April 4, 2002

原子核のクラスター構造

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1．(^{7}Li,^{7}Be) 反応

2．Li 原子核でのクラスター励起

3．中性子過剰核を用いた研究から

4．クラスターの分子構造

5．まとめ

1. Physical subjects

Study of isovector excitations
via charge exchange reaction with light heavy-ion

- Isovector resonances
- Relative spin-strength ($\Delta S=1 / \Delta S=0$)
- Nuclear interaction : V_τ, $V_{\sigma\tau}$

(^{7}Li,^{7}Be-γ) reaction
$\Delta S = 0, 1$
$\Delta T_z = +1$

Measurement of $\Delta S=0$ and $\Delta S=1$ excitations

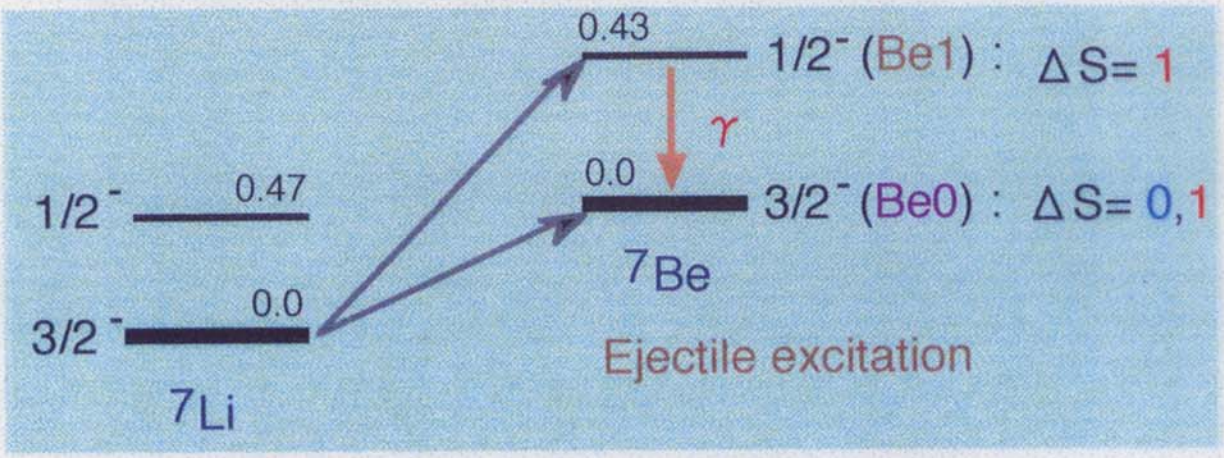
- Direct evidence of
  $\Delta S=0$ and $\Delta S=1$ isovector reasonances
- Distribution of
  relative ($\Delta S=0$)/($\Delta S=1$) strengths
- Underlying continuum shape

Isovector resonances in $\Delta S=0$ and $\Delta S=1$ excitations

1. Giant dipole resonance
2. Isovector electric monopole resonance in ^{60}Ni
3. Soft dipole resonance in ^{6}He
   cluster excitation

2. Principle of measurement

7Li→7Be transition and spin-selectivities



7Be-γ coincidence

Separation
between Be0 and Be1-reaction channels

Be0 : Without 7Be-γ coincidence

Be1 : With 7Be-γ coincidence

Deduction of ΔS=0 and ΔS=1 spectra

$$\sigma(\Delta S=0) = \sigma(\text{Be0}) - \sigma(\text{Be1})/R$$

$$\sigma(\Delta S=1) = \sigma(\text{Be1})$$

$R \equiv \sigma(\text{Be1})/\sigma(\text{Be0})$
is obtained from spin-flip transitions.

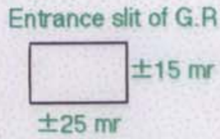
Experimental Procedure @ RCNP

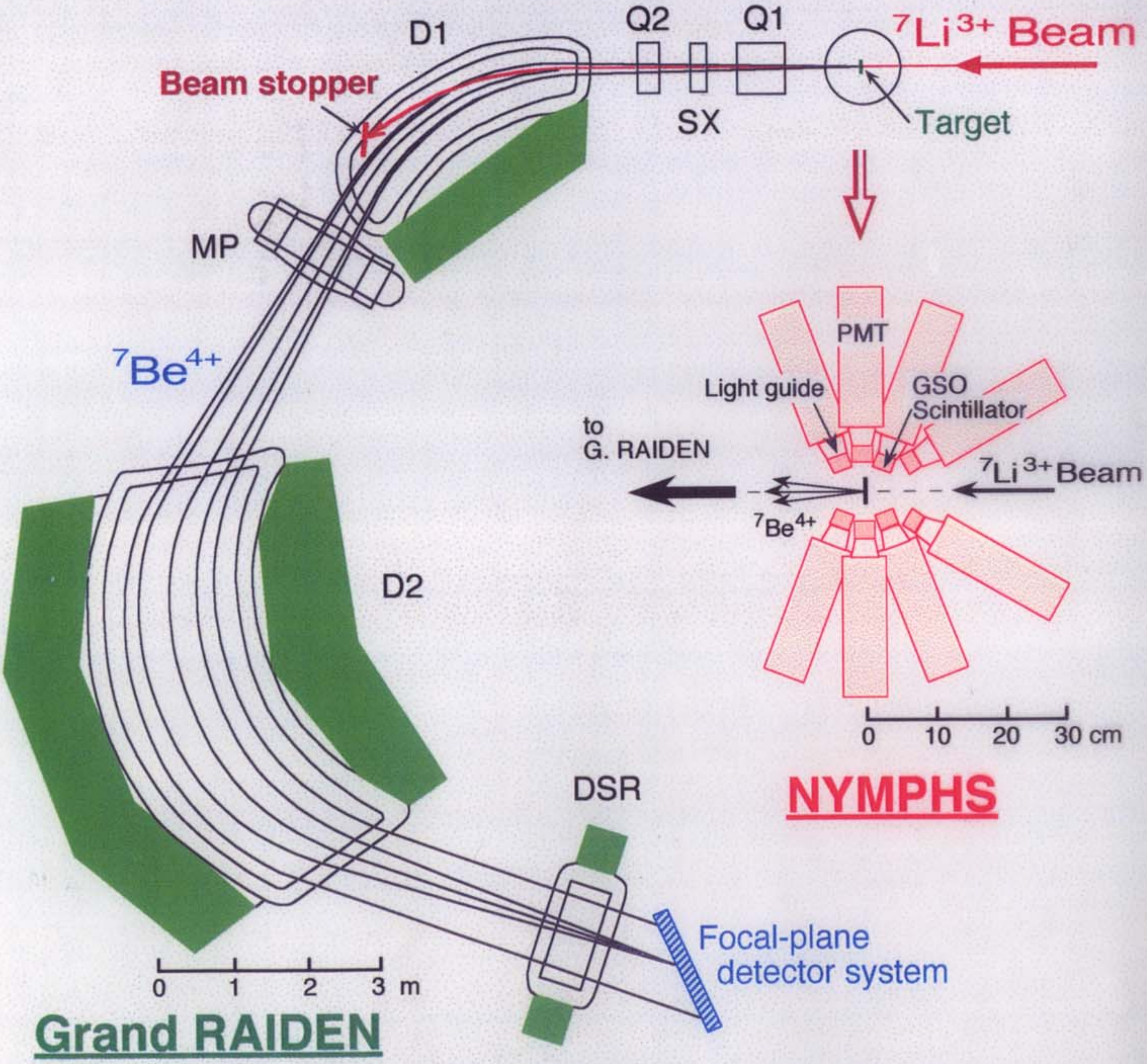
Beam : 7Li 3+, 65 *A*MeV (a few nA)

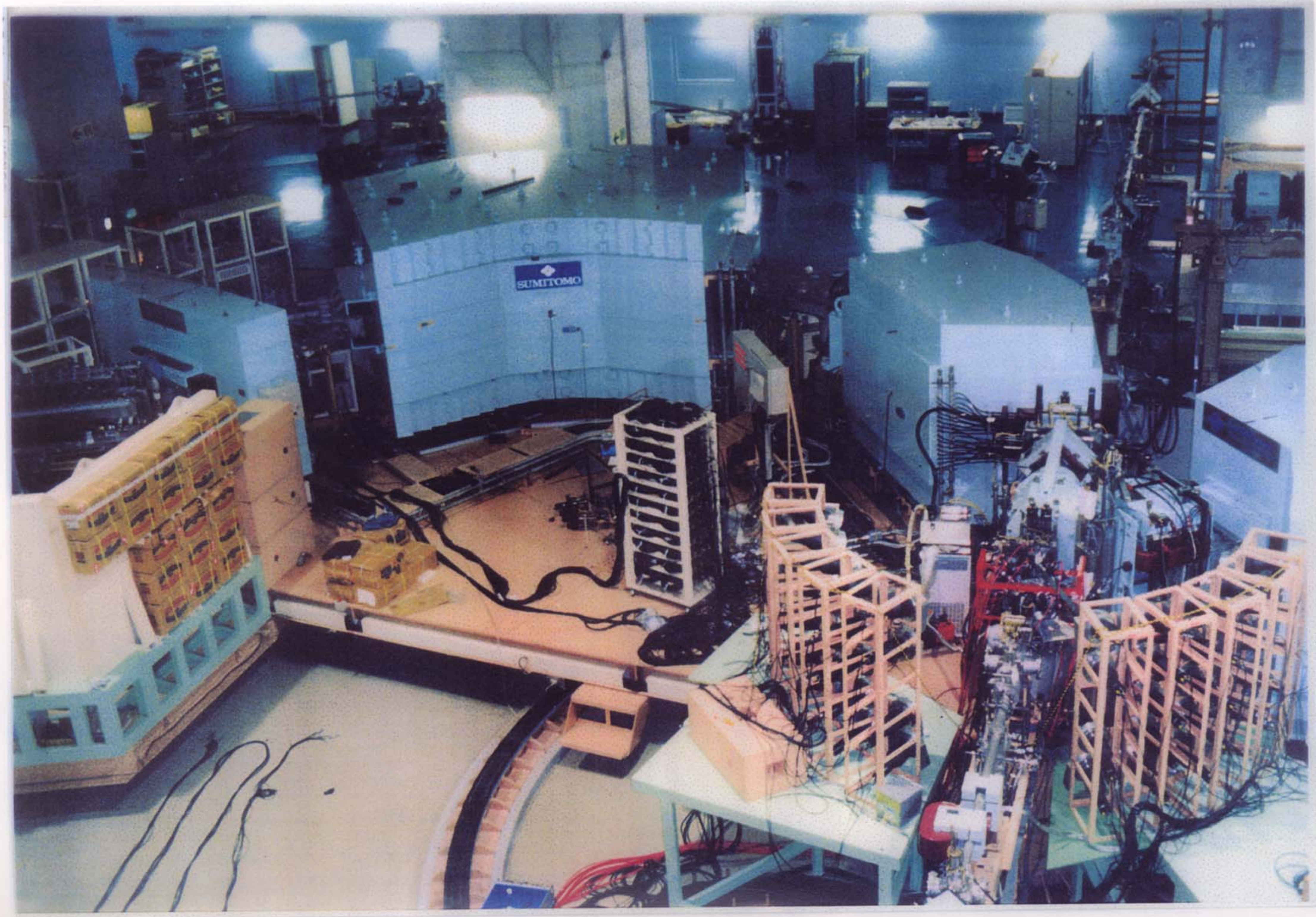
Targets : 6Li, 12C, 28Si, 60Ni

7Be4+ : Grand RAIDEN at $\theta = 0.3^\circ$, 1°

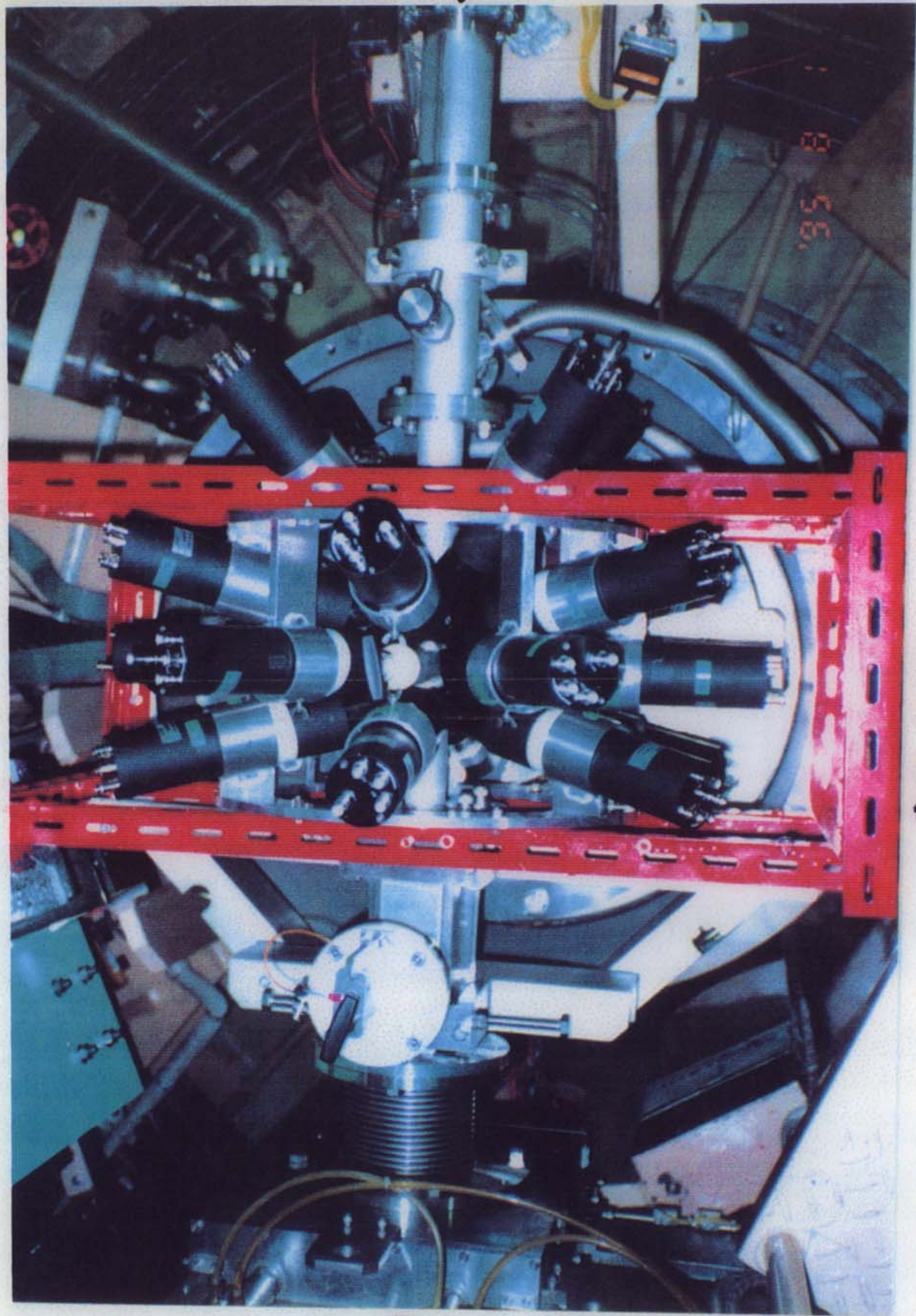
γ - ray : NYMPHS (GSO-detector array)
GSO at $\theta = 55^\circ$ 90° 125° 150°
detection of Doppler effect






SUMITOMO

$^7Li^{3+}$ Beam



"NYMPHS"

"G. RAIDEN"

Charge exchange Spin-flip & Spin-nonflip Reaction

Nakayama, S. *et al.*
Nucl. Instrum. Methods A404 (1998) 34.
Phys. Rev. Lett. 83 (1999) 690.
Phys. Rev. C60 (1999) 047303.

