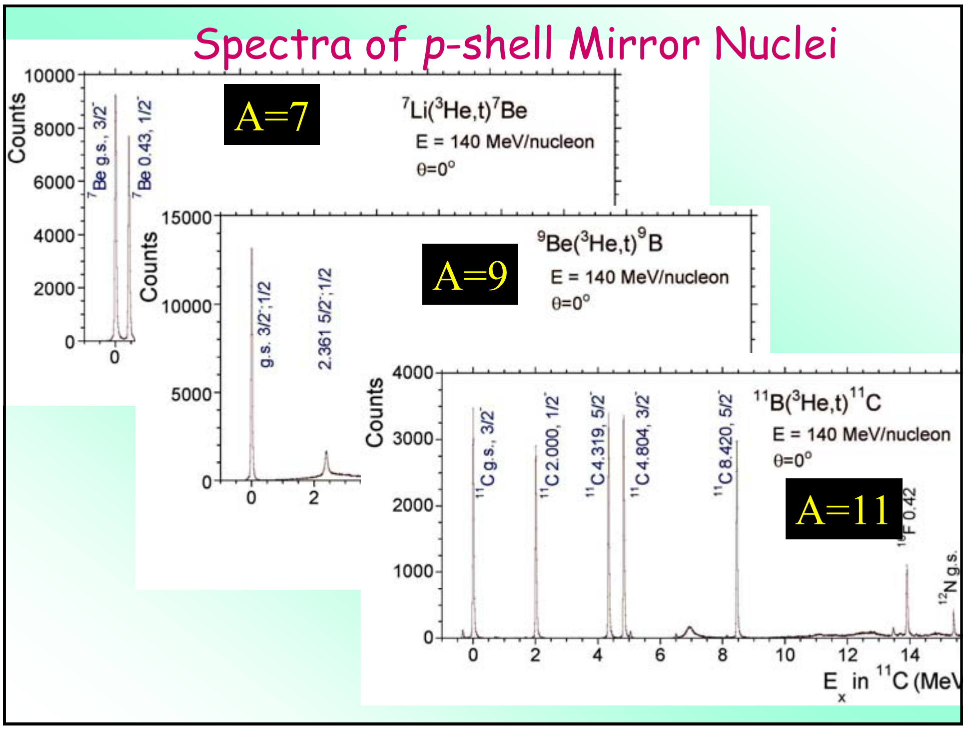
Dispersion Matching Techniques were applied!

ΔE=150 keV

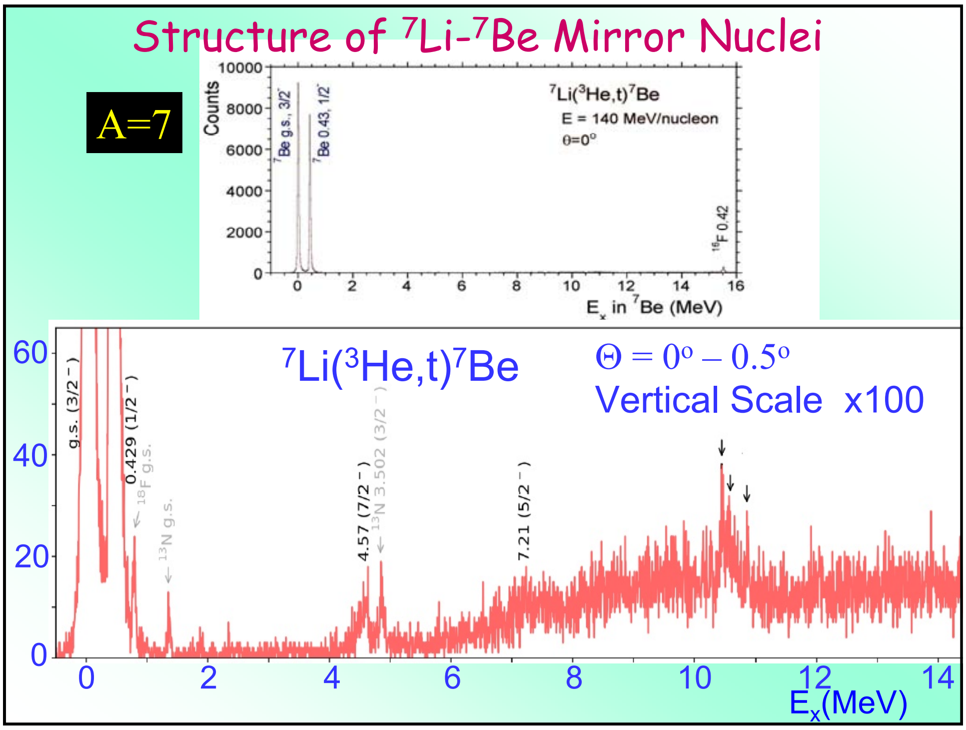
Ring Cyclotron

**GT transitions in each nucleus are UNIQUE !

- A = 7, 9, 11 nuclei -



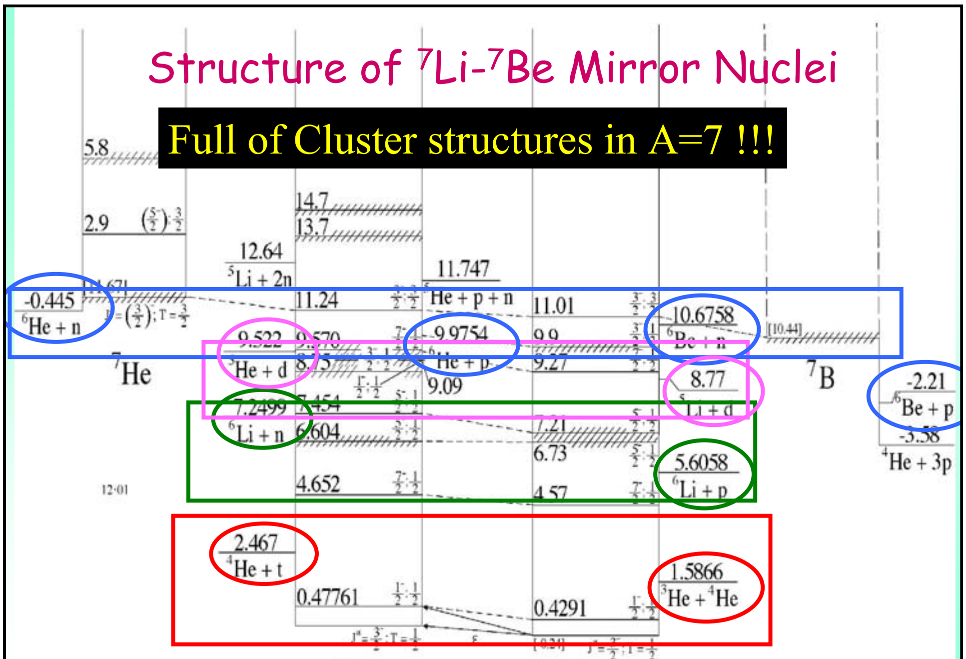
Spectra of *p*-shell Mirror Nuclei



Structure of ^{7}Li-^{7}Be Mirror Nuclei

Structure of ^{7}Li-^{7}Be Mirror Nuclei

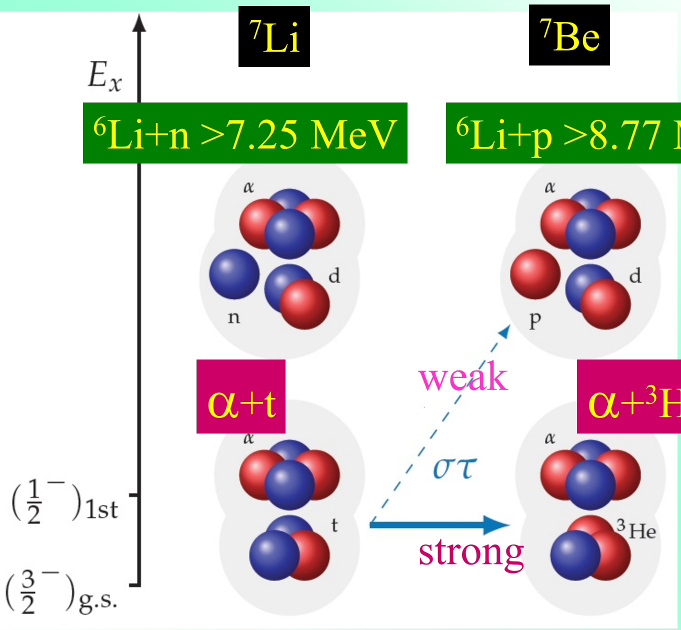
Full of Cluster structures in A=7 !!!