$^{7}Li + A \rightarrow {}^{7}Be + B$

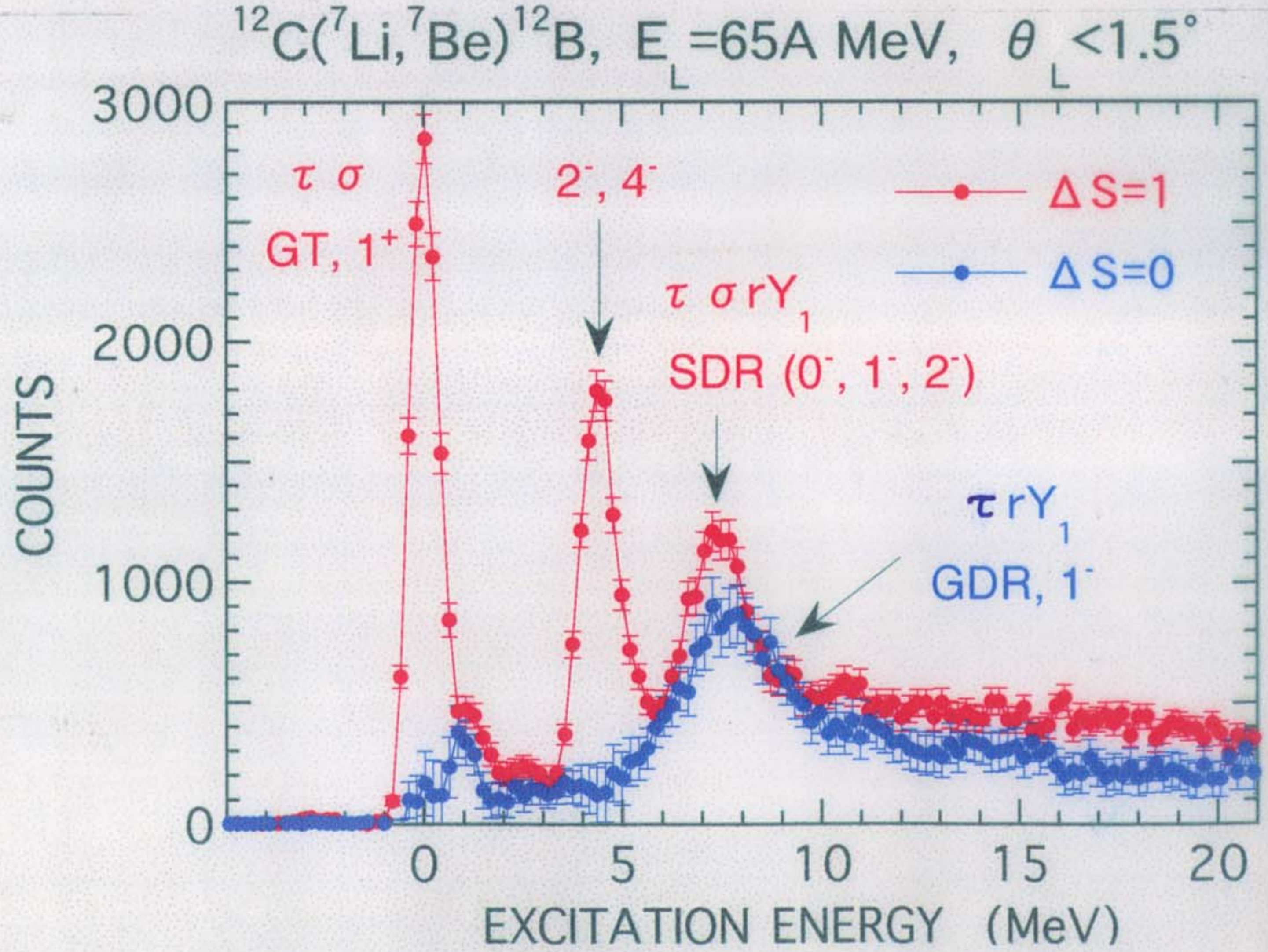
$T_z = +1/2$; $J^\pi = 3/2^-$

$T_z = -1/2$

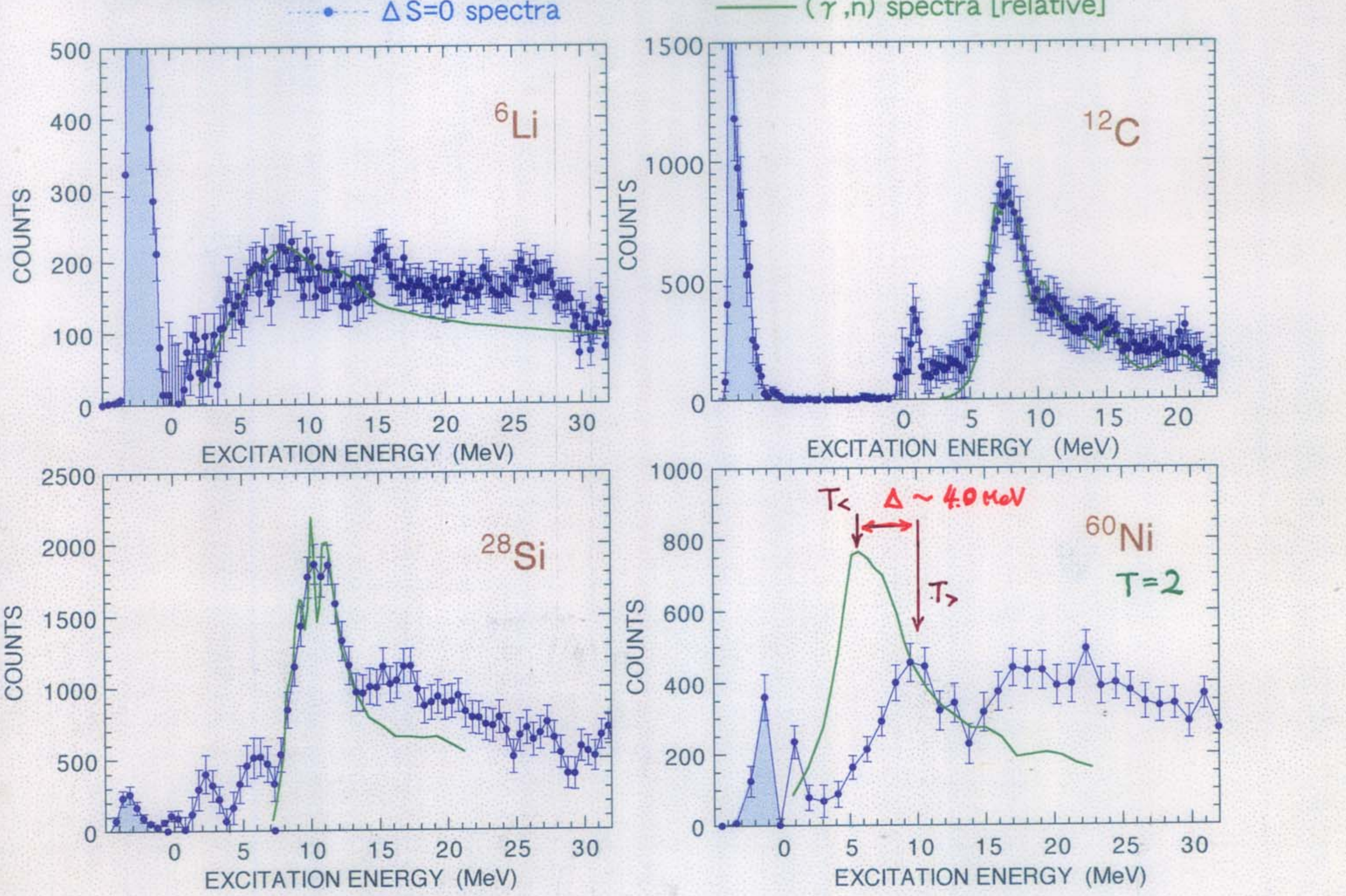
^{7}Be ($J^\pi = 3/2^-$) — $\Delta T_z = +1$, $\Delta S=0$ / $\Delta S=1$

$^{7}Be^*$ ($J^\pi = 1/2^-$) — $\Delta T_z = +1$, $\Delta S=1$

→ $^{7}Be + \gamma$



Comparison between $\Delta S=0$ and (γ,n) spectra



Cluster excitation in Li nuclei

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Univ. of Tokushima

1. Subjects

Li-isotopes = Cluster structures

^{6}Li(g.s) = d+ α 、 t+^{3}He

^{7}Li(g.s) = t+ α

→ Exotic cluster structures in Nuclei
(Residual nucleus : He)

S. Nakayama etal., Phys. Rev. Lett. 85 (2000) 262

Cluster excitation in Nuclei
(Target nucleus : Li)

S. Nakayama etal., Phys. Rev. Lett. 87 (2001) 122502

2. Experimental procedure

65A-MeV ^{7}Li beam : RING cyclotron of
RCNP, Osaka Univ.

Reaction : ^{6}Li, ^{7}Li(^{7}Li,^{7}Be) @ 65A MeV

Observables : Spin-flip and Spin non-flip spectra
Angular distributions

Collaborators

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Osaka Univ.

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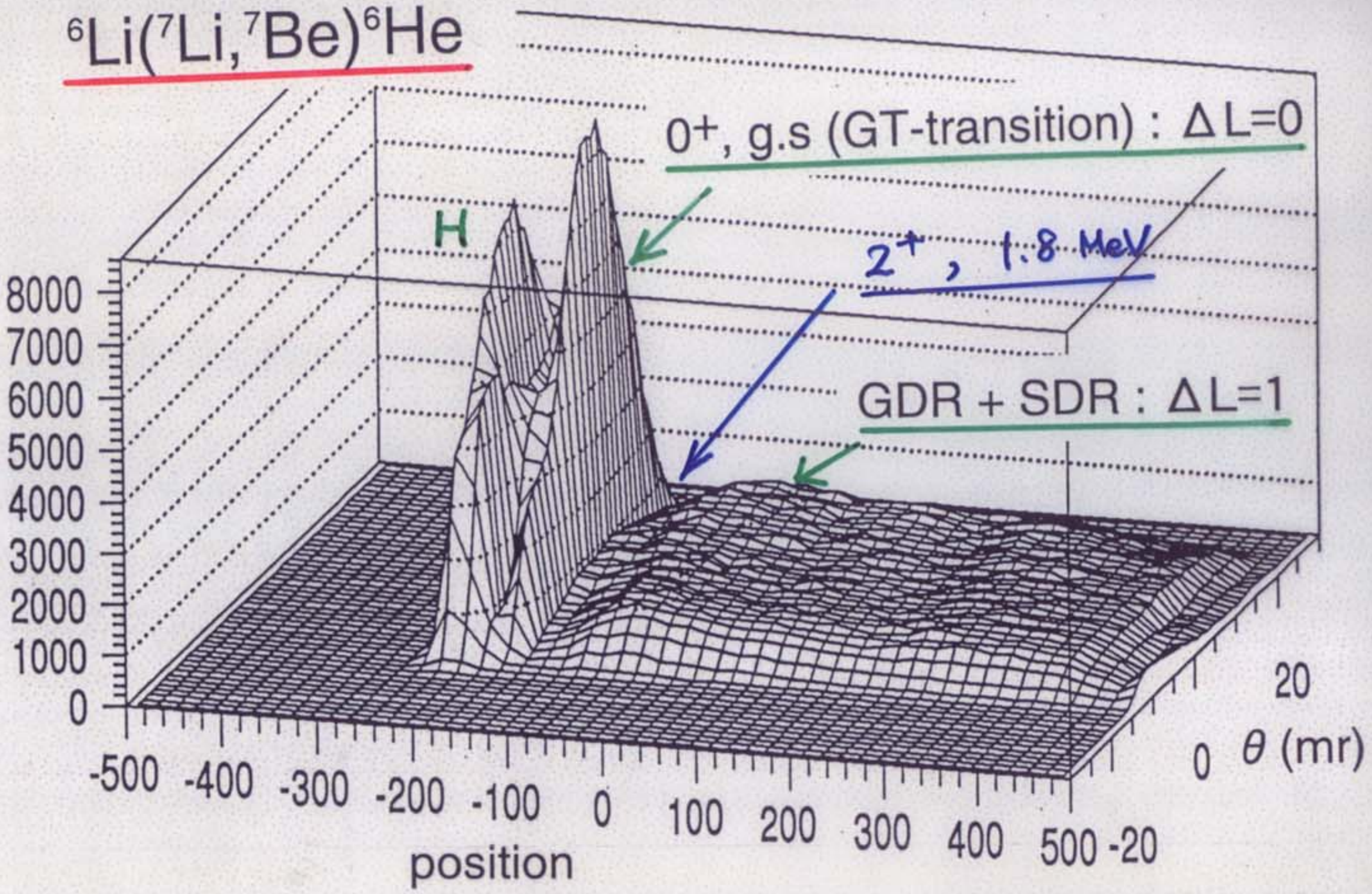
A. Tamii

Kobe Tokiwa Junior Coll.

M. Tanaka

SPring-8

H. Toyokawa



$^6Li(^7Li,^7Be)^6He$
0^+, g.s (GT-transition) : ΔL=0
H
2^+, 1.8 MeV
GDR + SDR : ΔL=1
8000
7000
6000
5000
4000
3000
2000
1000
0
-500 -400 -300 -200 -100 0 100 200 300 400 500
position
-20 0 20
θ (mr)

Resonances in $^{6,7}Li$

1. (γ,n) reaction (GDR)

B.L. Berman and S.C. Fultz., Rev. Mod. Phys. 47 (1975) 713.

^{6}Li: E_x= 8.5 MeV in ^{6}He

^{7}Li: E_x= 6 MeV in ^{7}He

2. (n,p) and (^{7}Li,^{7}Be) reactions

(p,n): F.P. Brady et al., J. Physics G10 (1984) 353.
(^{7}Li,^{7}Be): S.B. Sakuta et al., EuroPhys. Lett. 22 (1993) 511.
J. Janecke etal., Phys. Rev. C54 (1996) 1070.

^{6}Li: E_x= 8 (GDR) , 15, 23 MeV

^{7}Li: E_x= 7 (GDR) , 18 MeV

Q (E_x=23 MeV in ^{6}He) $\sim$ Q (E_x=18 MeV in ^{7}He)

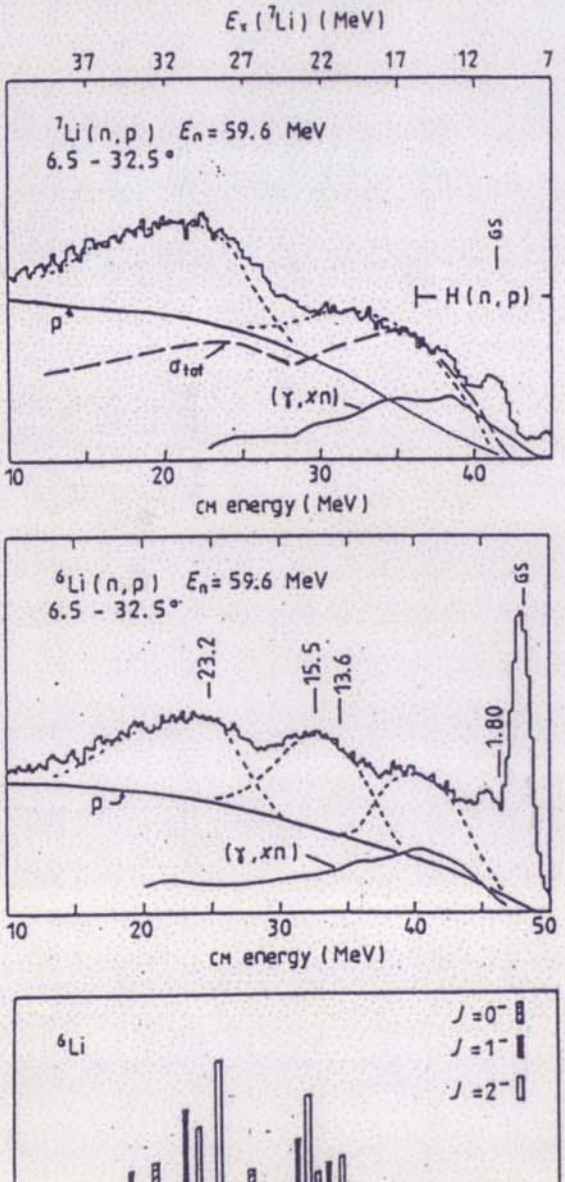
→ Common constituent in $^{6,7}Li$
(α-cluster)