^{7}Li

^{7}Be

Structure of ^{7}Li-^{7}Be Mirror Nuclei


^{7}Li

^{7}Be

^{6}Li+n >7.25 MeV

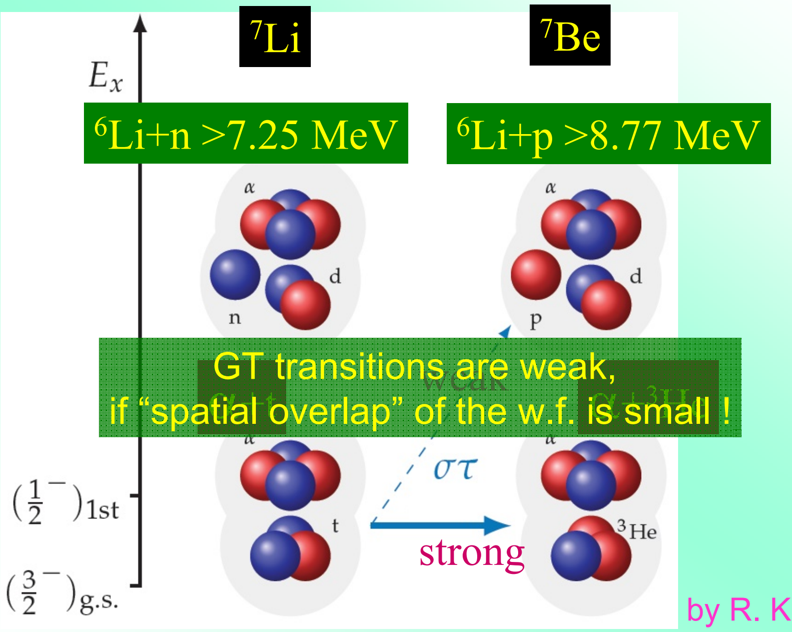
^{6}Li+p >8.77 MeV

α+t

α+^{3}He

by R. Kehl

Structure of ^{7}Li-^{7}Be Mirror Nuclei

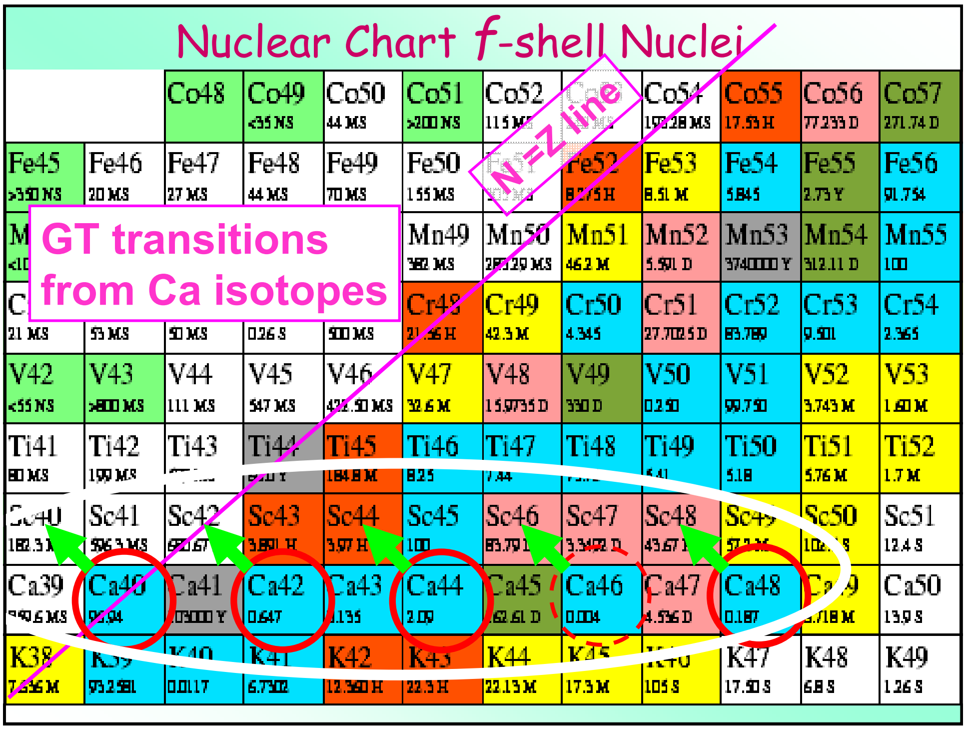


GT transitions are weak,
if “spatial overlap” of the w.f. is small !

by R. Kehl

**GT transitions in each nucleus are UNIQUE !

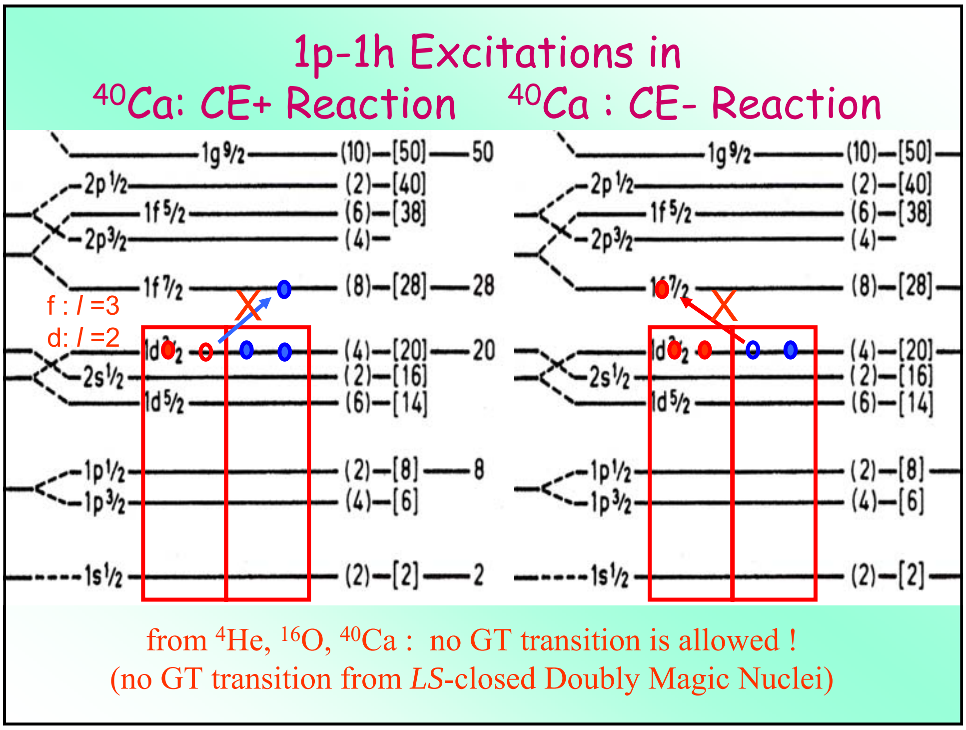
- Ca isotopes -



Nuclear Chart *f*-shell Nuclei

		Co48	Co49 <35 NS	Co50 44 MS	Co51 >200 NS	Co52 115 MS	[illegible]	Co54 193.28 MS	Co55 17.53 H	Co56 77.233 D	Co57 271.74 D
Fe45 >350 NS	Fe46 20 MS	Fe47 27 MS	Fe48 44 MS	Fe49 70 MS	Fe50 155 MS	[illegible]	Fe52 8.275 H	Fe53 8.51 M	Fe54 5.845	Fe55 2.73 Y	Fe56 91.754
M <10					Mn49 382 MS	Mn50 283.29 MS	Mn51 46.2 M	Mn52 5.591 D	Mn53 3740000 Y	Mn54 312.11 D	Mn55 100
C 21 MS	53 MS	50 MS	0.26 S	500 MS	Cr48 21.56 H	Cr49 42.3 M	Cr50 4.345	Cr51 27.7025 D	Cr52 83.789	Cr53 9.501	Cr54 2.365
V42 <55 NS	V43 >800 MS	V44 111 MS	V45 547 MS	V46 422.50 MS	V47 32.6 M	V48 15.9735 D	V49 330 D	V50 0.250	V51 99.750	V52 3.743 M	V53 1.60 M
Ti41 80 MS	Ti42 199 MS	Ti43 [illegible]	Ti44 [illegible] Y	Ti45 184.8 M	Ti46 8.25	Ti47 7.44	Ti48 [illegible]	Ti49 5.41	Ti50 5.18	Ti51 5.76 M	Ti52 1.7 M
Sc40 182.3 M	Sc41 596.3 MS	Sc42 680.67	Sc43 3.891 H	Sc44 3.97 H	Sc45 100	Sc46 83.79 D	Sc47 3.3492 D	Sc48 43.67 H	Sc49 57.2 M	Sc50 102.5 S	Sc51 12.4 S
Ca39 859.6 MS	Ca40 96.94	Ca41 103000 Y	Ca42 0.647	Ca43 0.135	Ca44 2.09	Ca45 162.61 D	Ca46 0.004	Ca47 4.536 D	Ca48 0.187	Ca49 8.718 M	Ca50 13.9 S
K38 7.636 M	K39 93.2581	K40 0.0117	K41 6.7302	K42 12.360 H	K43 22.3 H	K44 22.13 M	K45 17.3 M	K46 105 S	K47 17.50 S	K48 6.8 S	K49 1.26 S

GT transitions from Ca isotopes

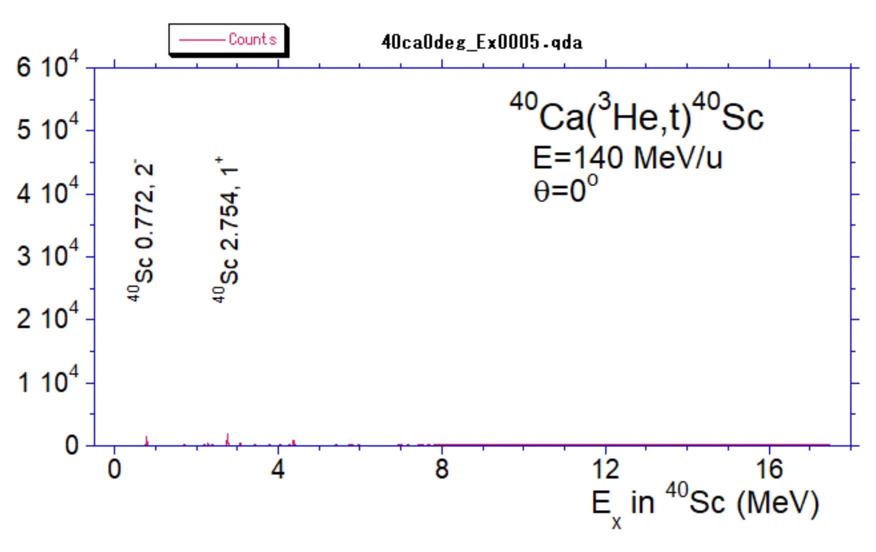


1p-1h Excitations in

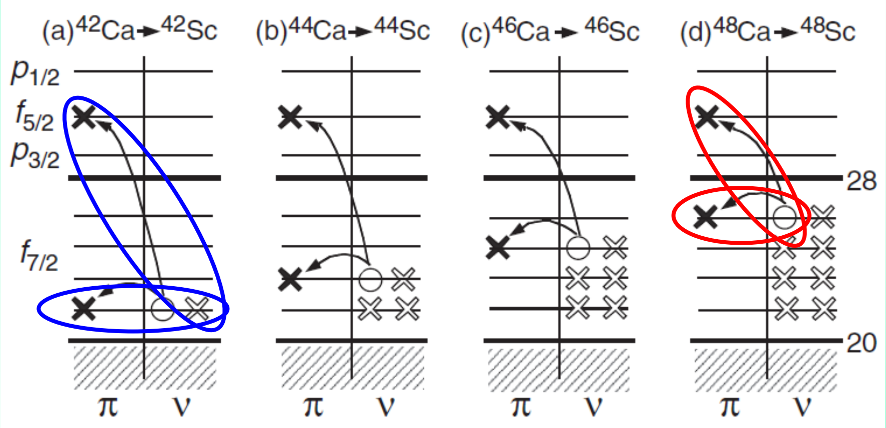
^{40}Ca: CE+ Reaction ^{40}Ca : CE- Reaction

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

^{40}Ca(^{3}He,t)^{40}Sc



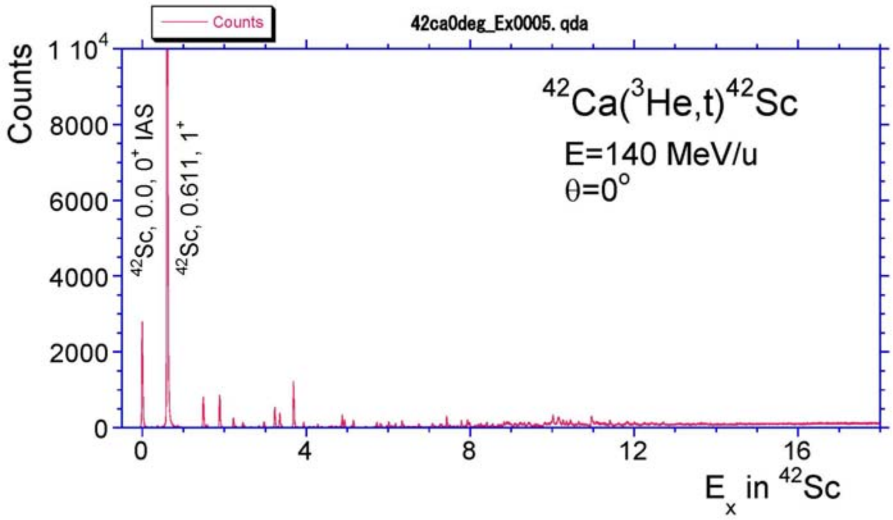
GT Configurations in Sc isotopes



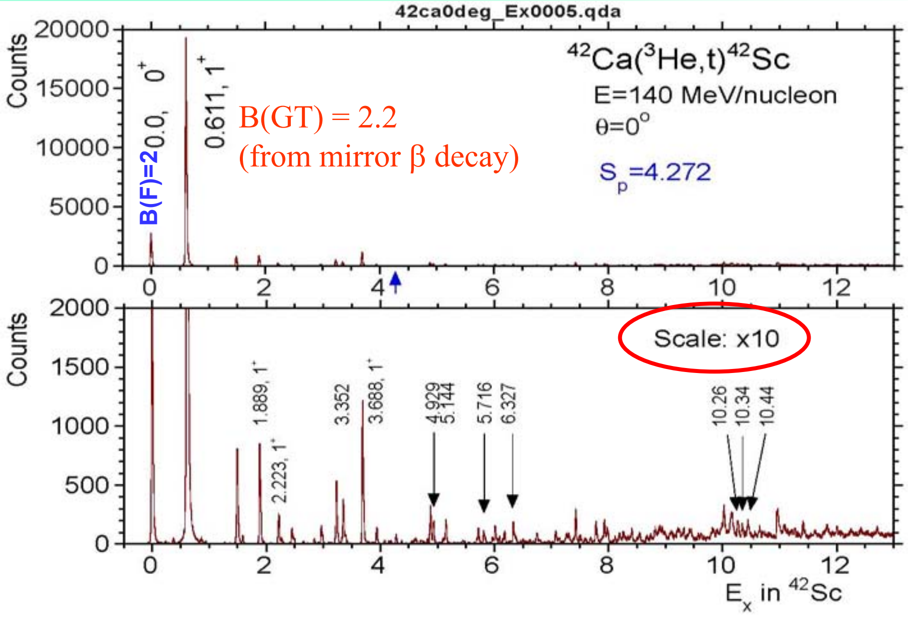
particle-particle nature □□ particle-hole nature

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

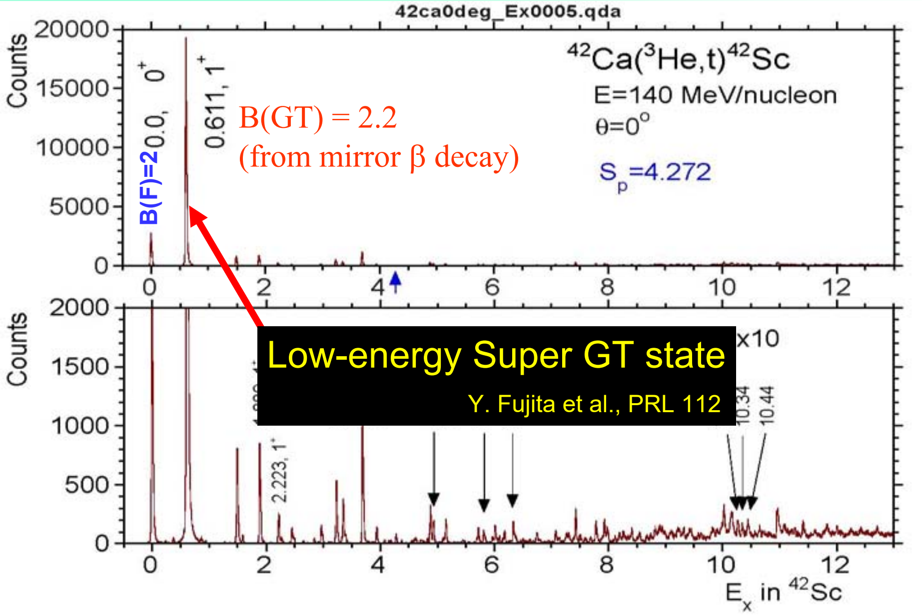
^{42}Ca(^{3}He,t)^{42}Sc



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



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

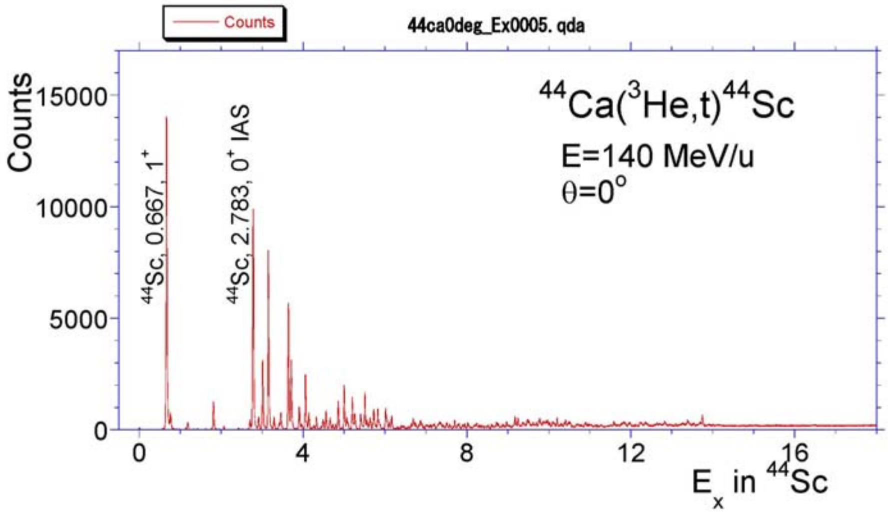


B(GT) = 2.2
(from mirror β decay)