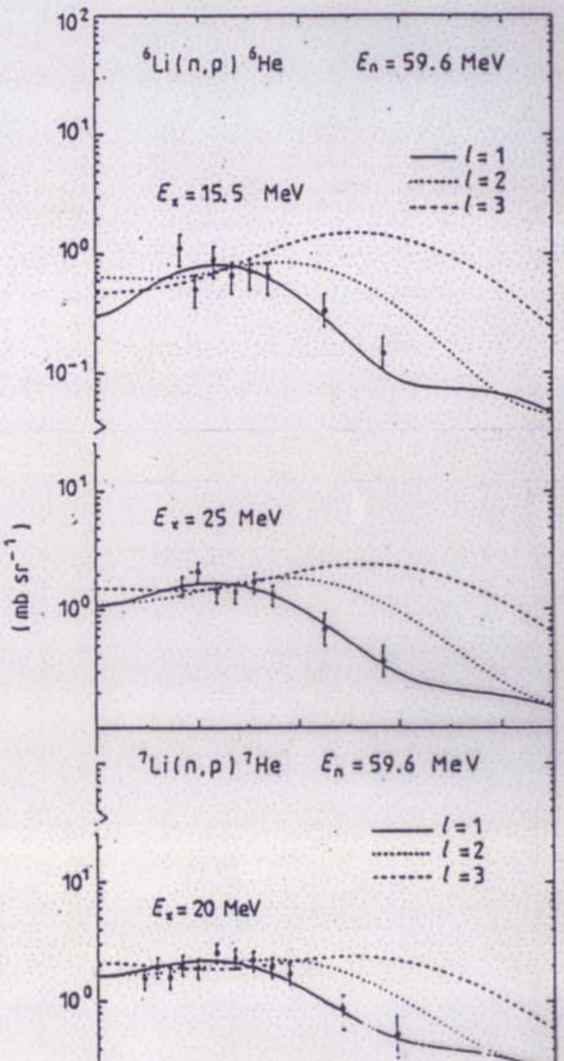
3. ΔS=0 and ΔS=1 spectra in (^{7}Li,^{7}Be) reaction

GDR, SDR in $^{6,7}Li$ and ^{4}He

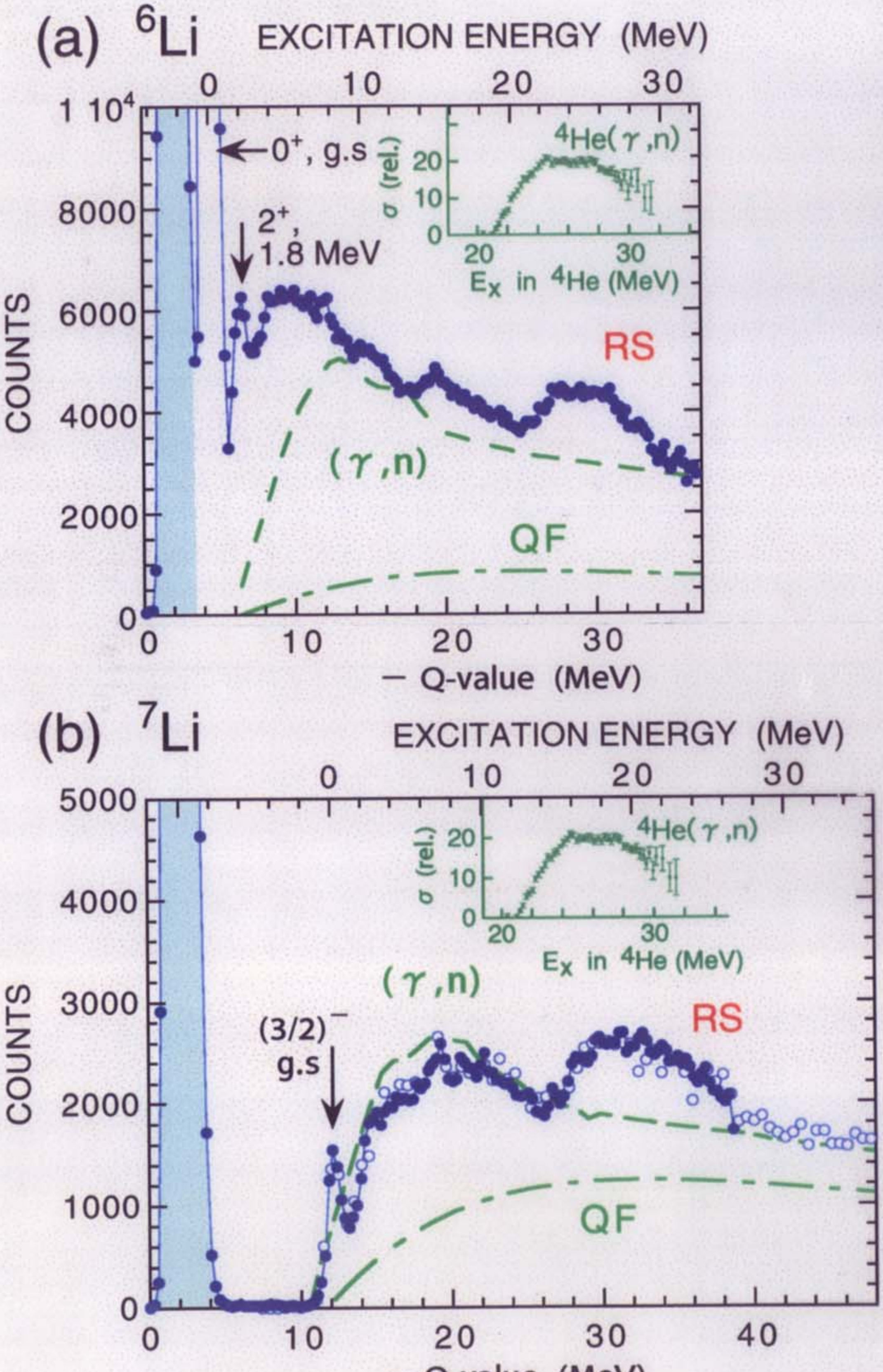
Brady et al., J. Phys. G10, 363 (1984)

$^{6,7}Li(n,p)$ @ 60 MeV





$^{6,7}Li(^{7}Li, ^{7}Be)^{6,7}He$ @ 65 A MeV , $\theta_L < 2°$

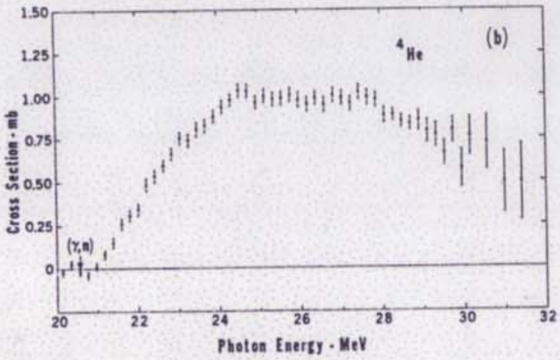


GDR & SDR in ^{4}He

1. GDR : $\Delta S=0$, $\Delta L=1$

^{4}He(γ,n) reaction

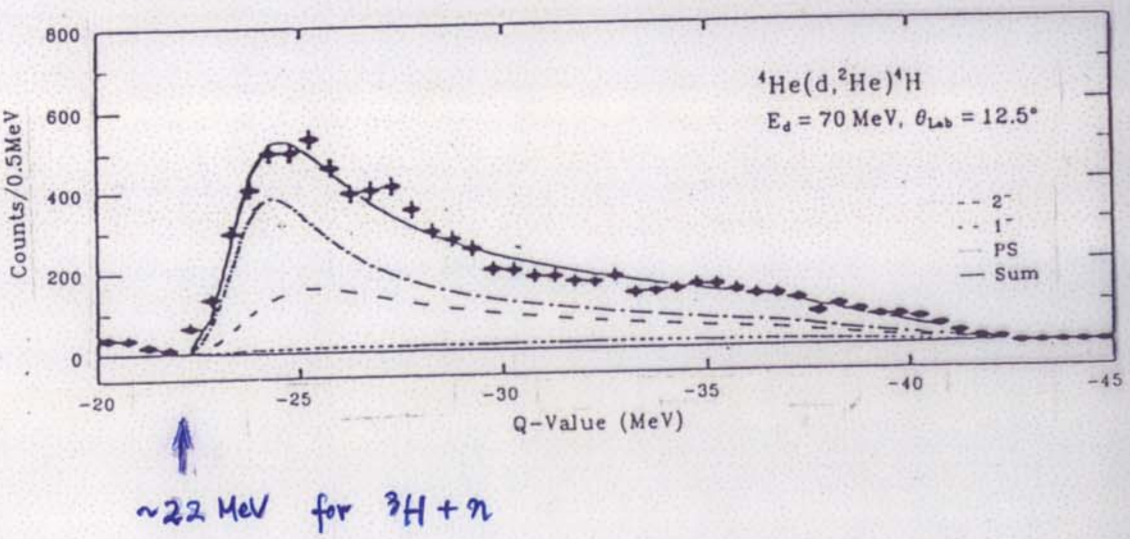
Berman & Fultz, Rev. Mod. Phys. 47 (1975) 713.

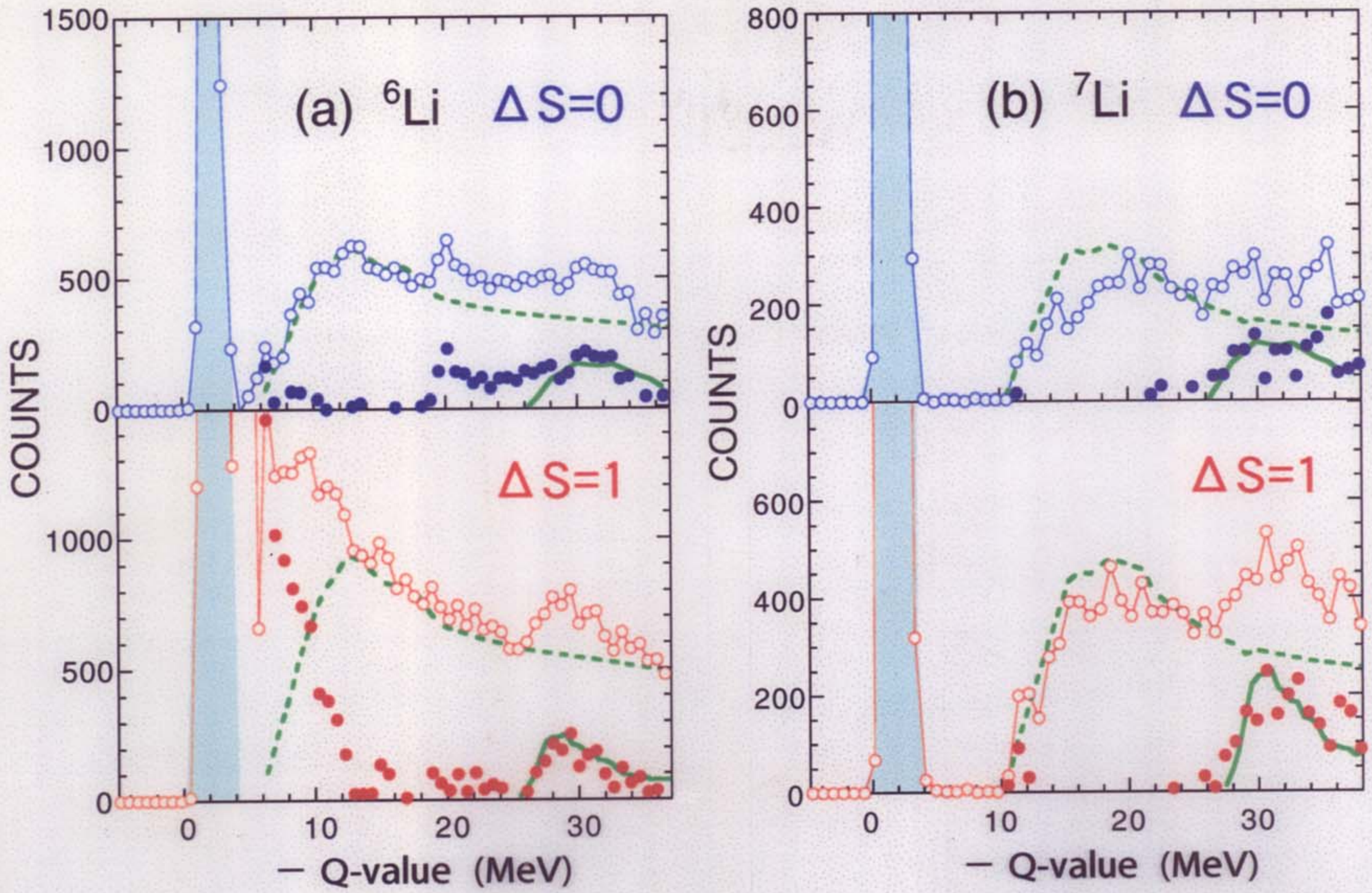


2. SDR : $\Delta S=1$, $\Delta L=1$

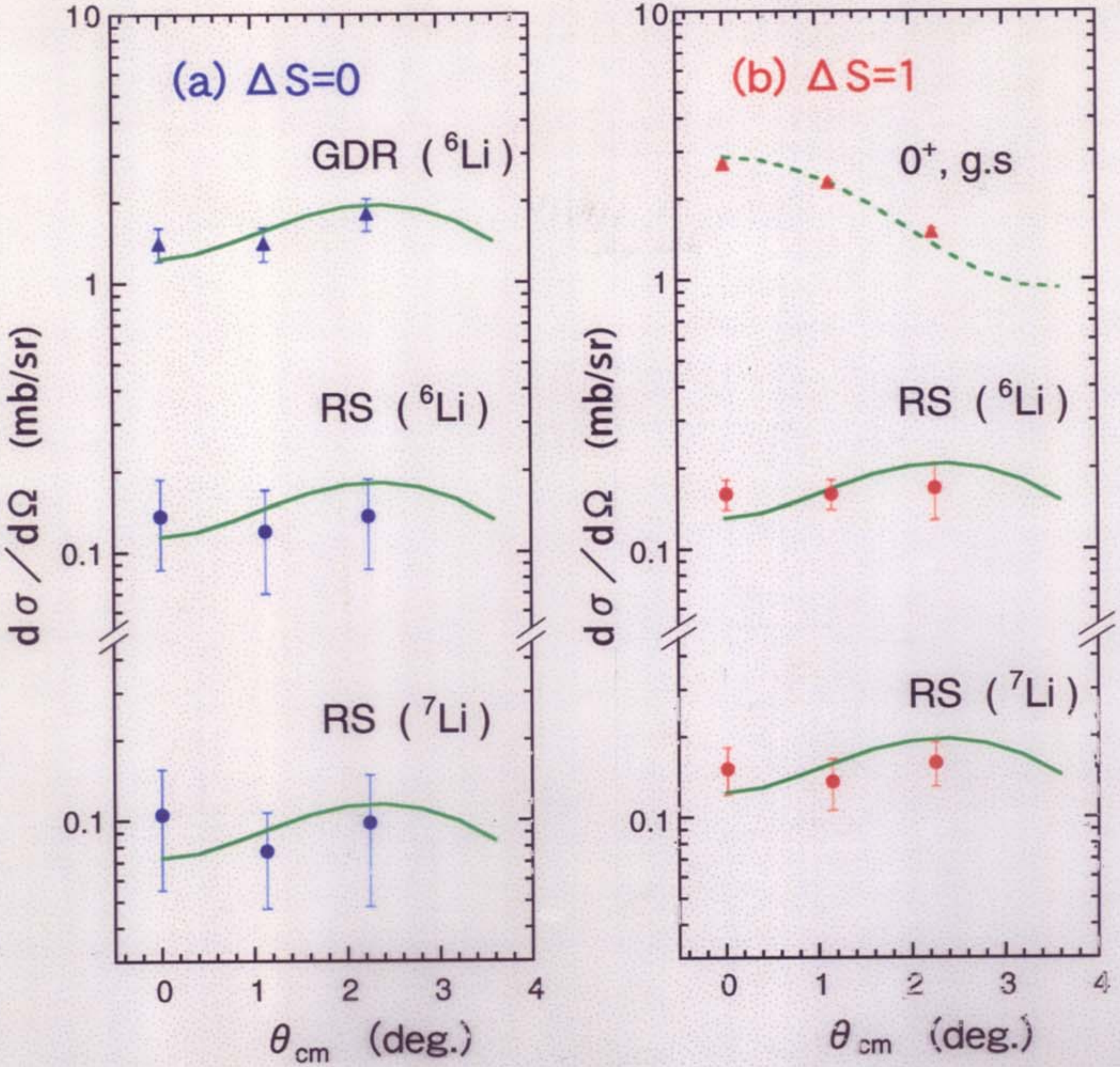
^{4}He(d,^{2}He) reaction

Okamura *et al.*, RCNP Annual Report 1988, p.22





(a) 6Li ΔS=0
ΔS=1
(b) 7Li ΔS=0
ΔS=1
COUNTS
COUNTS
1500
1000
500
0
1000
500
0
800
600
400
200
0
600
400
200
0
0
10
20
30
0
10
20
30
− Q-value (MeV)
− Q-value (MeV)



(a) ΔS=0
GDR (6Li)
RS (6Li)
RS (7Li)
(b) ΔS=1
0+, g.s
RS (6Li)
RS (7Li)
dσ/dΩ (mb/sr)
θcm (deg.)
10
1
0.1
0
1
2
3
4

Table 1: Isovector dipole resonances observed via by the (^{7}Li,^{7}Be) reactions on ^{6}Li and ^{7}Li at 65A MeV.