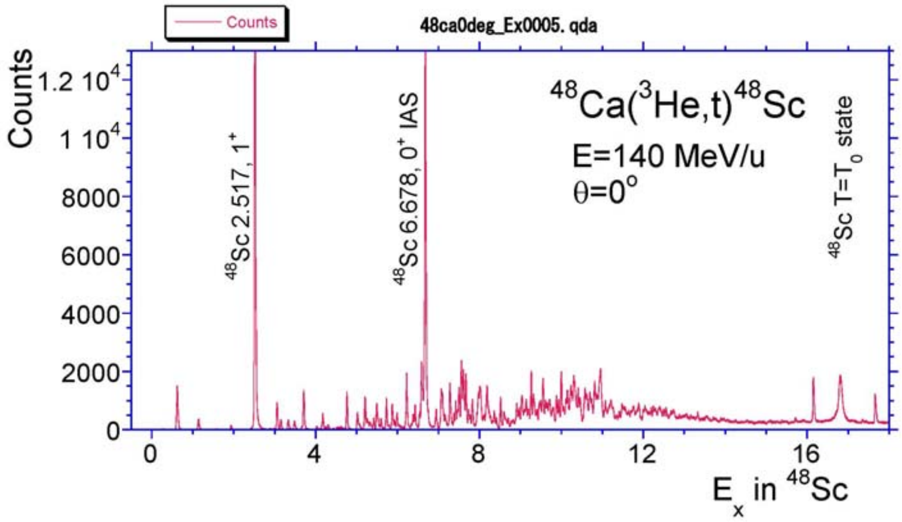
Low-energy Super GT state

Y. Fujita et al., PRL 112

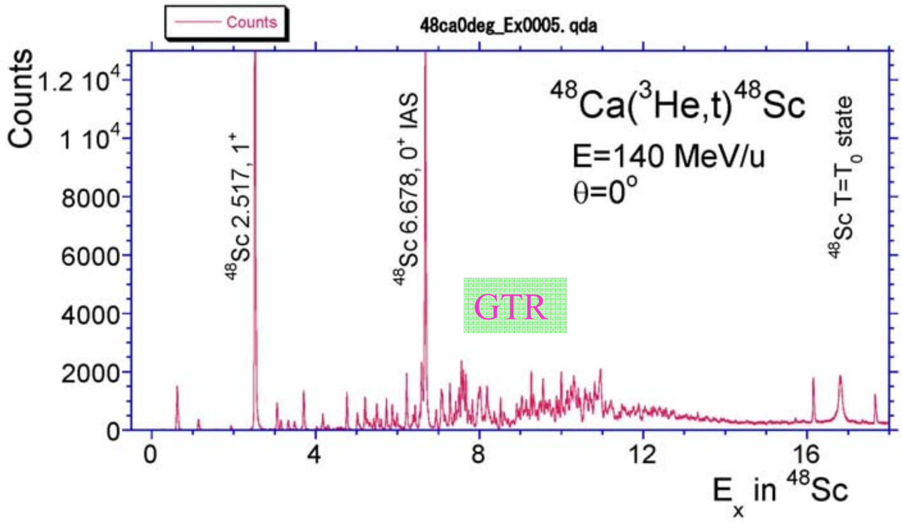
^{44}Ca(^{3}He,t)^{44}Sc

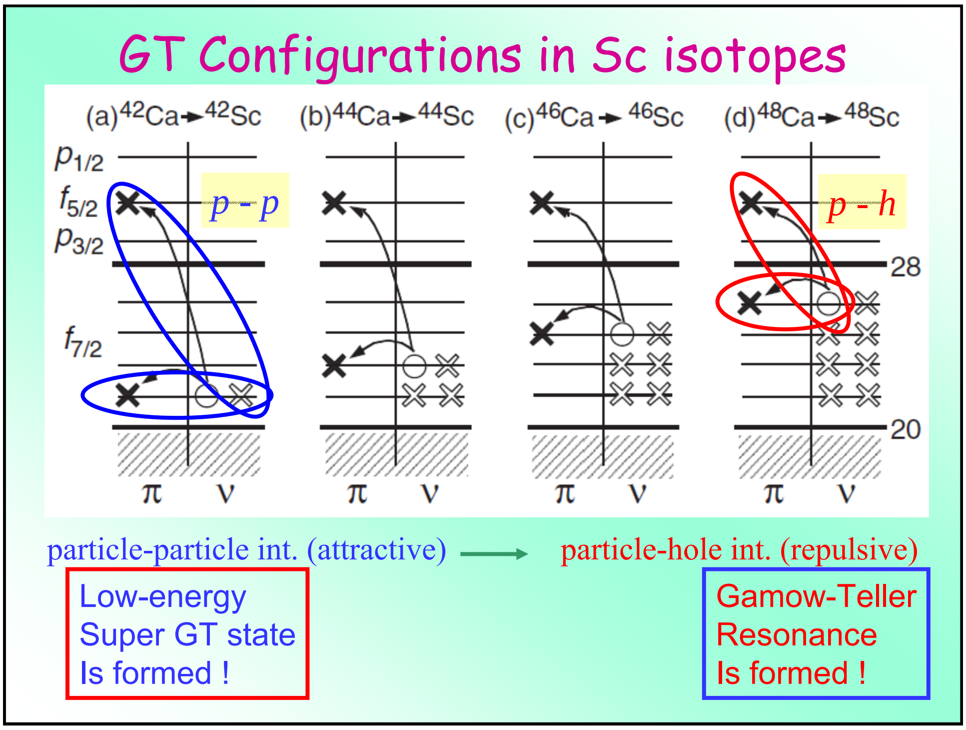


^{48}Ca(^{3}He,t)^{48}Sc



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



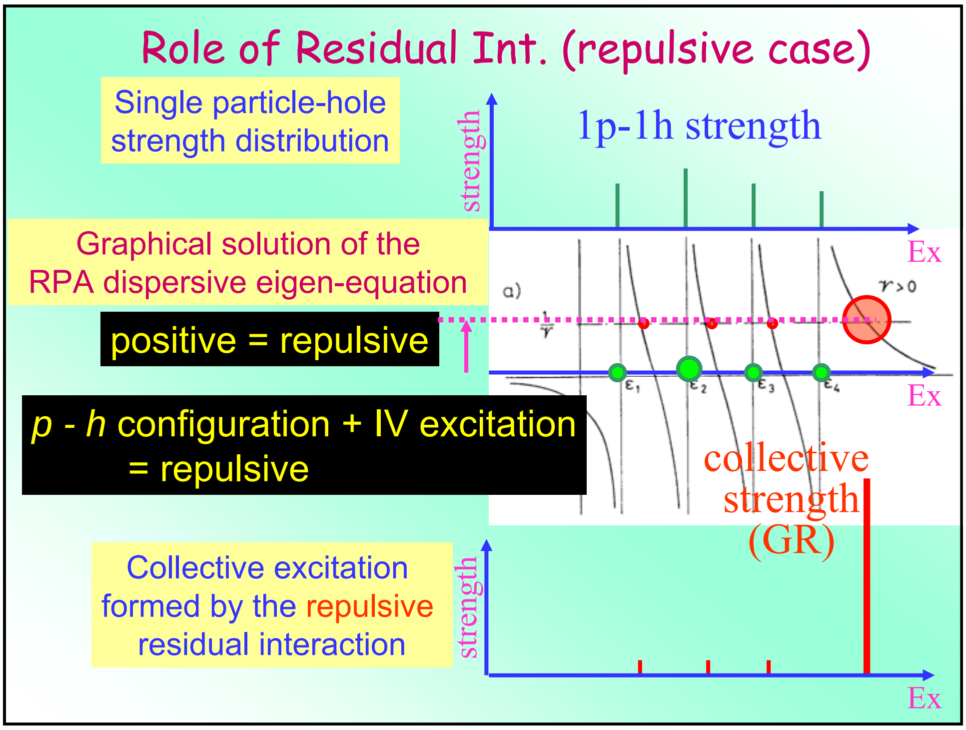


GT Configurations in Sc isotopes

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

Low-energy
Super GT state
Is formed !

Gamow-Teller
Resonance
Is formed !



Role of Residual Int. (repulsive case)

Single particle-hole strength distribution

Graphical solution of the RPA dispersive eigen-equation

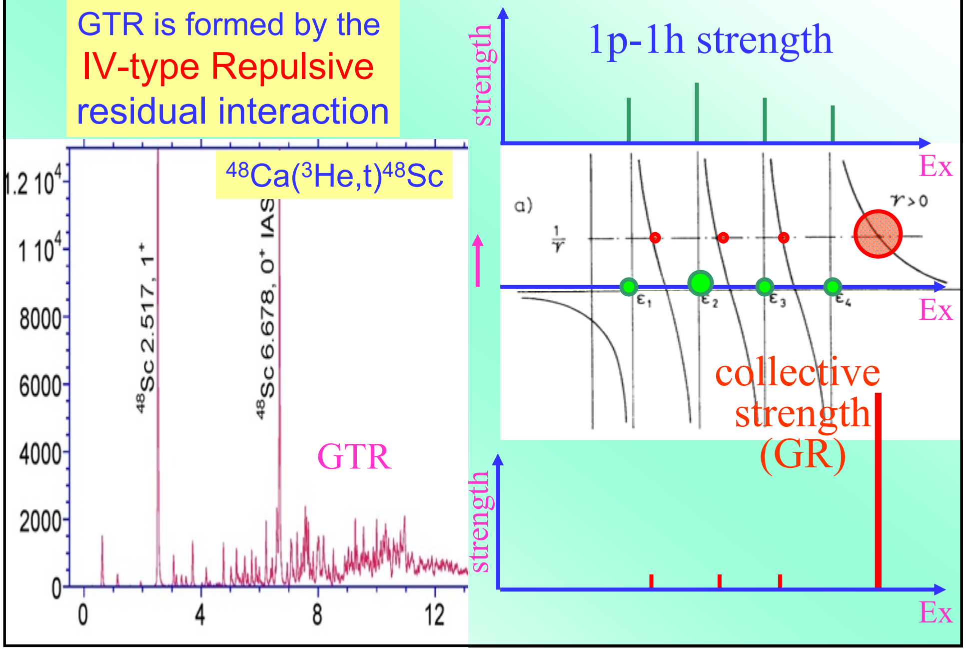
positive = repulsive

p - *h* configuration + IV excitation = repulsive

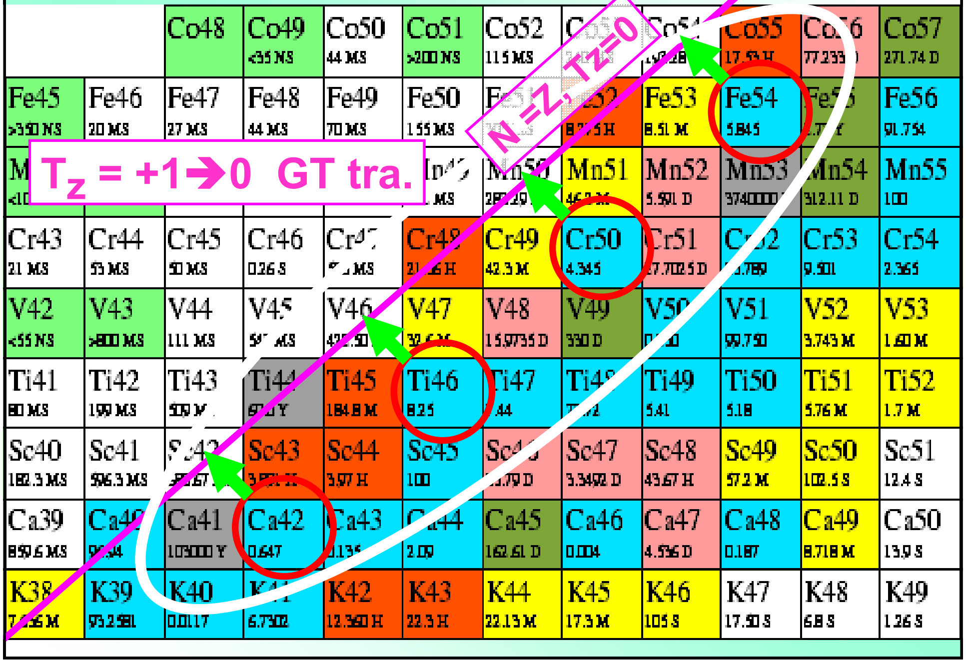
Collective excitation formed by the repulsive residual interaction

Role of Residual Int. (repulsive)

GTR is formed by the
IV-type Repulsive
residual interaction



Nuclear Chart *f*-shell Nuclei



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M <10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] MS	Mn50 283.29	Mn51 46.2 M	Mn52 5.591 D	Mn53 3740000	Mn54 312.11 D	Mn55 100
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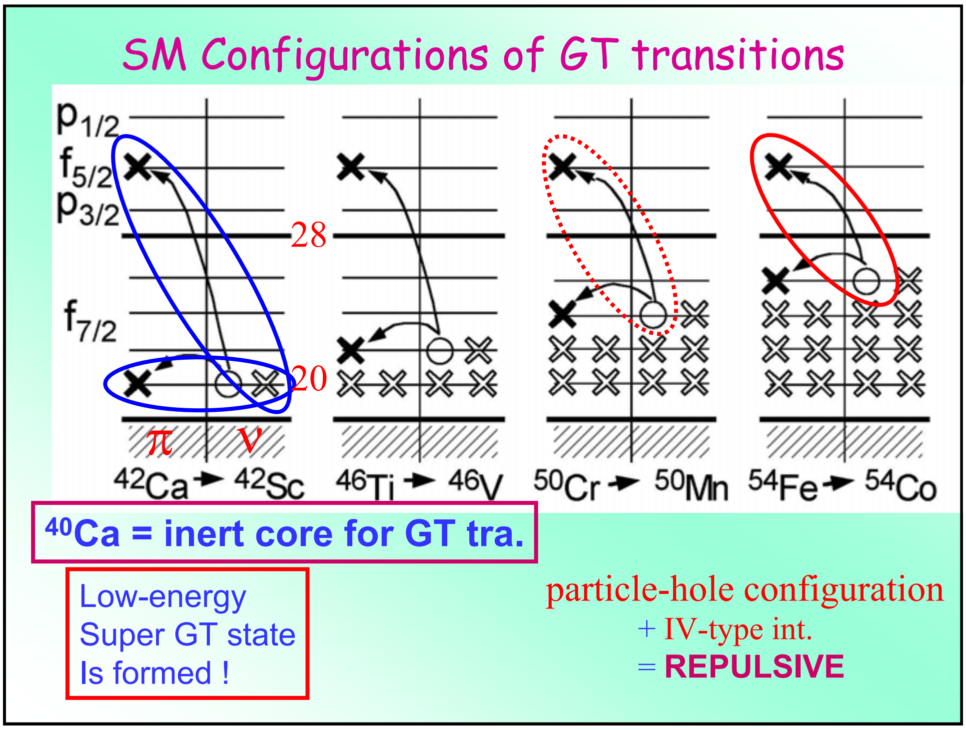
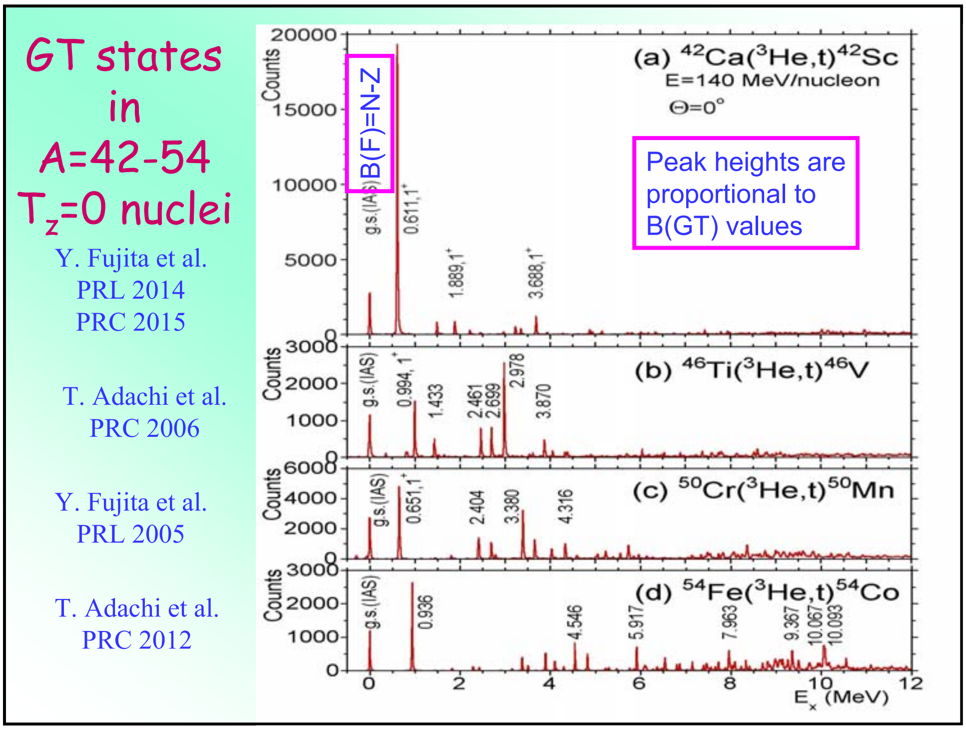