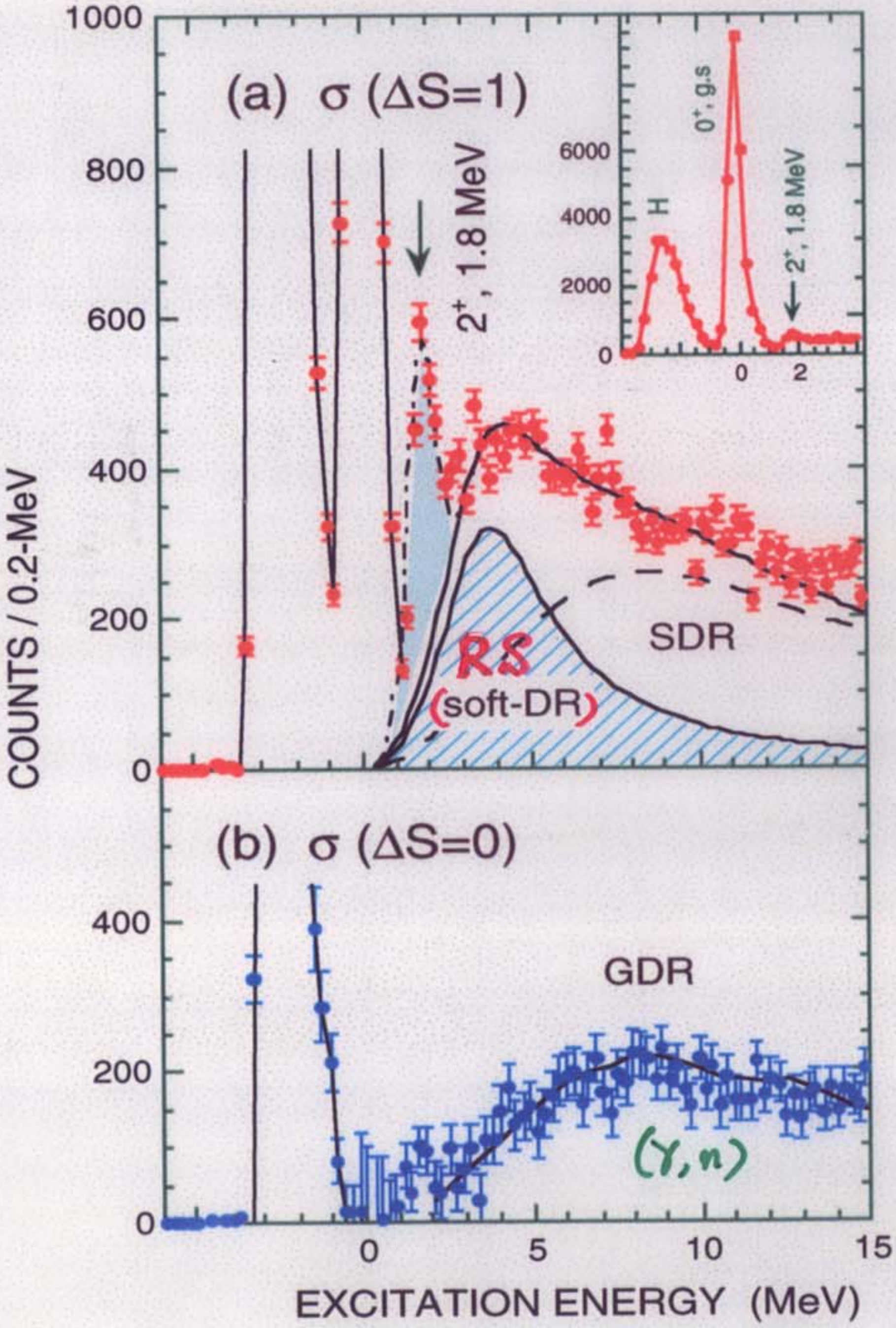
Target	^{6}Li			^{7}Li	
	analogue of the GDR	RS ΔS=0	RS ΔS=1	RS ΔS=0	RS ΔS=1
Q−value (MeV)	−12.5	−31	−29	−32	−30
$\sigma(0°)$ (mb/sr)	1.4±0.2	0.17±0.05	0.20±0.02	0 .14±0.06	0.18±0.03

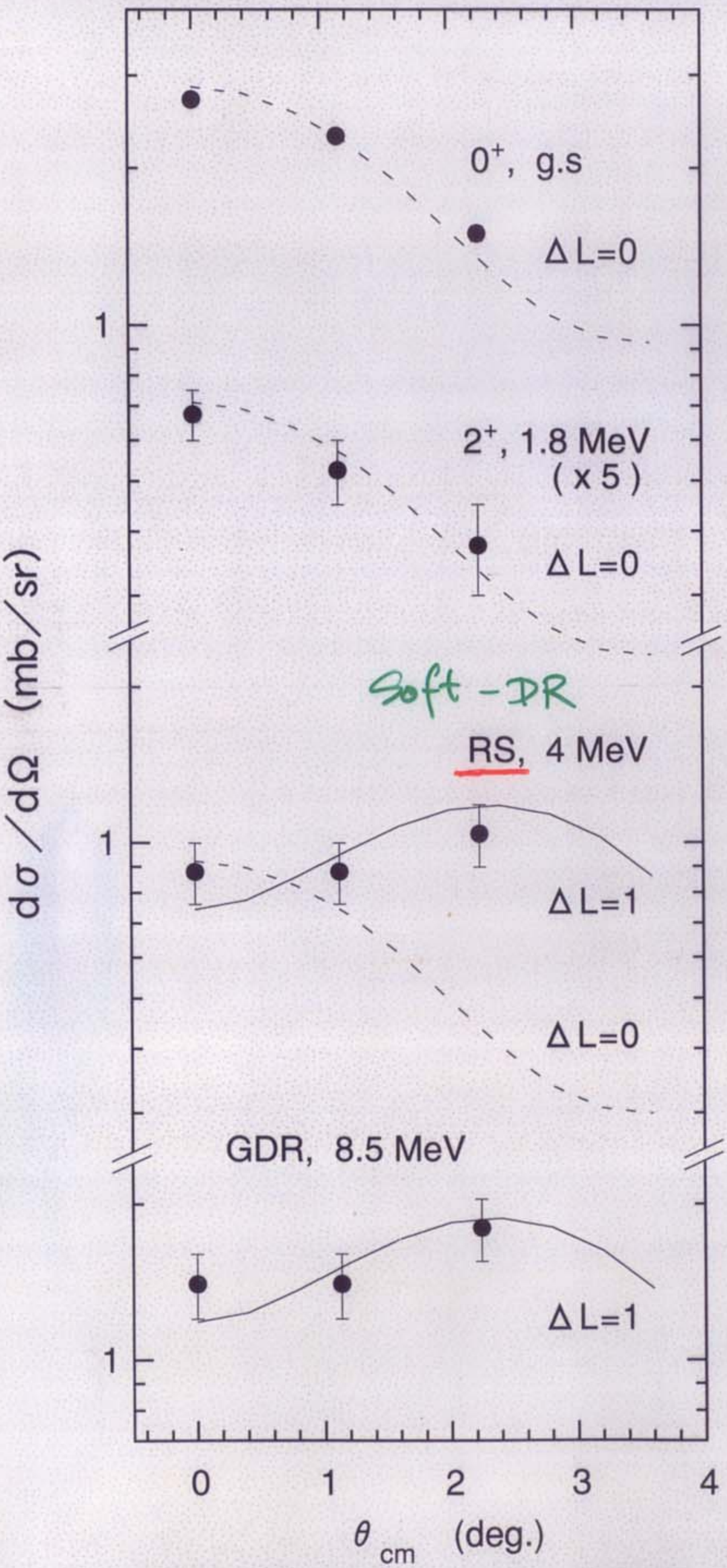
σ(SDR) / σ(GDR) ~ 1.4 in ^{6}Li and ^{7}Li

- $\sigma(\Delta S=1) / \sigma(\Delta S=0)$ = 1.2±0.4 for ^{6}Li; 1.3±0.6 for ^{7}Li
- $\sigma(\Delta S=0)_{6Li} \sim \sigma(\Delta S=0)_{7Li}$
- $\Delta L=1$

→ RS at Q~30 MeV is inferred to be the dipole resonance of the α-cluster in ^{6}Li and ^{7}Li

Evidence for the soft-DR
in $^6Li(^7Li,^7Be)^6He$ reaction





0+, g.s
ΔL=0
1
2+, 1.8 MeV
(x 5)
ΔL=0
Soft -DR
RS, 4 MeV
1
ΔL=1
ΔL=0
GDR, 8.5 MeV
ΔL=1
1
0
1
2
3
4
dσ / dΩ (mb/sr)
θ cm (deg.)

Table 1: Isovector dipole resonances studied by the ^{6}Li(^{7}Li,^{7}Be)^{6}He reaction at 65 AMeV.

	GDR	SDR	RS
E_x (MeV)	12.1±1.5 $^{a)}$	b)	4±1
Γ (MeV)	15±3	b)	4±1
$\sigma(0°)$ (mb/sr)	1.4±0.2	1.7±0.3	0.9±0.2

a) Excitation energy in ^{6}Li.

b) E_x and Γ for the SDR are assumed to be the same as those for the GDR.

Energy-weigted sum-rule (EWSR)

EWSR(GDR) = C NZ/A

EWSR(soft-DR) = C $(N-Z)^2/A(A-4)$

where $C = \frac{9}{4\pi}\frac{h^2 e^2}{2m}$

[Y. Alhassid *et al.*, Phys. Rev. Lett. **49** (1982) 1482.]

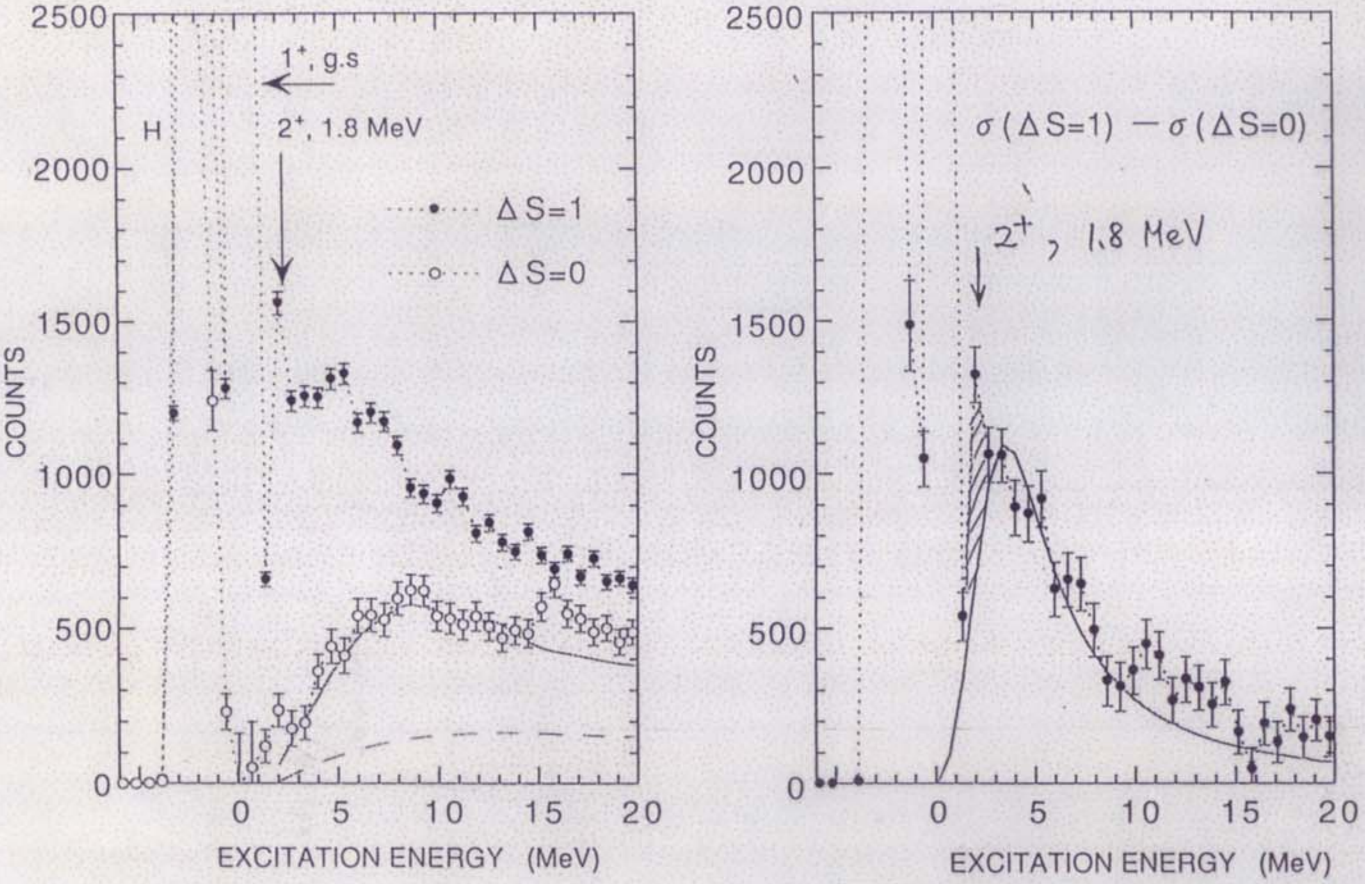
$$\rightarrow \frac{\text{EWSR(GDR)}}{\text{EWSR(soft-DR)}} = \frac{NZ(A-4)}{(N-Z)^2} = 4$$

Observed cross section x E_x (mb/sr x MeV)

$$\frac{\sigma\,(\text{GDR})*E_x}{\sigma\,(\text{RS})*E_x} = \frac{1.4*12.1}{0.9*4} = 4.7 \pm 1.5$$

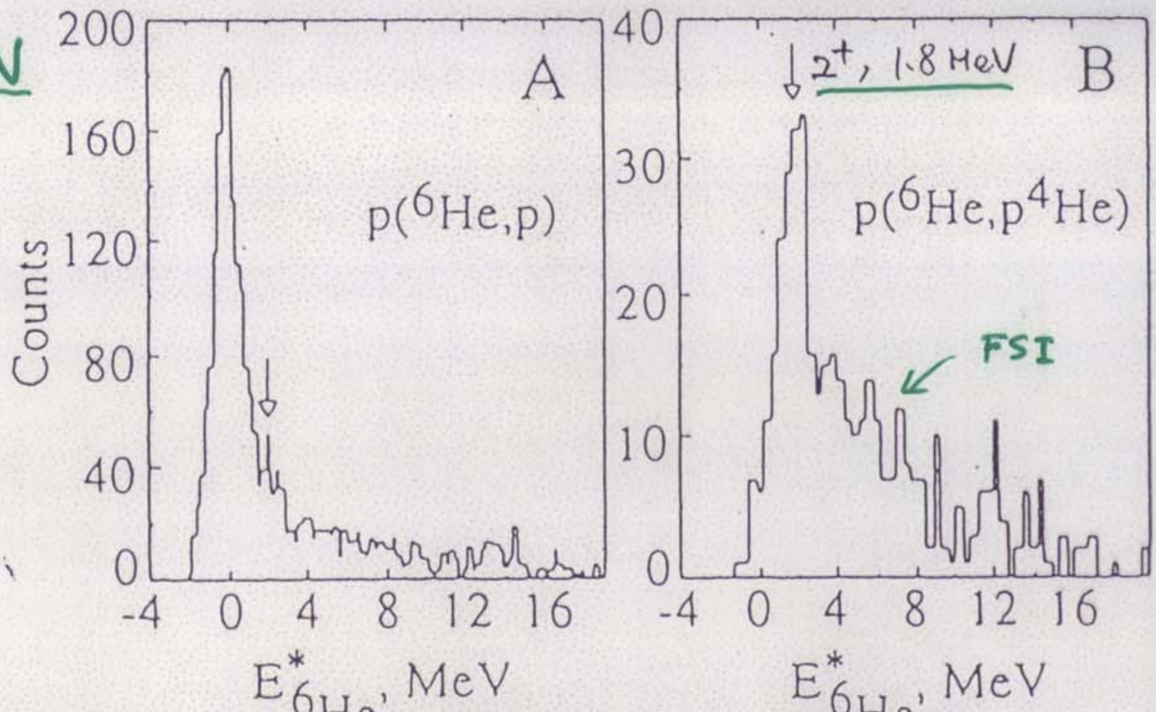
Observable: $\Delta S=1$, $\Delta L=1$, $E_x=4$ MeV, $\sigma = 0.9$ mb/sr

→ RS is a candidate for the soft-dipole resonance.



A.A. Korsheninnikov et al., Nucl. Phys. A617 (1997) 45

RIKEN



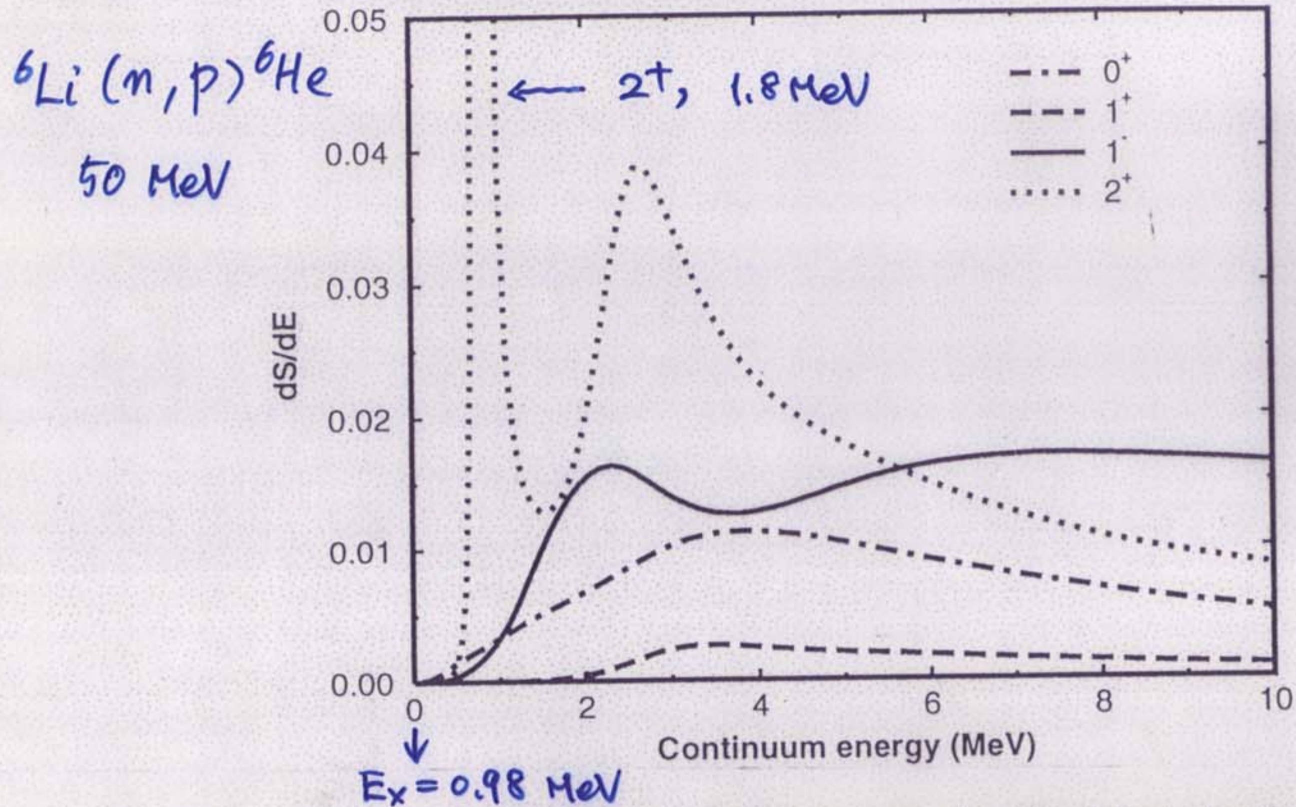


Fig. 10. Charge-exchange strength functions to the ^{6}He continuum, for different final-state spins and parities.

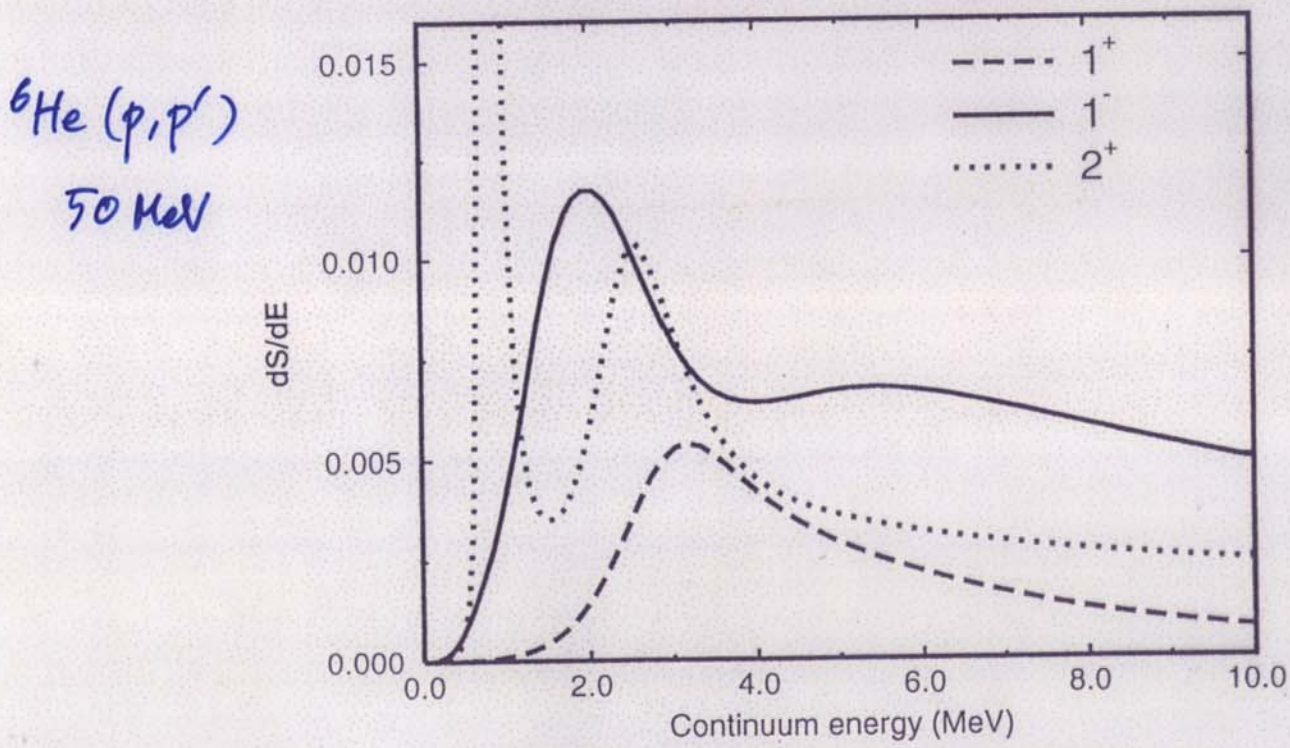


Fig. 11. Inelastic strength functions to the ^{6}He continuum, for different final-state spins and parities.

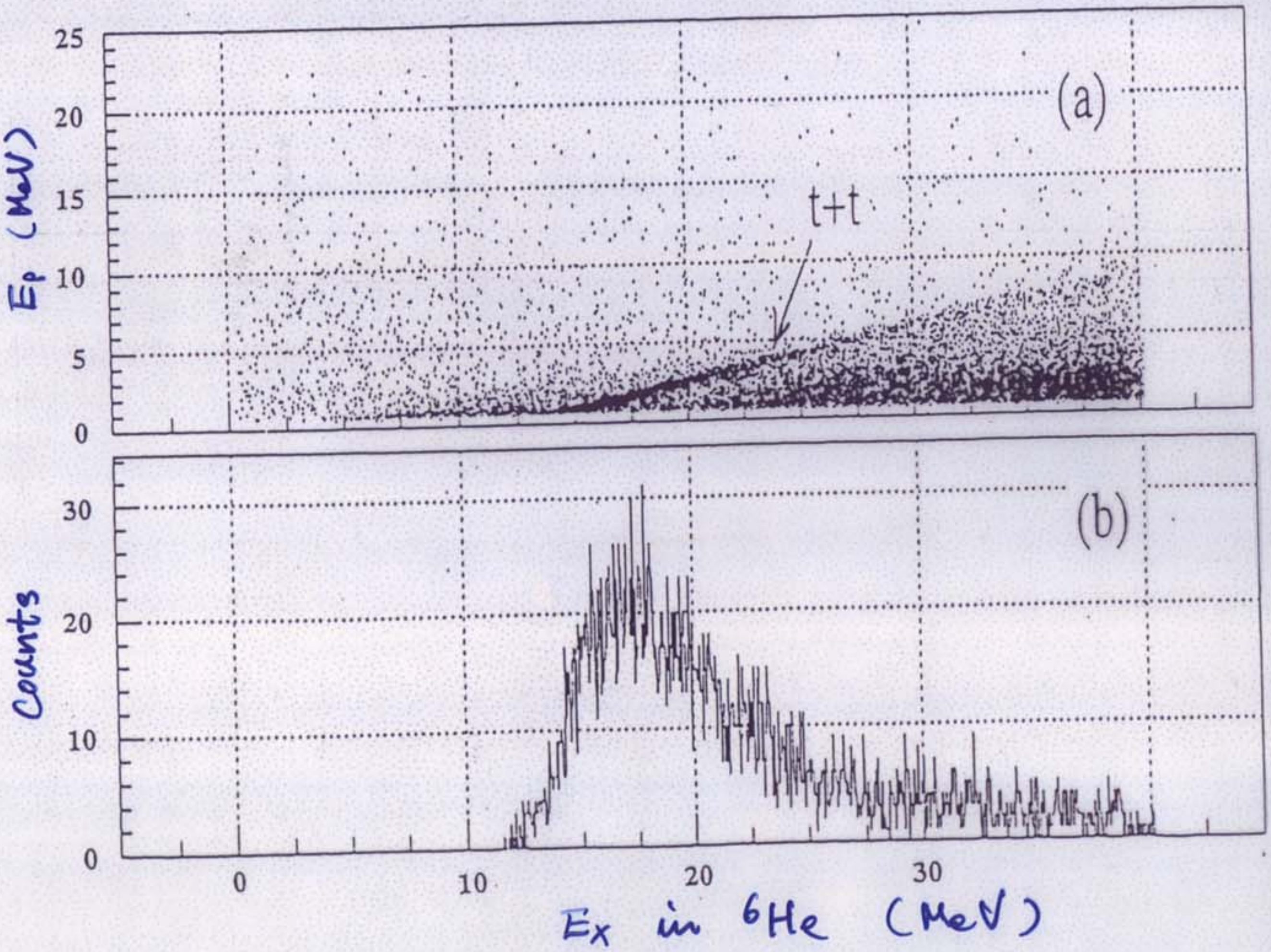
4.3. 0^- spin-flip dipole mode

The response function shows a very wide bump at 6–7 MeV with a width of the order 4–6 MeV. An analysis of the potentials shows an absence of pockets in both diagonal and

Coincidence measurement

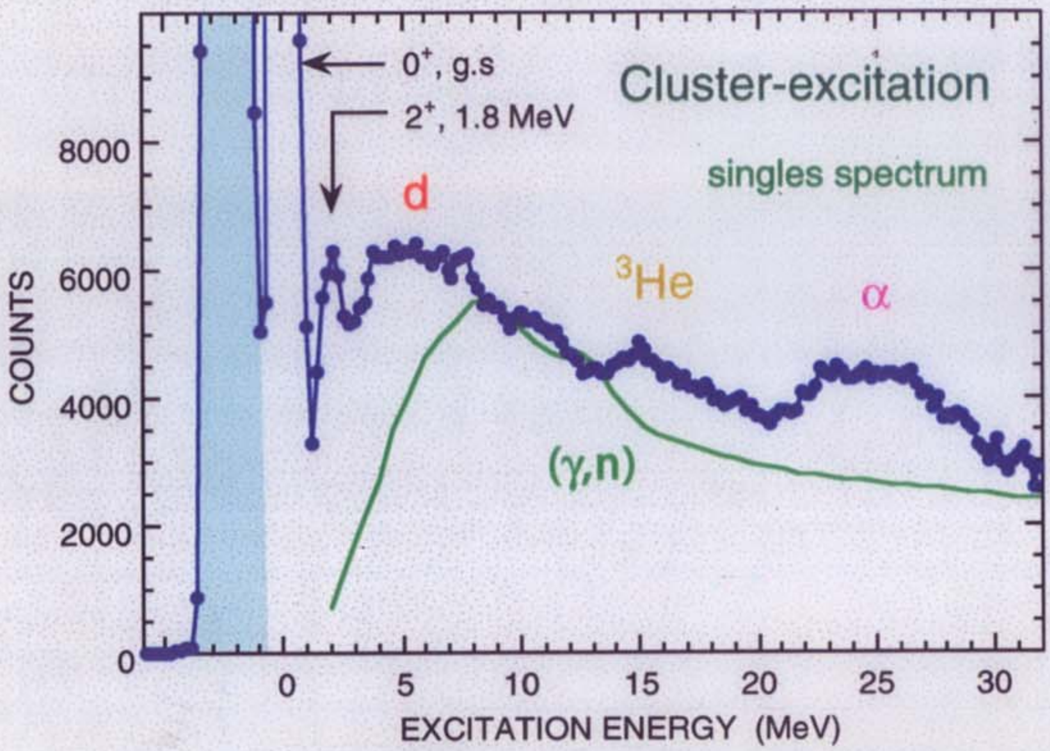
between ^{7}Be-ejectiles and triton-decay particles