SM Configurations of GT transitions

^{40}Ca = inert core for GT tra.

Low-energy
Super GT state
Is formed !

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



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

B(F)=N-Z

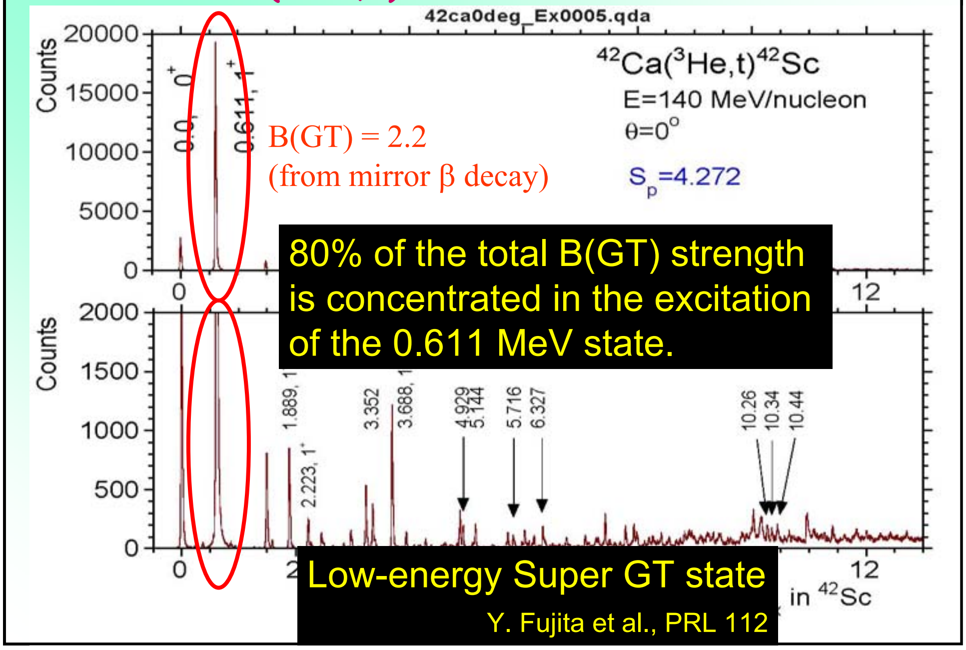
Peak heights are proportional to B(GT) values

***Low-energy Super GT transition (LeSGT) & LeSGT state

Strongly excited lowest-GT state
in the ^{42}Ca(^{3}He,t)^{42}Sc reaction

---

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



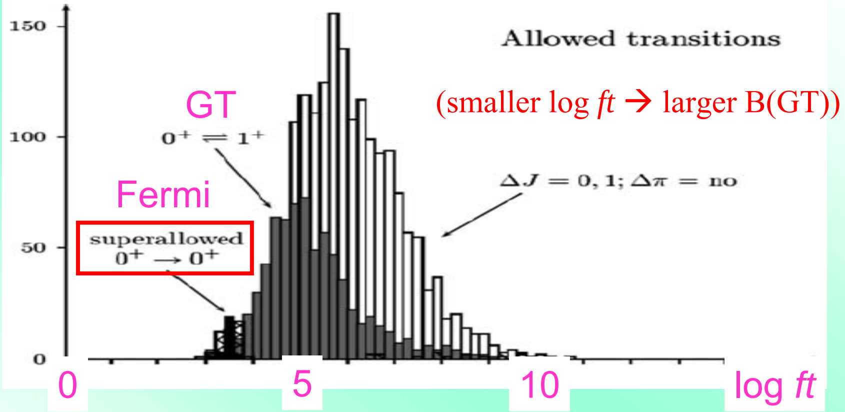
B(GT) = 2.2
(from mirror β decay)

80% of the total B(GT) strength is concentrated in the excitation of the 0.611 MeV state.

Low-energy Super GT state

Y. Fujita et al., PRL 112

Super-allowed GT transitions in β decay



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

Super-allowed
GT transitions

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,

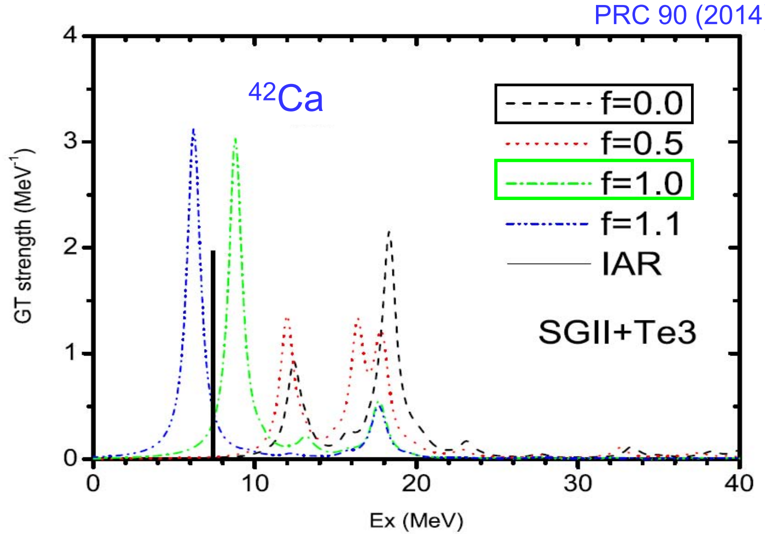
IV $$V_{T=1}(\mathbf{r}_1, \mathbf{r}_2) = V_0 \frac{1 - P_\sigma}{2}\left(1 - \frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}_1 - \mathbf{r}_2), \quad (1)$$

IS $$V_{T=0}(\mathbf{r}_1, \mathbf{r}_2) = f V_0 \frac{1 + P_\sigma}{2}\left(1 - \frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}_1 - \mathbf{r}_2), \quad (2)$$

Results (using Skyrme int. SGII)
at *f* =0: there is little strength in the lower energy part,
at *f* =1.0~1.7: coherent low-energy strength develops!

QRPA-cal. GT-strength (with IS-int.)

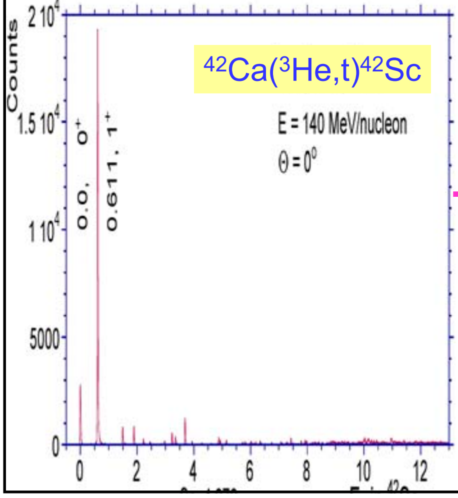
by Bai, Sagawa, Colo et al.
PRC 90 (2014)

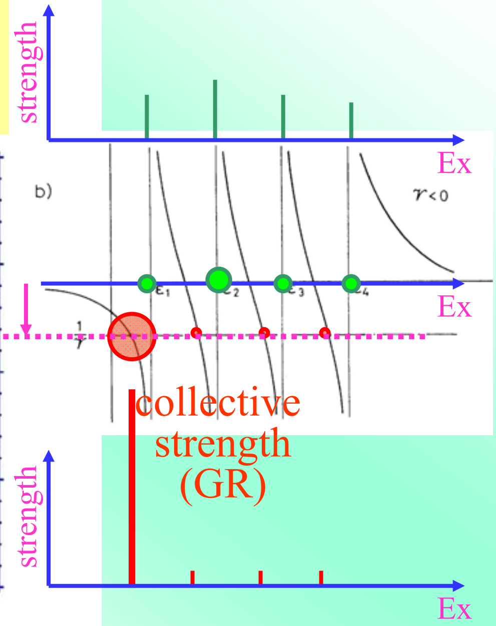


^{42}Ca→^{42}Sc (Q-value)

Role of Residual Int. (attractive)

LeSGT state is formed by the
IS-type Attractive
residual interaction





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

SM cal. (GXPF1J) M. Honma

States in ^{42}Sc			Configurations						Transition strengths	
E_x (MeV)		T	$f7 \rightarrow f7$	$f7 \rightarrow f5$	$f5 \rightarrow f7$	$p3 \rightarrow p3$	$p3 \rightarrow p1$	$p1 \rightarrow p3$	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	1^+_2	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** !

——— Matrix Elements are **out of phase** !

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

SM cal. (GXPF1J) M. Honma

States in ^{42}Sc			Configurations						Transition strengths	
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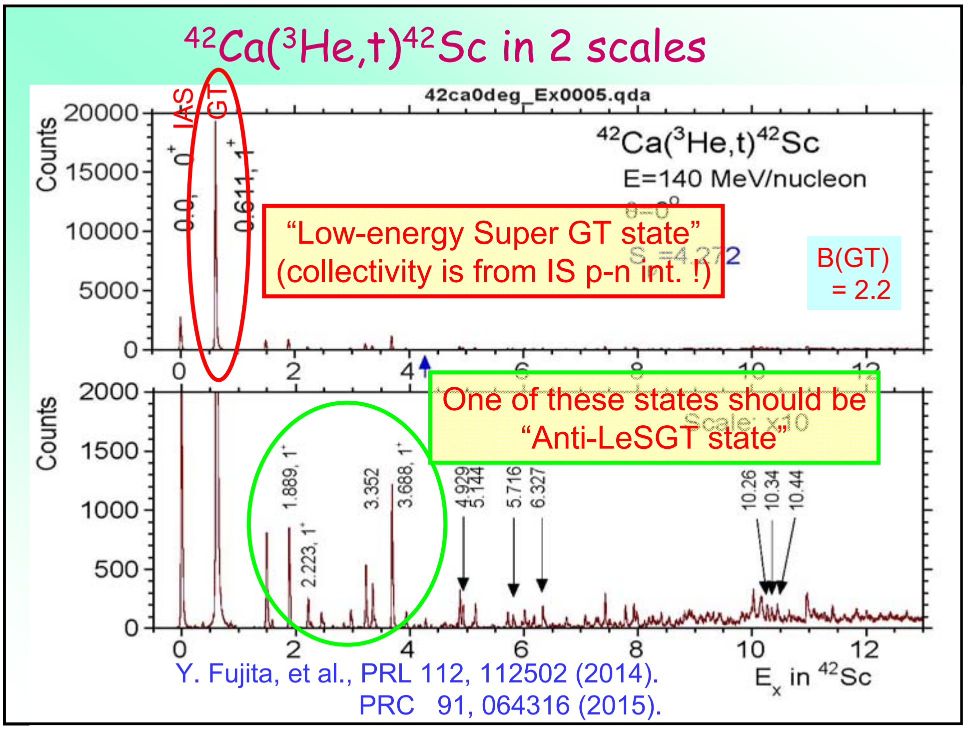


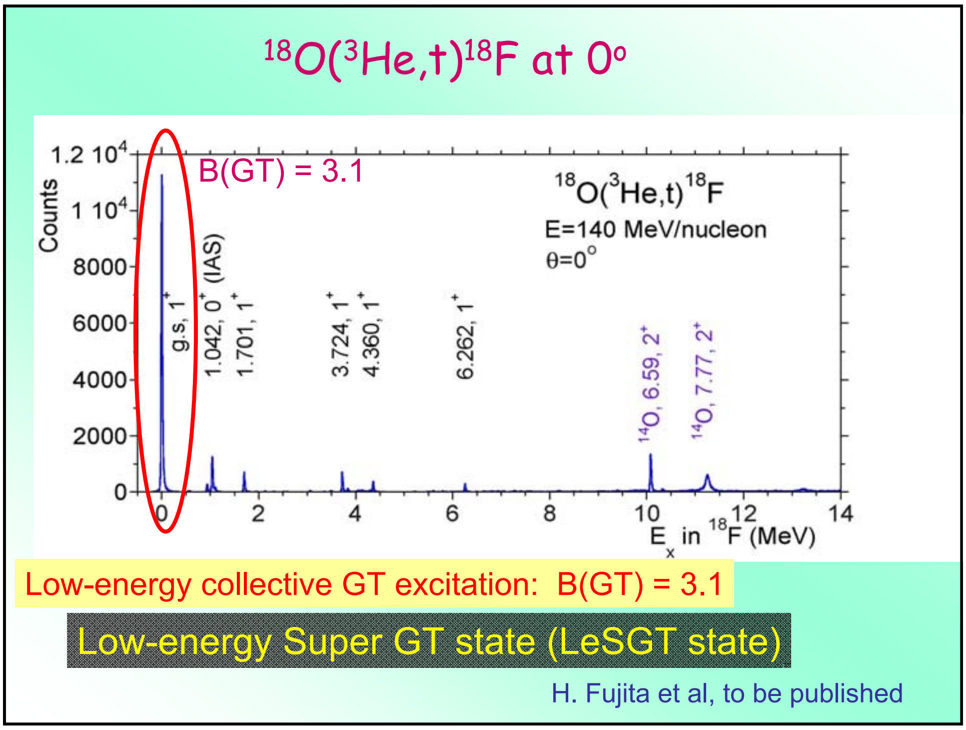
$^{42}Ca(^3He,t)^{42}Sc$ in 2 scales

"Low-energy Super GT state"
(collectivity is from IS p-n int. !)

B(GT) = 2.2

One of these states should be "Anti-LeSGT state"

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



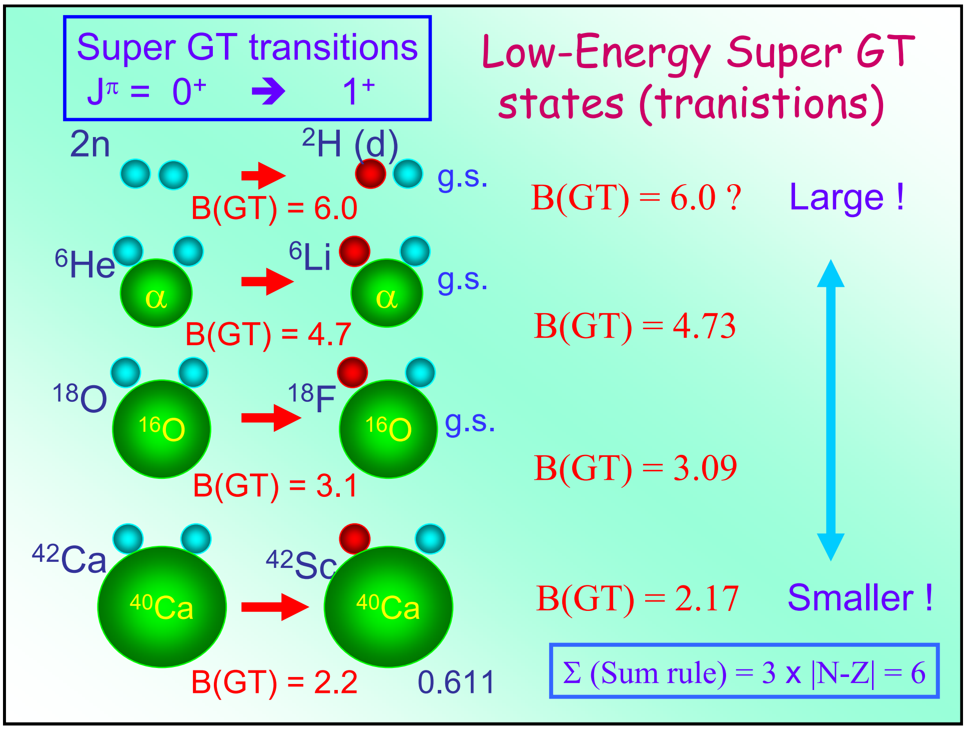
$^{18}O(^3He,t)^{18}F$ at 0°

B(GT) = 3.1

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
$J^\pi = 0^+ \rightarrow 1^+$

Low-Energy Super GT states (tranistions)

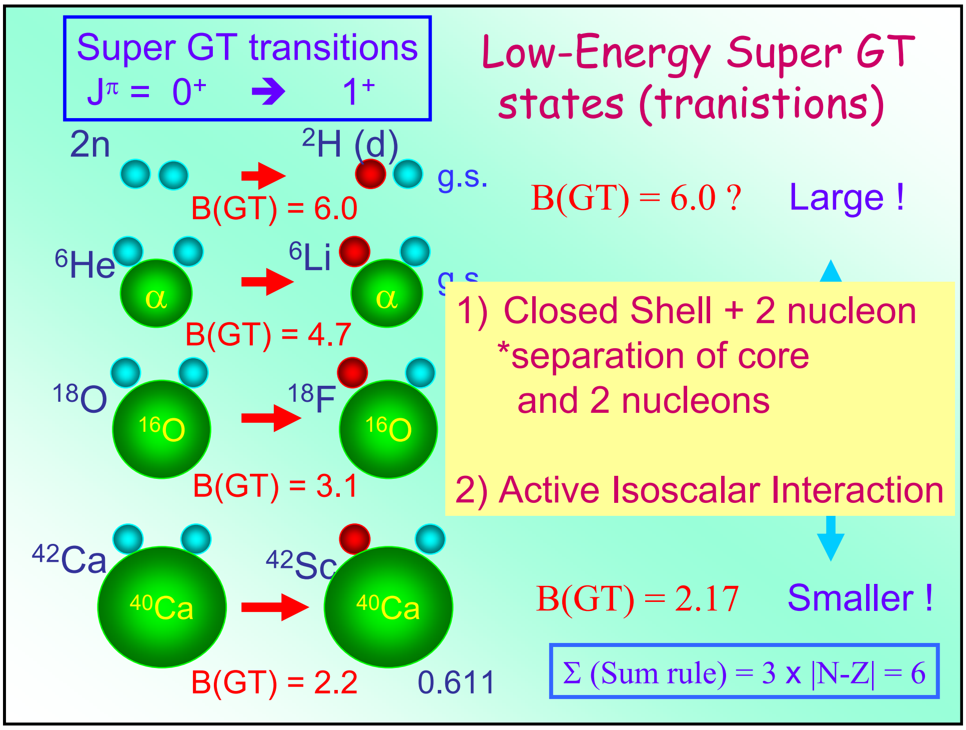
B(GT) = 6.0 ? Large !

B(GT) = 4.73

B(GT) = 3.09

B(GT) = 2.17 Smaller !