$^6Li(^7Li, ^7Be)^6He$ @ 65A MeV



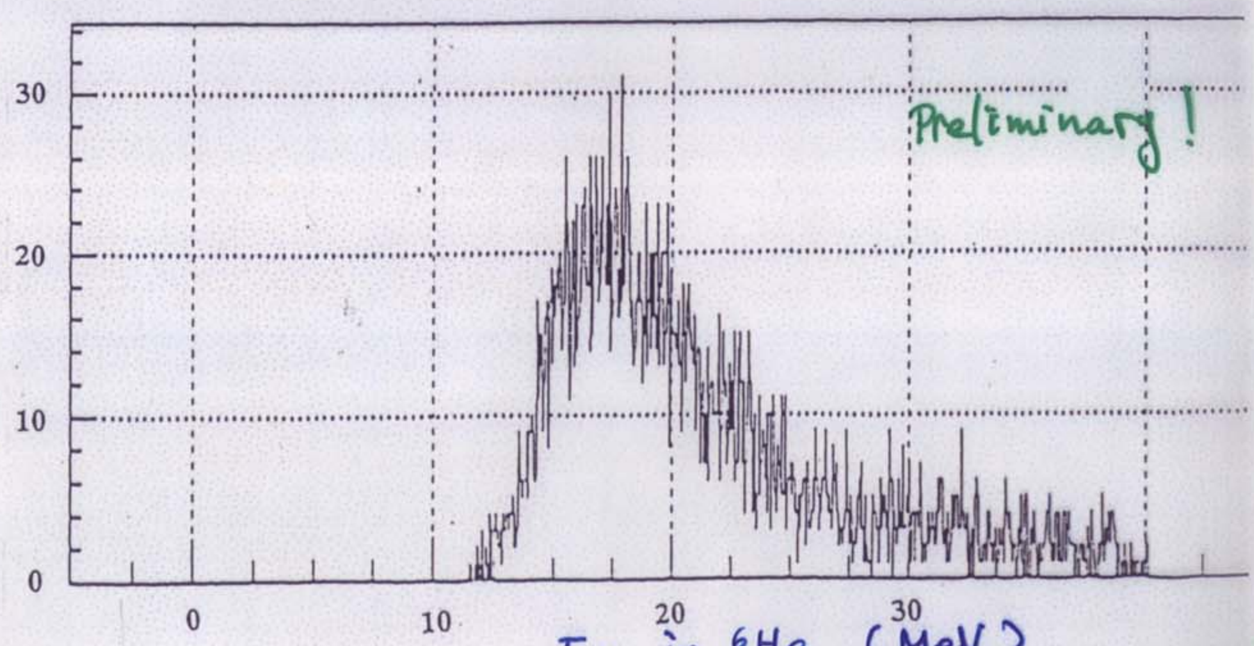
E52

$^6Li(^7Li,^7Be)^6He$, E_L=65A MeV, $\theta_L<2°$

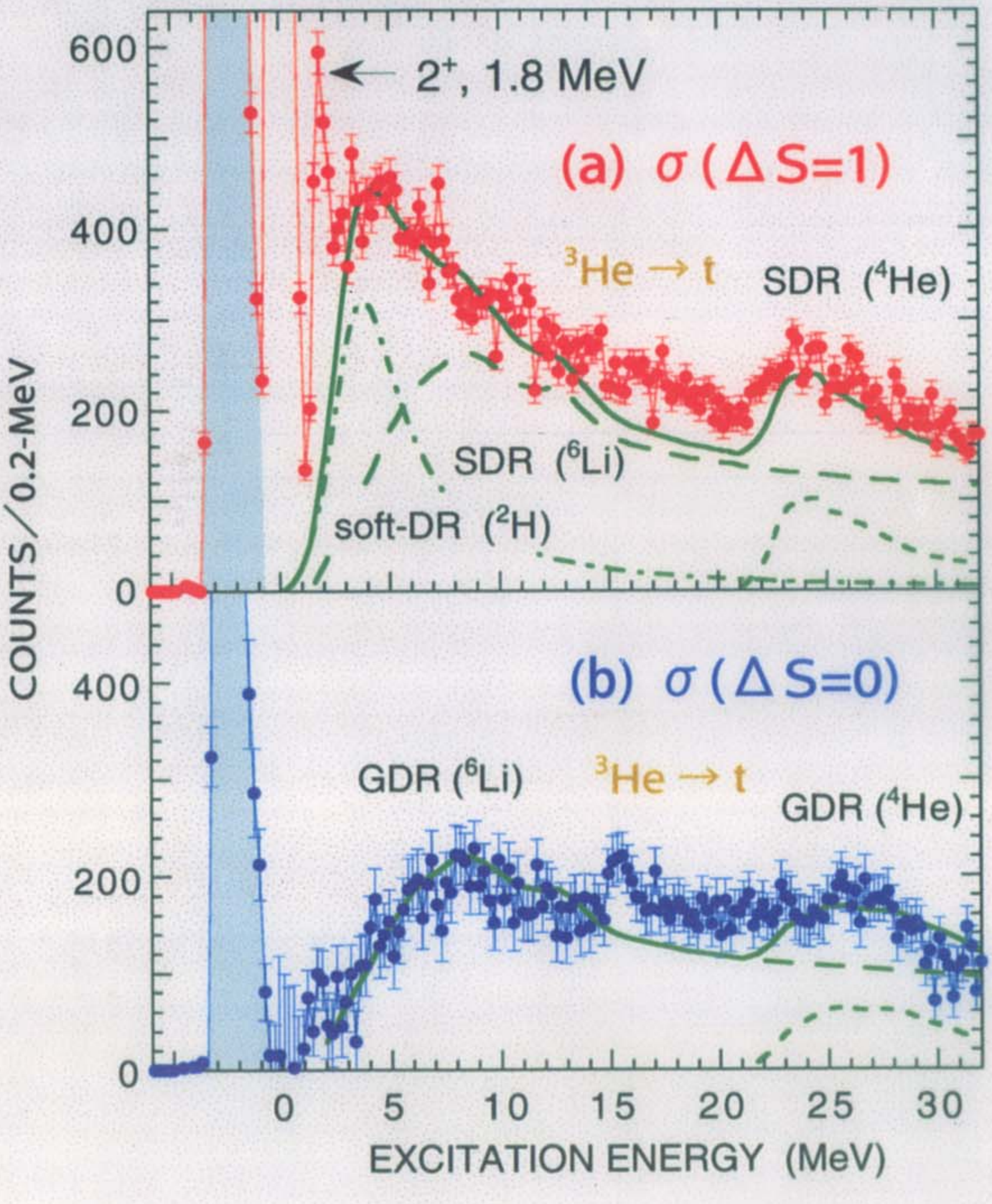


Projection of triton-decay

E164

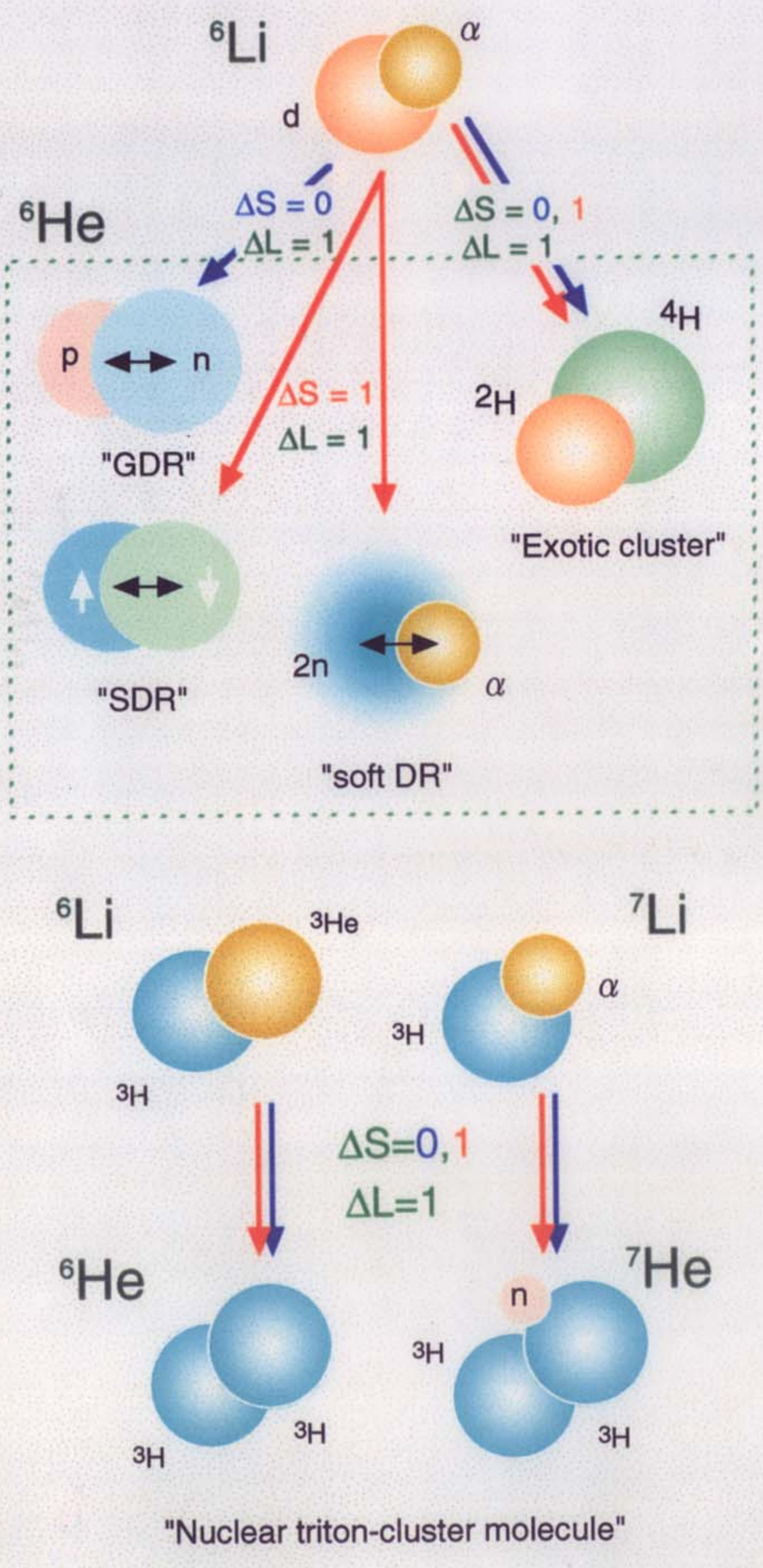


$^6Li(^7Li, ^7Be)^6He$, E_L=65A MeV, $\theta_L < 1.5°$



Schematic picture of Cluster-Excitation

$^{6,7}Li(^{7}Li,^{7}Be)^{6,7}He$ @65A MeV



SUMMARY

Cluster-Excitation in Li Nuclei

(^{7}Li,^{7}Be) reaction at 65*A* MeV

$\Delta S=0$, $\Delta S=1$ spectra

ΔL (angular distributions)

- **α-cluster excitation**

  higher E_x than that of a free α by ~ 3 MeV

  → medium effect ?

  formation of exotic cluster structure

  (^{2}H -^{4}H, ^{3}H -^{4}H)

- **d-cluster excitation**

  dipole oscillation between α - 2n

  ↓ E_x= 4 MeV, Γ = 4 MeV

  candidate for a soft-dipole resonance

- **^{3}He-cluster excitation**

  dipole oscillation between t-t

  ↓ ΔS = 0, 1 , ΔL = 1

  ^{6}Li (t+^{3}He; $^3S_1$) → ^{6}He (t+t ; $^3P_1$ or $^1P_1$)

3．中性子過剰核を用いた研究から

○ Radiative capture reaction

as a probe of clustering in the g.s

○ Break-up reaction

as a probe of cluster molecule states

○ Cluster transfer reaction

as a probe of cluster molecule states

Cluster structure in ^6He (g.s)

Radiative Proton Capture on ^{6}He

E. Sauvan,[1,*] F.M. Marqués,[1,†] H.W. Wilschut,[2] N.A. Orr,[1] J.C. Angélique,[1] C. Borcea,[3] W.N. Catford,[4] N.M. Clarke,[5] P. Descouvemont,[6] J. Díaz,[7] S. Grévy,[1] A. Kugler,[8] V. Kravchuk,[2] M. Labiche,[1,‡] C. Le Brun,[1,§] E. Lienard,[1] H. Löhner,[2] W. Mittig,[9] R.W. Ostendorf,[2] S. Pietri,[1] P. Roussel-Chomaz,[9] M.G. Saint Laurent,[9] H. Savajols,[9] V. Wagner,[8] and N. Yahlali[7]

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(Received 20 February 2001; published 3 July 2001)

Radiative capture of protons is investigated as a probe of clustering in nuclei far from stability. The first such measurement on a halo nucleus is reported here for the reaction ^{6}He(p,γ) at 40 MeV. Capture into ^{7}Li is observed as the strongest channel. In addition, events have been recorded that may be described by quasifree capture on a halo neutron, the α core, and ^{5}He. The possibility of describing such events by capture into the continuum of ^{7}Li is also discussed.

$^5He + p \rightarrow {}^6Li + \gamma$

$^4He + p \rightarrow {}^5Li + \gamma$

$n + p \rightarrow d + \gamma$

$^6He + p \rightarrow {}^7Li + \gamma$

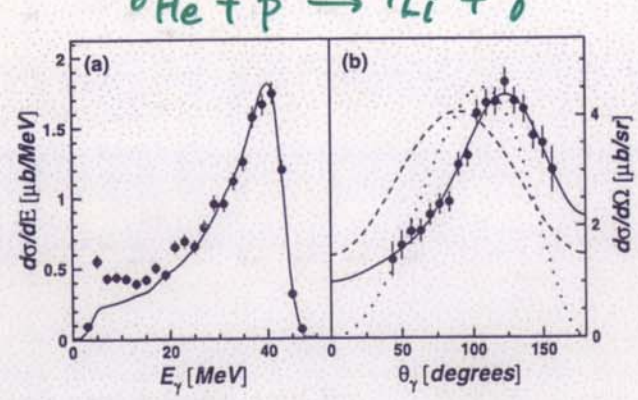

FIG. 1. Energy (a) and angular distributions (b) in the ^{6}He + p c.m. for photons in coincidence with ^{7}Li. The solid line in (a) is the response of the Château to $E_\gamma = 42$ MeV. The lines in (b) correspond to a classical electrodynamics calculation (dotted), a microscopic cluster model (dashed), both normalized to the data, and to a Legendre polynomial fit [13] (solid).

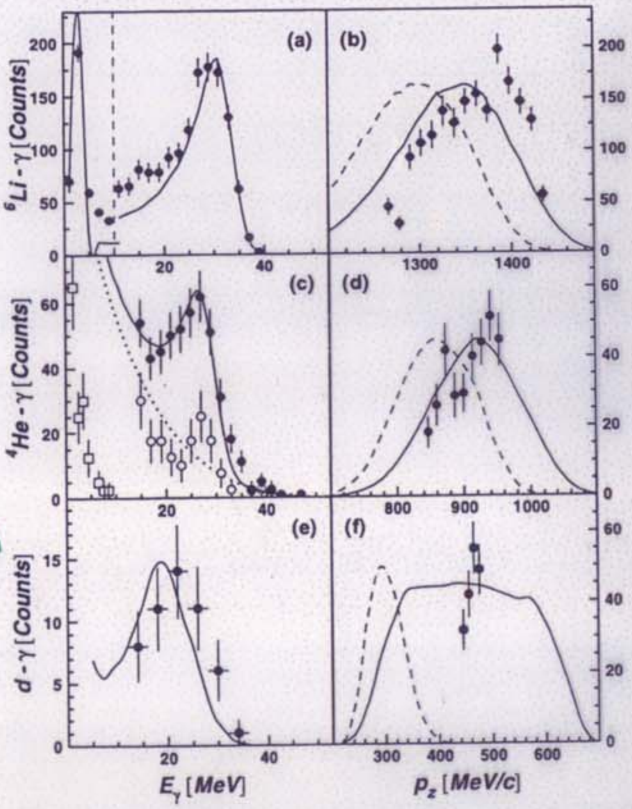

FIG. 2. γ-ray energy spectrum in the ^{6}He + p c.m. and momentum distribution of the coincident fragment for ^{6}Li (upper), α particles (middle), and deuterons (lower panels). The lines correspond to calculations of QFC on the ^{5}He cluster, the α core, and one halo neutron, respectively, on the right with/without (solid/dashed) fragment FSI (see text). The distribution in (a) was divided by 3 below 10 MeV, and the open symbols in (c) are from an analysis investigating the role of the neutron background (see text).