Σ (Sum rule) = 3 x |N-Z| = 6


2n
^{2}H (d)
g.s.
B(GT) = 6.0
^{6}He
α
^{6}Li
α
B(GT) = 4.7
^{18}O
^{16}O
^{18}F
^{16}O
B(GT) = 3.1
^{42}Ca
^{40}Ca
^{42}Sc
^{40}Ca
B(GT) = 2.2
0.611

Super GT transitions
$J^\pi = 0^+ \rightarrow 1^+$

Low-Energy Super GT states (tranistions)

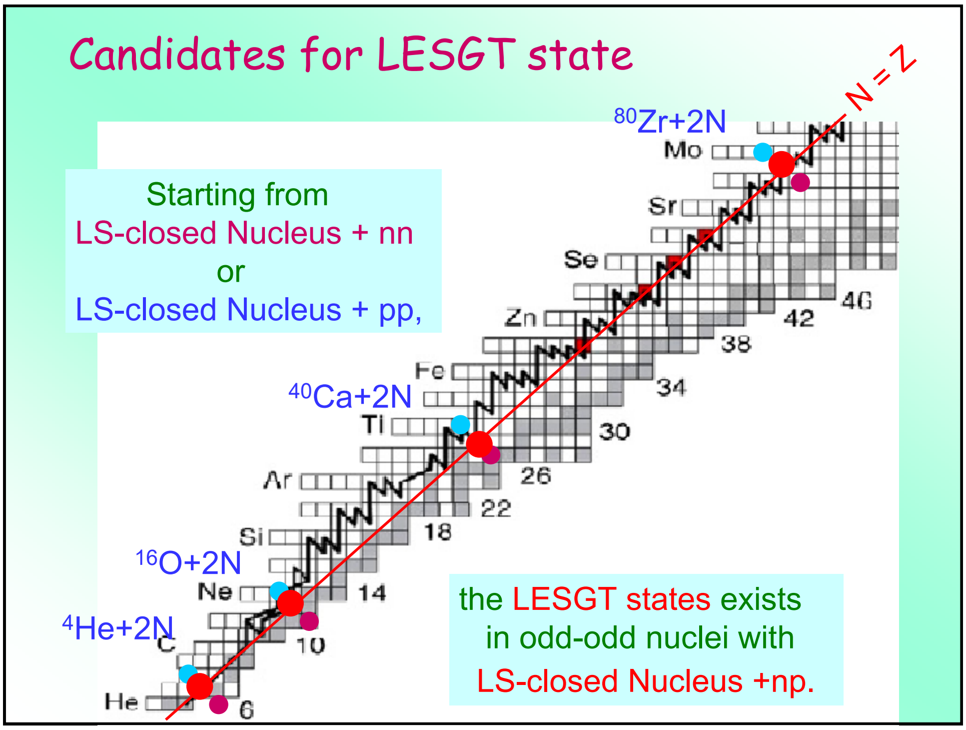
B(GT) = 6.0 ? Large !

1) Closed Shell + 2 nucleon
   *separation of core
   and 2 nucleons

2) Active Isoscalar Interaction

B(GT) = 2.17 Smaller !

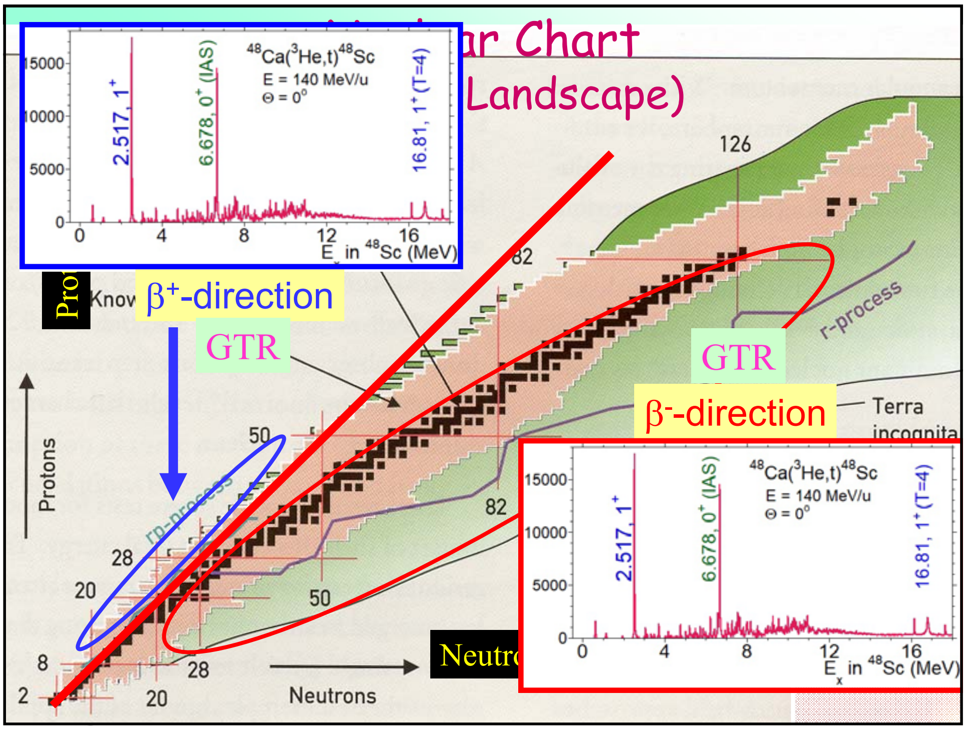
Σ (Sum rule) = 3 x |N-Z| = 6



Candidates for LESGT state

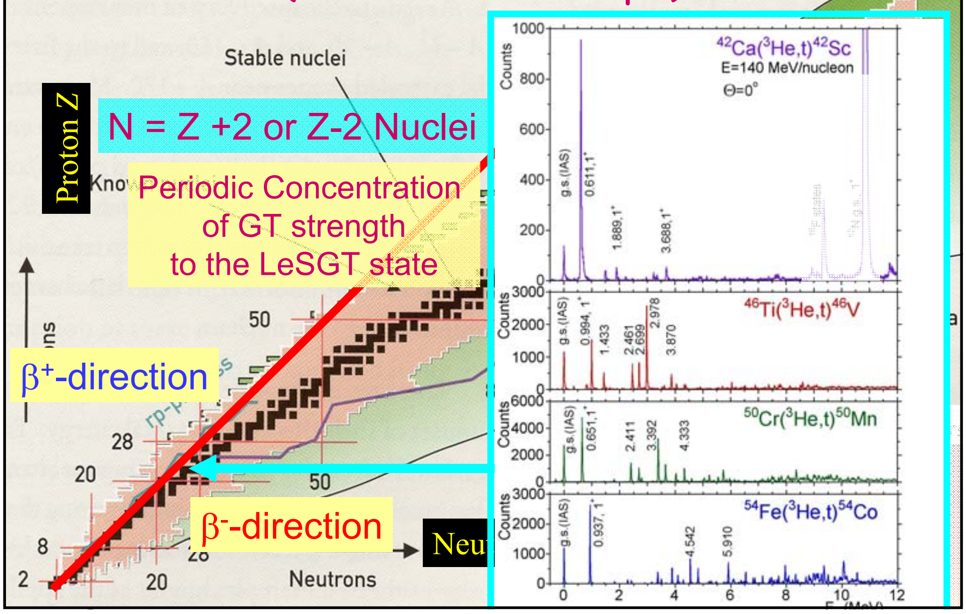
Starting from
LS-closed Nucleus + nn
or
LS-closed Nucleus + pp,

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



ar Chart
Landscape)

Nuclear Chart
(Nuclear Landscape)



N = Z +2 or Z-2 Nuclei

Periodic Concentration
of GT strength
to the LeSGT state

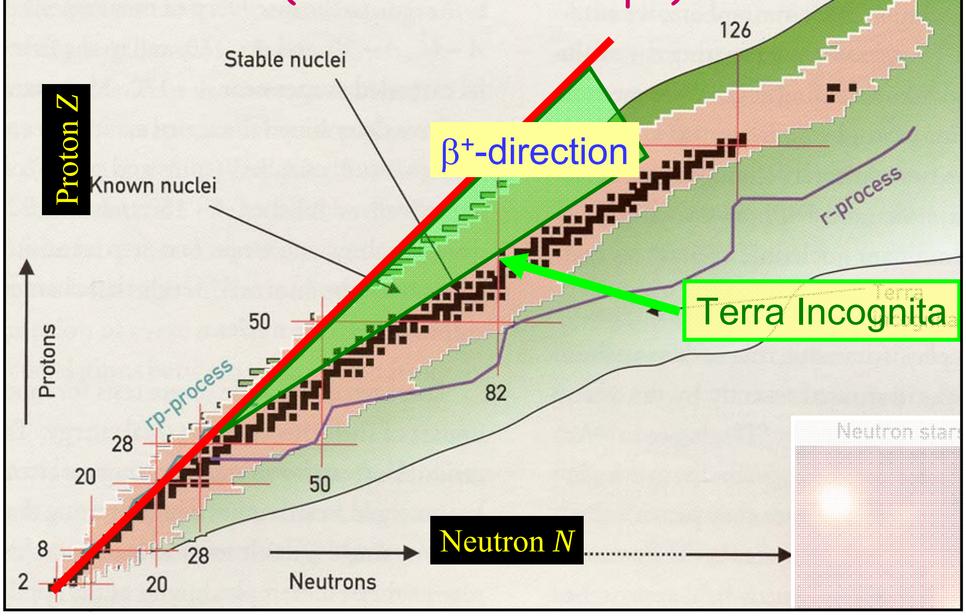
β^+-direction

β^--direction

Proton Z

Neu

Nuclear Chart
(Nuclear Landscape)



β^+-direction

Terra Incognita

Proton Z

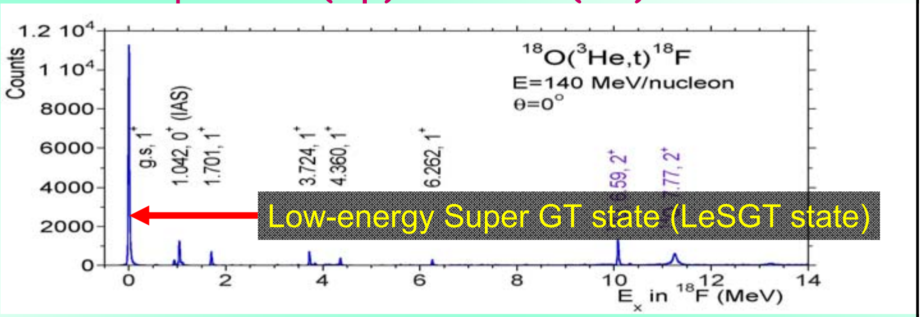
Neutron *N*

**Particle – Hole Conjugate ?

Doubly-Closed-Shell Nucleus + 2 nucleons
^{18}O (^{18}Ne) → ^{18}F
[^{16}O +2n (+2p)] [^{16}O + (p + n)]
g.s. → g.s. : LeSGT transition

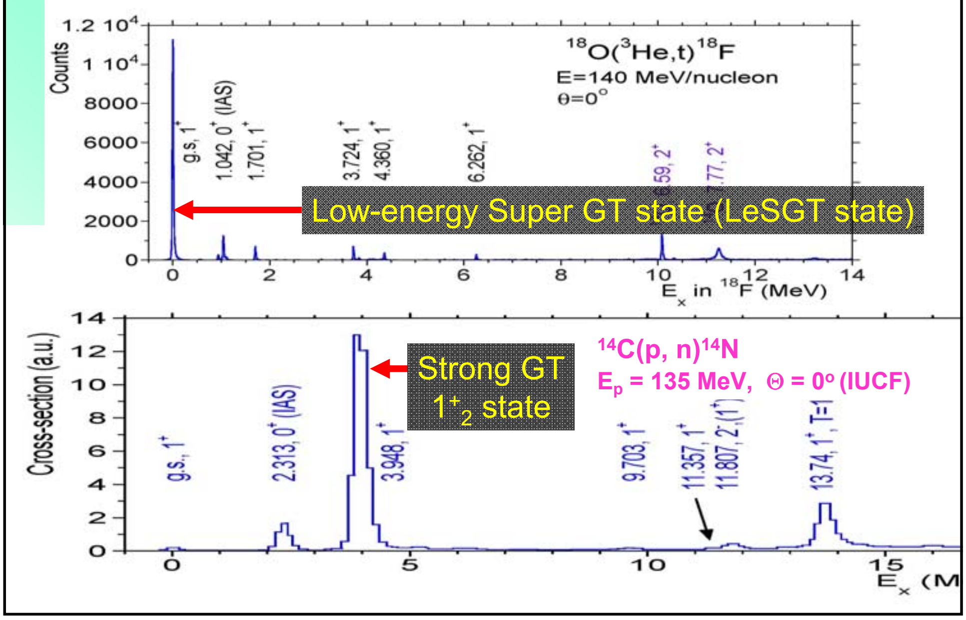
Doubly-Closed-Shell Nucleus - 2 nucleons
^{14}O (^{14}C) → ^{14}N
[^{16}O - 2n (-2p)] [^{16}O - (p + n)]
g.s. → g.s. : LeSGT transition ???