$2n + p \rightarrow t + \gamma$ } not observed !
$t + p \rightarrow {}^4He + \gamma$

Freer et al. Phys. Rev. Lett. 82 (1999) 1383

Rotational band in molecular cluster state

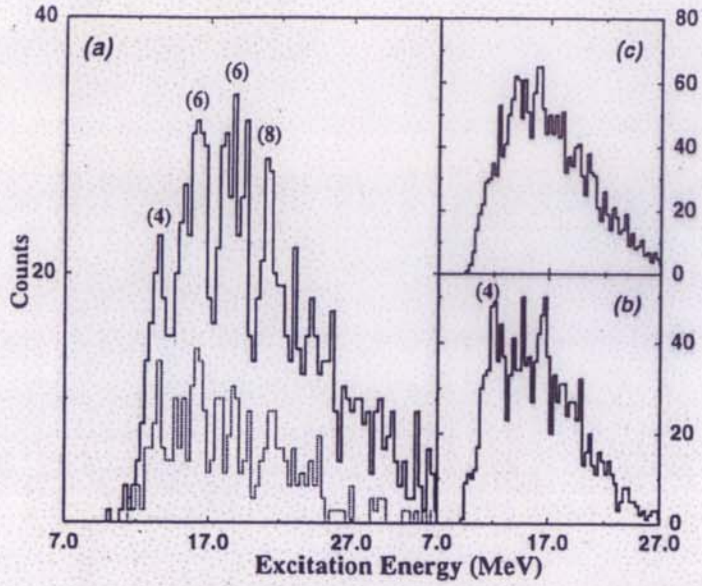

FIG. 2. The reconstructed ^{12}Be excitation energy spectra (a) $^{12}Be \rightarrow {}^{6}He + {}^{6}He$ for proton plus carbon recoils, (b) $^{12}Be \rightarrow {}^{8}He + {}^{4}He$ for carbon recoils, and (c) $^{12}Be \rightarrow {}^{8}He + {}^{4}He$ for proton recoils. The dotted histogram in (a) represents $^{6}He + {}^{6}He$ decay events identified with the $Q = -10$ MeV peak in Fig. 1a and, hence, is dominated by events with carbon recoils.

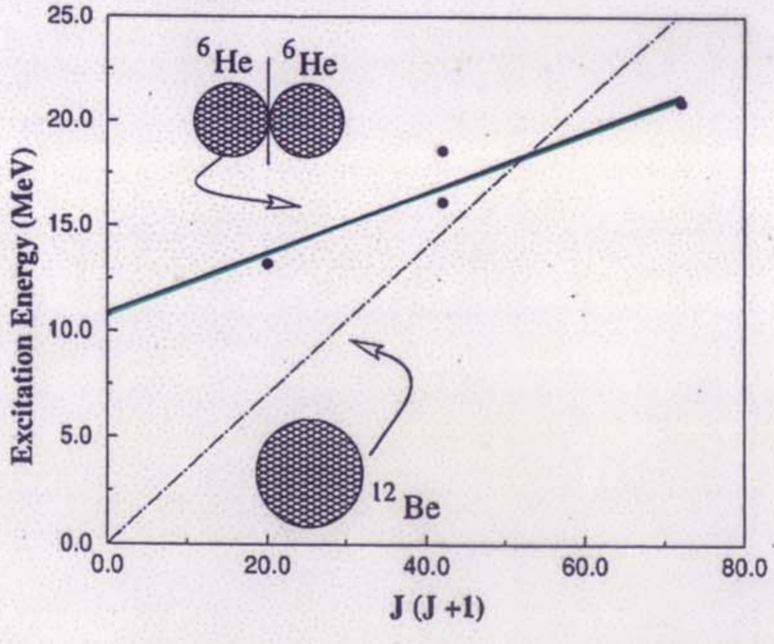

FIG. 4. The energy-spin systematics of the $^{6}He + {}^{6}He$ breakup states (black dots). The solid line is a linear fit to the four points, and the dot-dashed line shows the extrapolated trajectory of a ground state band with a rotational energy of 350 keV.

Cluster Transfer Reactions for Neutron-Rich Nuclei

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CNS, University of Tokyo

^{6}He - transfer reaction

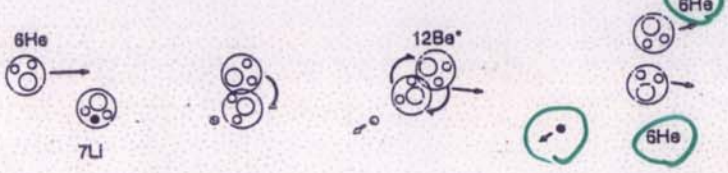


Figure 1: Schematic view of the $^{7}Li(^{6}He,^{12}Be^{*})^{1}H$ reaction followed by the $^{6}He+^{6}He$ decay.

p - ^{6}He coincidence

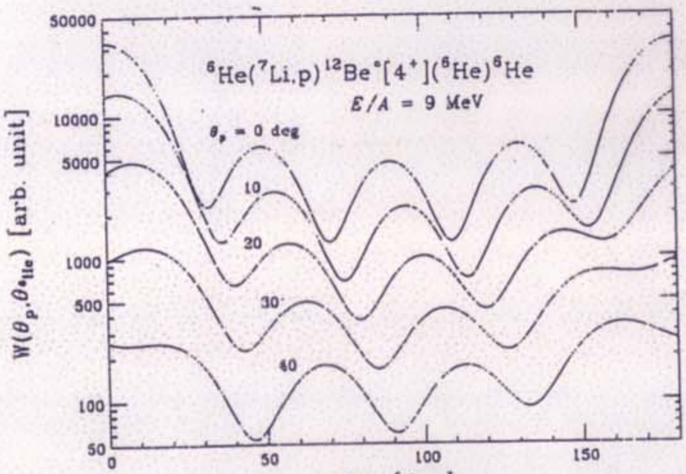


Figure 2: Calculated angular correlation function for the $^{6}He(^{7}Li,p)^{12}Be^{*}[4^{+}](^{6}He)^{6}He$ reaction. All the angles are measured in the total center-of-mass system.

4．クラスターの分子構造

Reaction

CEX : (^{7}Li,^{7}Be), (^{3}He,t), (^{6}Li,^{6}He), ...

Pick-up : (p,d), (d,^{3}He), (^{3}He, α); (p,t), (p,^{3}He), (d,^{6}Li), (α,^{7}Li), ...

Stripping : (d,p), (^{3}He,d), (α,^{3}He); (^{3}He,p), (^{7}Li,t), (^{7}Li, α), ...

Cluster excitation

target ^{6}Li : α + d , ^{3}He + t

^{7}Li : α + t

^{9}Be : ^{8}Be + n

^{10}B : ^{8}Be + d

^{11}B : ^{8}Be + t

A= 6,7 : t and/or ^{3}He

12≧A≧8 : 2α + xn

^{9}Li : 3t - 分子状態

^{12}C : 3α - 分子状態

Measurement

triple-coincidence with γ and cluster-particles

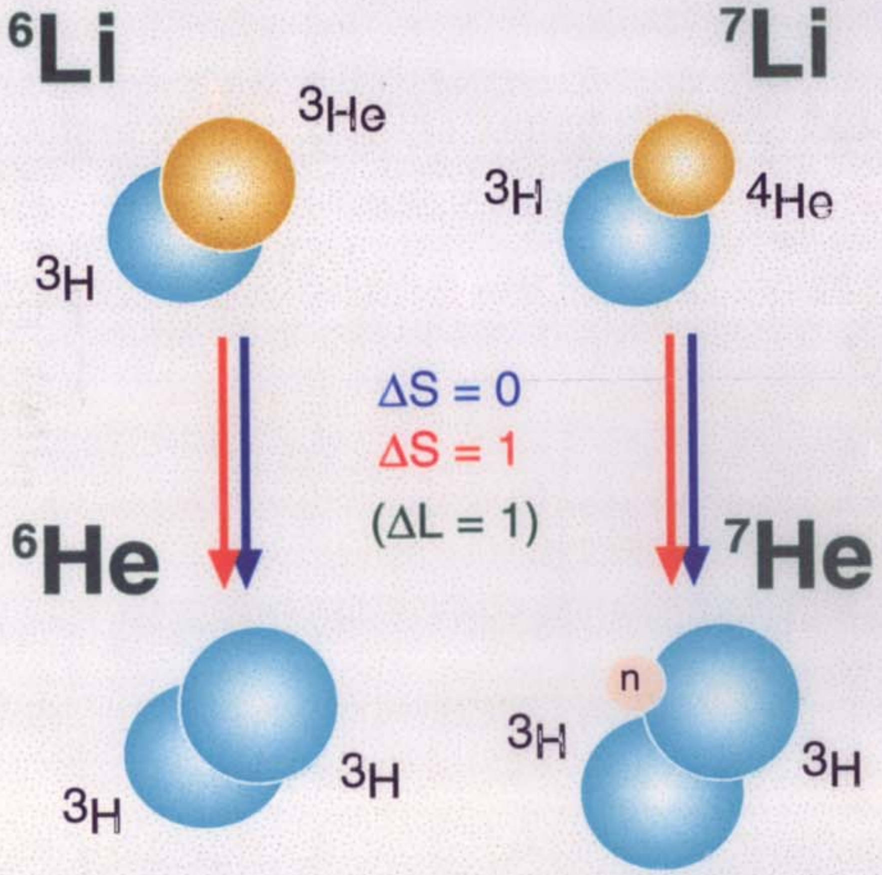
correlation pattern → spin-parity

γ -decay mode

→ transition between molecular states

Schematic picture of Cluster-Excitation

^{6,7}Li(^{7}Li,^{7}Be)^{6,7}He @65A MeV



Nuclear triton-cluster molecule

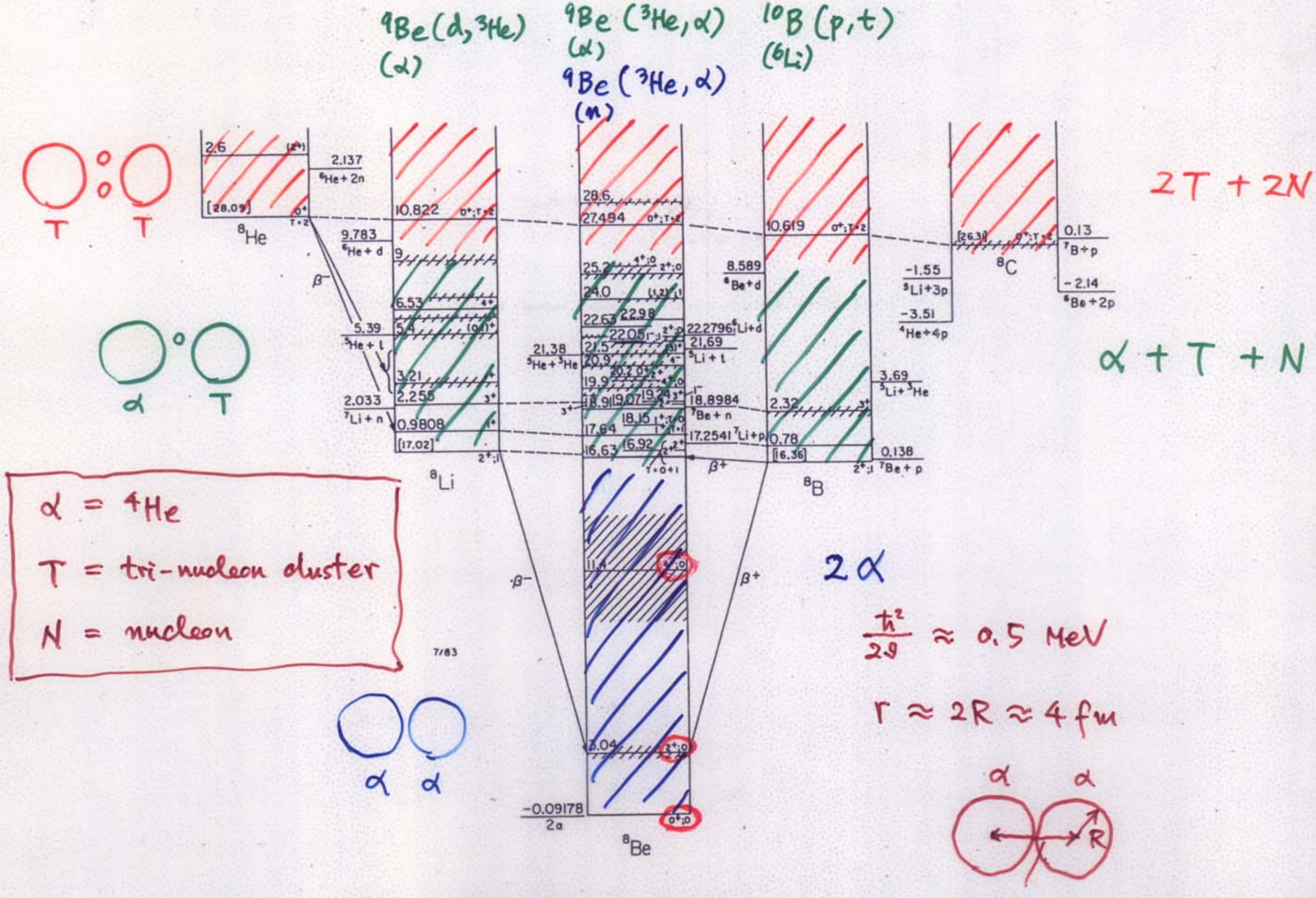


Fig. 14. Isobar diagram, $A = 8$; for notation, see fig. 3.

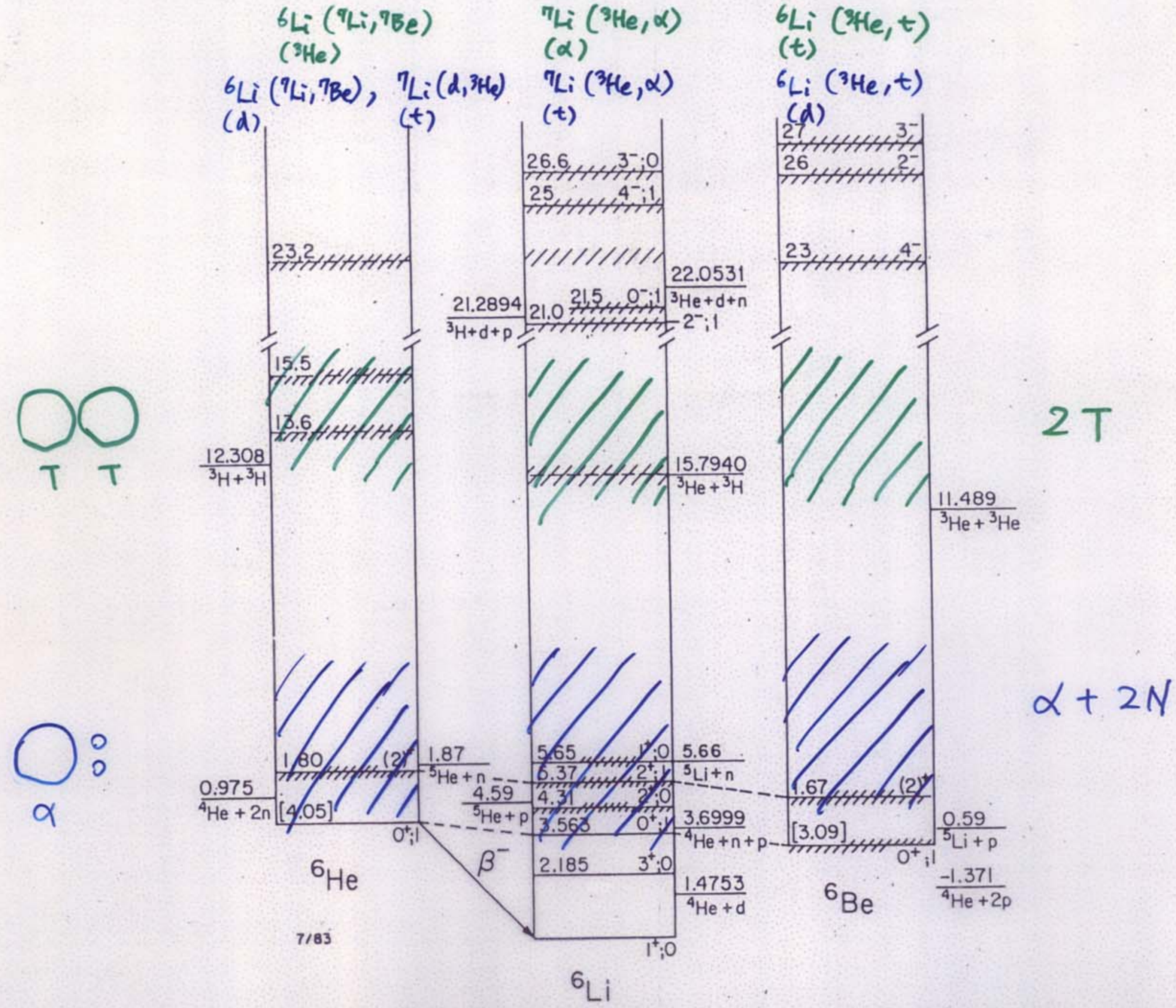


Fig. 7. Isobar diagram, $A = 6$; for notation, see fig. 3.