Is There Similarity of GT Transitions from 2-particle (2p) & 2-hole (2h) Nuceli ?



Low-energy Super GT state (LeSGT state)

Is There Similarity of GT Transitions from 2-particle (2p) & 2-hole (2h) Nuceli ?

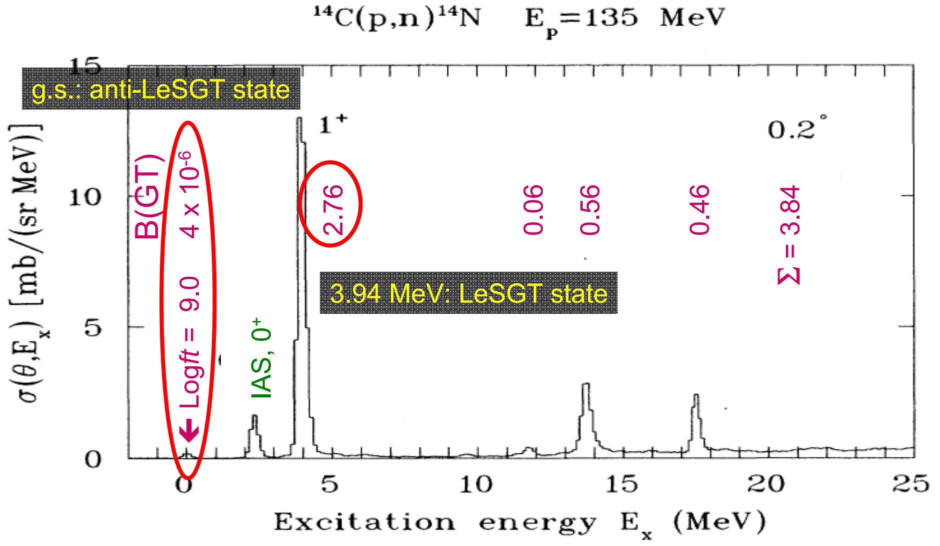


Low-energy Super GT state (LeSGT state)

Strong GT 1^+_2 state

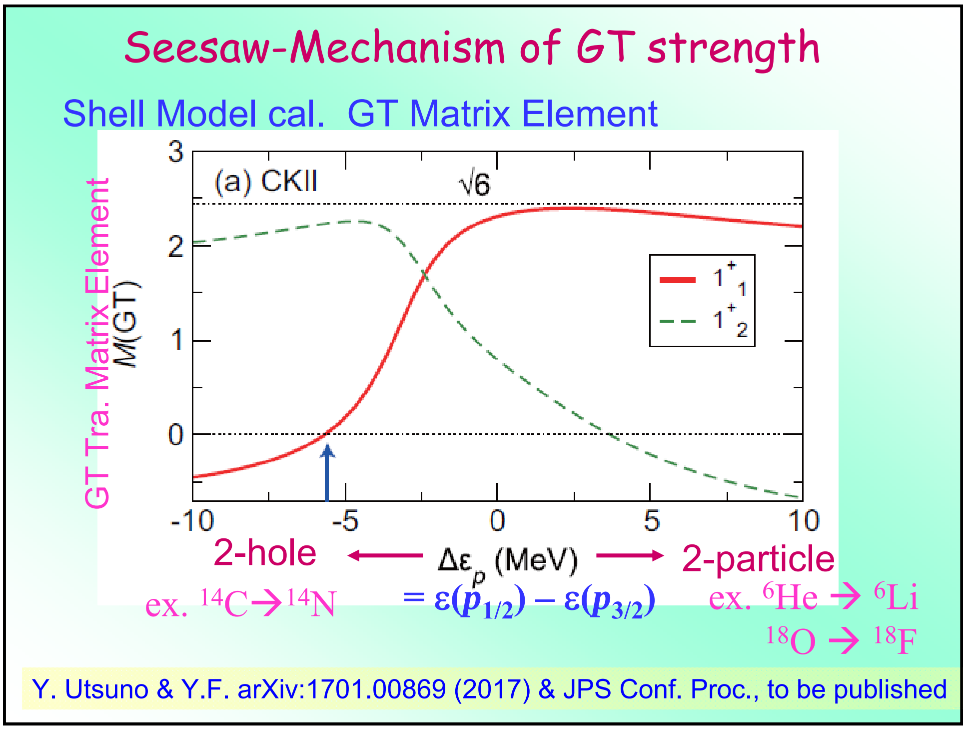
$^{14}C(p, n)^{14}N$
E_p = 135 MeV, Θ = 0° (IUCF)

GT-tra. from 2-hole Structure: $^{14}C \rightarrow ^{14}N$



g.s.: anti-LeSGT state

3.94 MeV: LeSGT state



Seesaw-Mechanism of GT strength

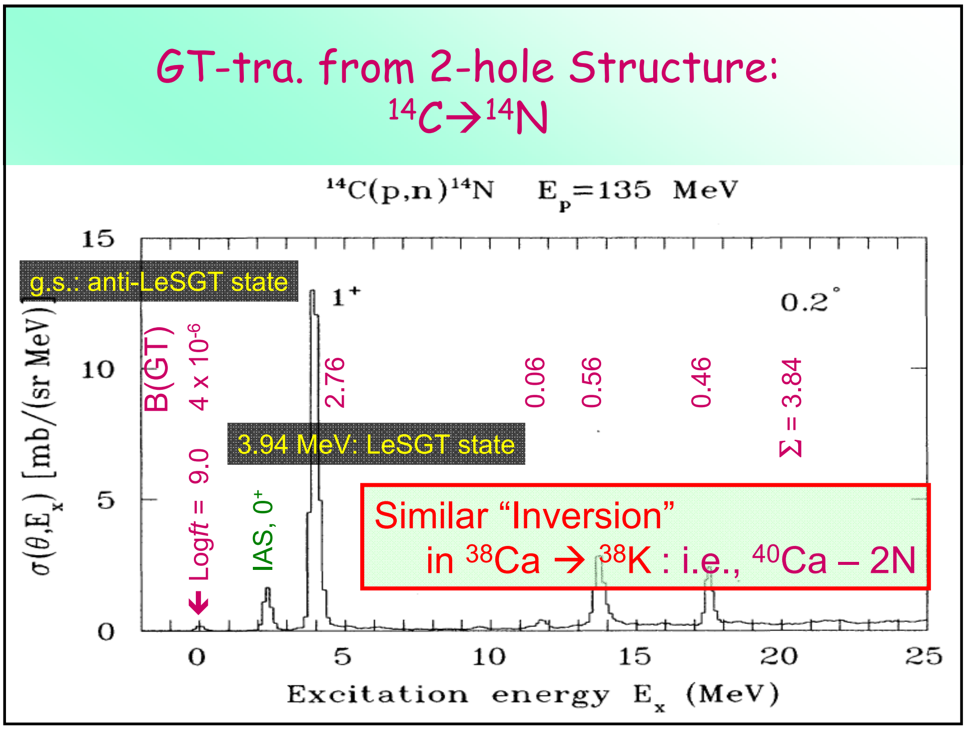
Shell Model cal. GT Matrix Element

2-hole ← $\Delta\varepsilon_p$ (MeV) → 2-particle

ex. $^{14}C \rightarrow {}^{14}N$ $= \varepsilon(p_{1/2}) - \varepsilon(p_{3/2})$ ex. $^{6}He \rightarrow {}^{6}Li$

$^{18}O \rightarrow {}^{18}F$

Y. Utsuno & Y.F. arXiv:1701.00869 (2017) & JPS Conf. Proc., to be published



GT-tra. from 2-hole Structure: $^{14}C \rightarrow {}^{14}N$

g.s.: anti-LeSGT state

3.94 MeV: LeSGT state

Similar “Inversion” in $^{38}Ca \rightarrow {}^{38}K$: i.e., ^{40}Ca – 2N

Summary

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

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

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

→ Fine structure of GT-Resonances

→ Low-energy Super GT state (LESGT state)

→ anti-LESGT state

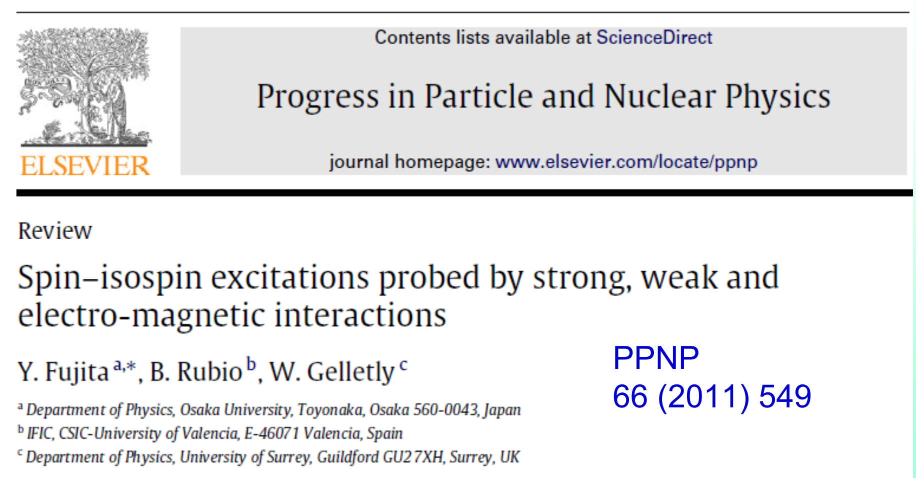
→ an Overview of GT transitions

GT tra. is a Key to open the Jewel Box of Nuclear Structure !

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
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

Advertisement



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Progress in Particle and Nuclear Physics

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Review

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

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66 (2011) 549

End of publicity