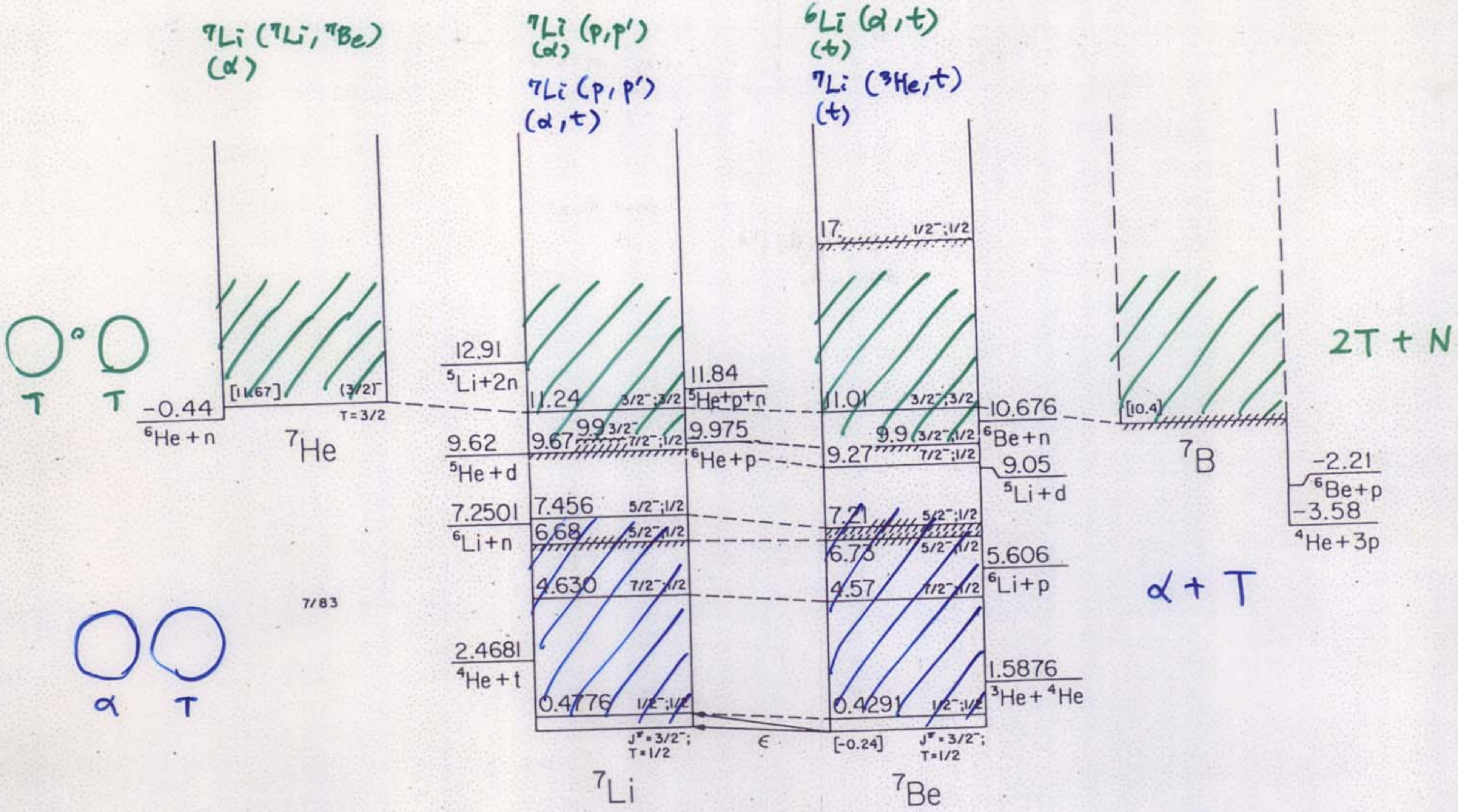


Fig. 10. Energy levels of $A=7$; for notation, see fig. 3.

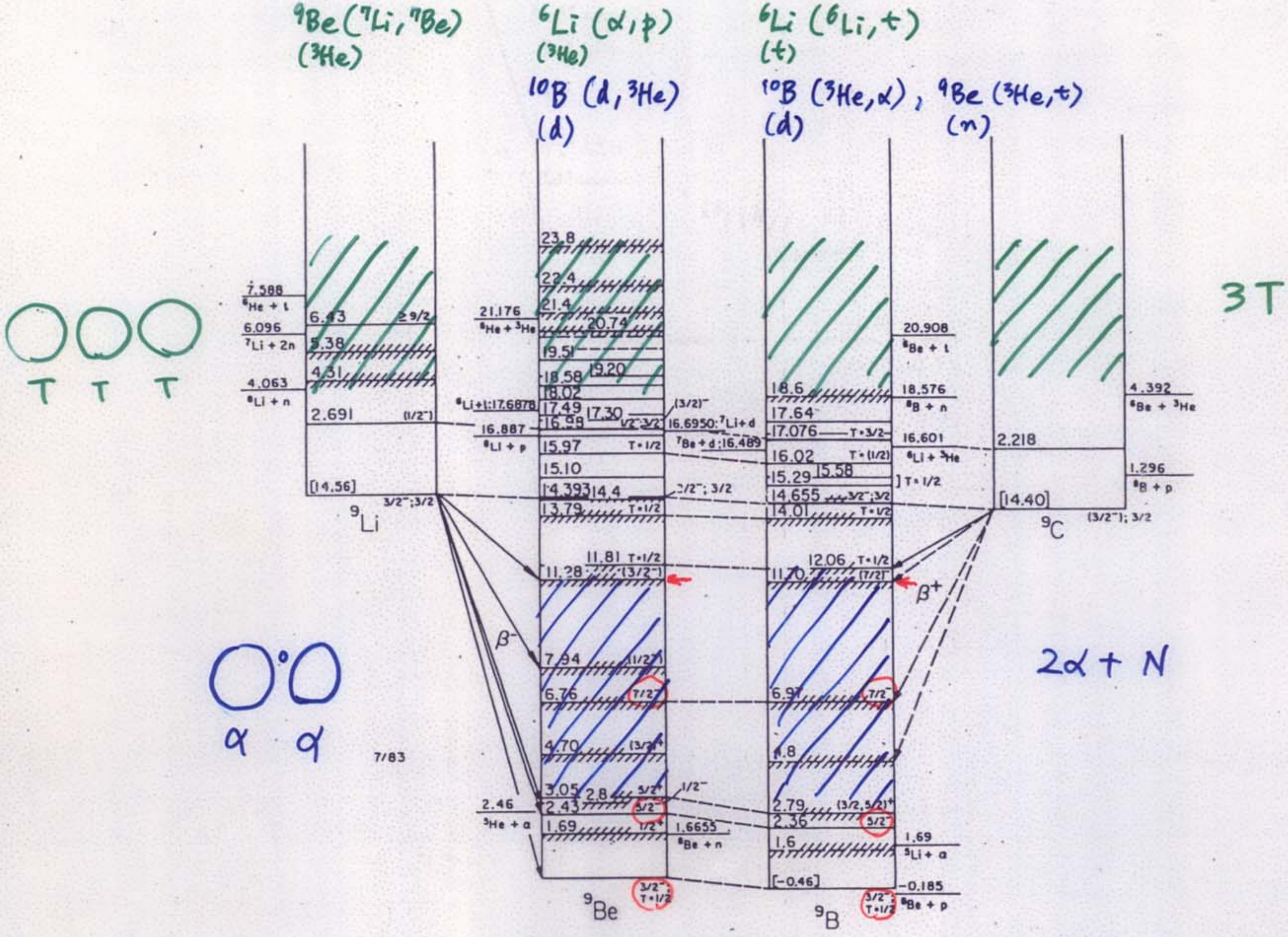


Fig. 18. Isobar diagram, $A = 9$; for notation, see fig. 3.

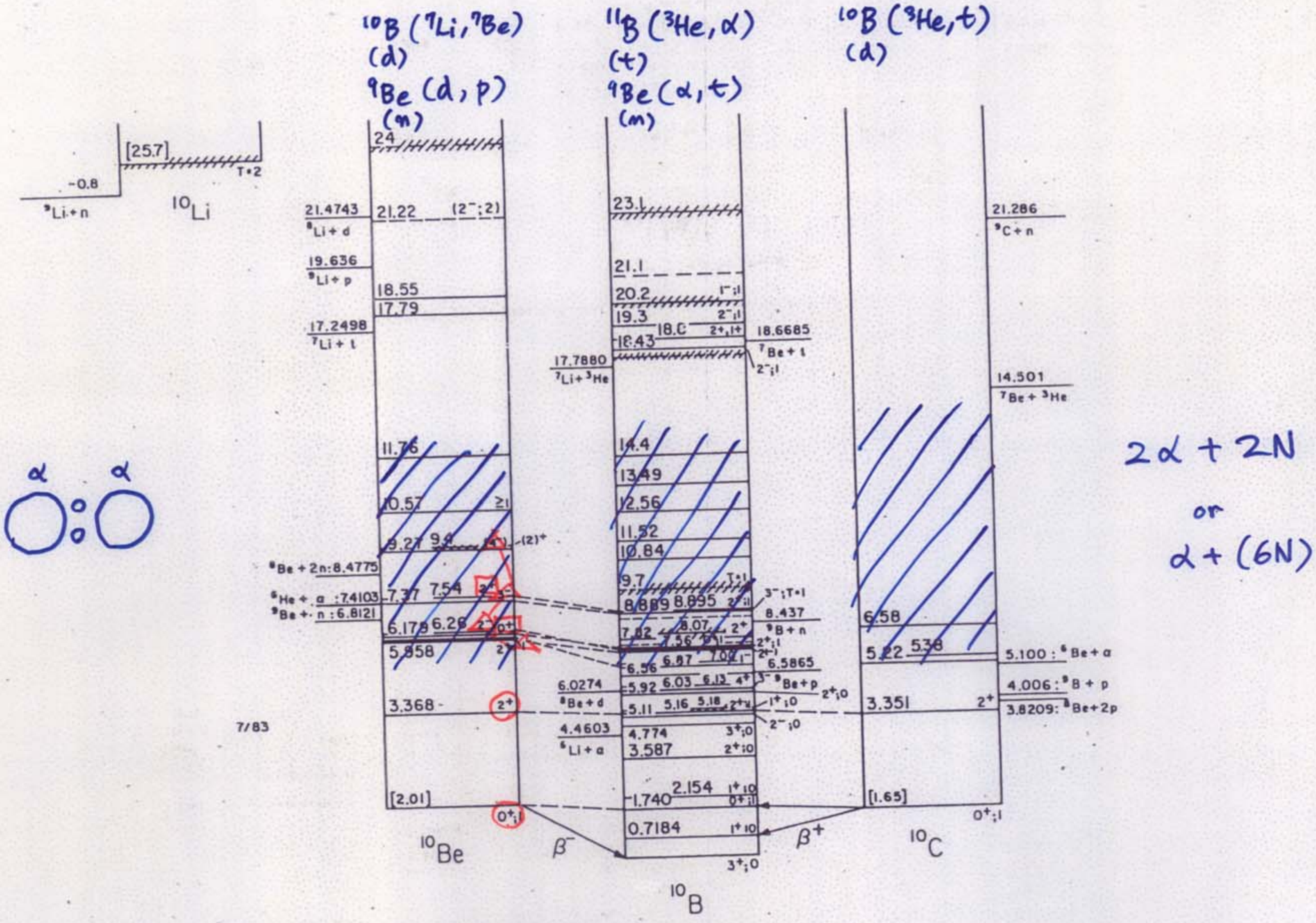


Fig. 22. Isobar diagram, $A = 10$; for notation, see fig. 3.

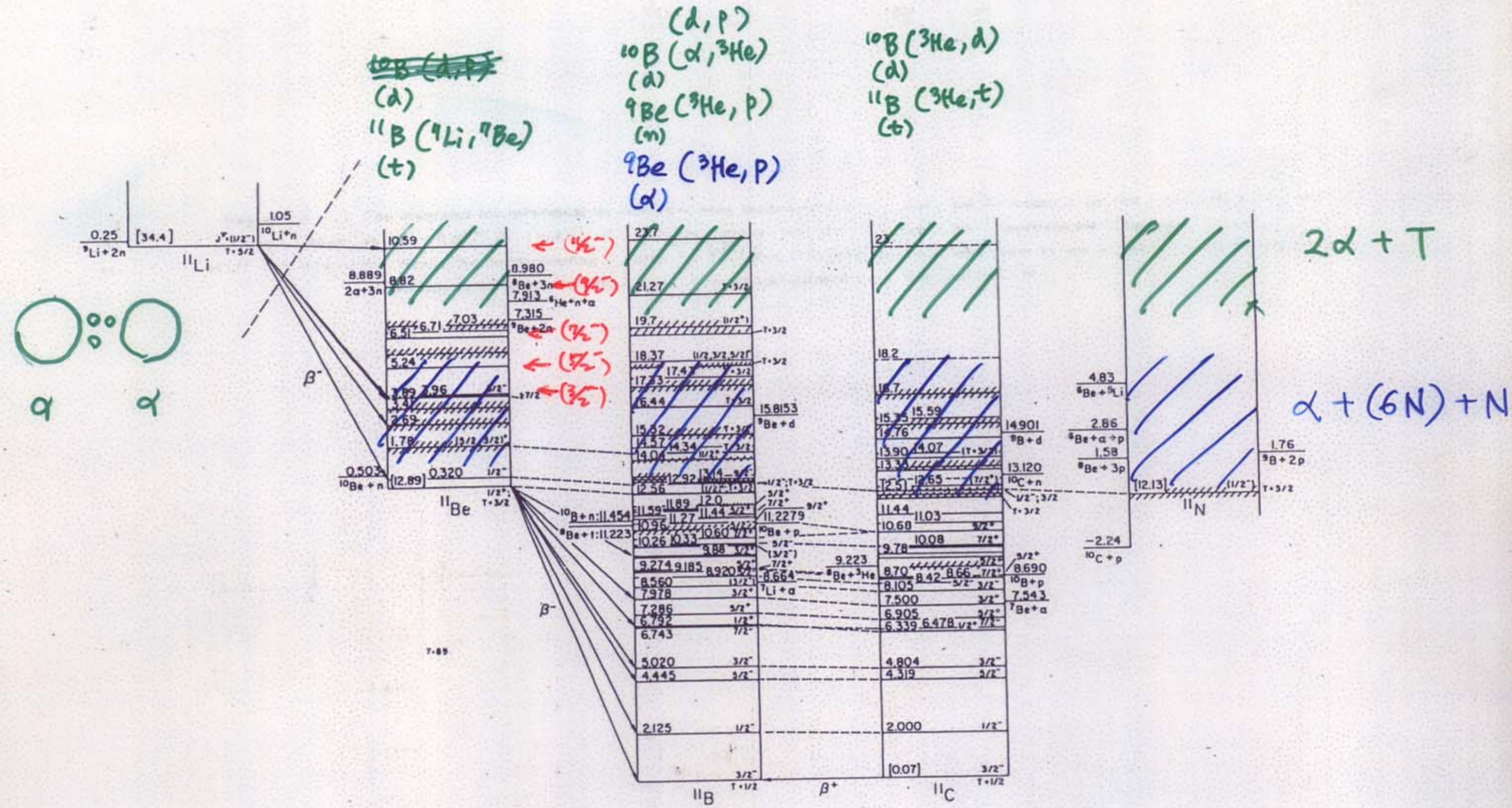


Fig. 4. Isobar diagram, $A = 11$. The diagrams for individual isobars have been shifted vertically to eliminate the neutron–proton mass difference and the Coulomb energy, taken as $E_C = 0.60Z(Z-1)/A^{1/3}$. Energies in square brackets represent the (approximate) nuclear energy, $E_N =$ $M(Z, A) - ZM(H) - NM(n) - E_C$, minus the corresponding quantity for ^{11}B: here M represents the atomic mass excess in MeV. Levels which are presumed to be isospin multiplets are connected by dashed lines. See text for ^{11}N.

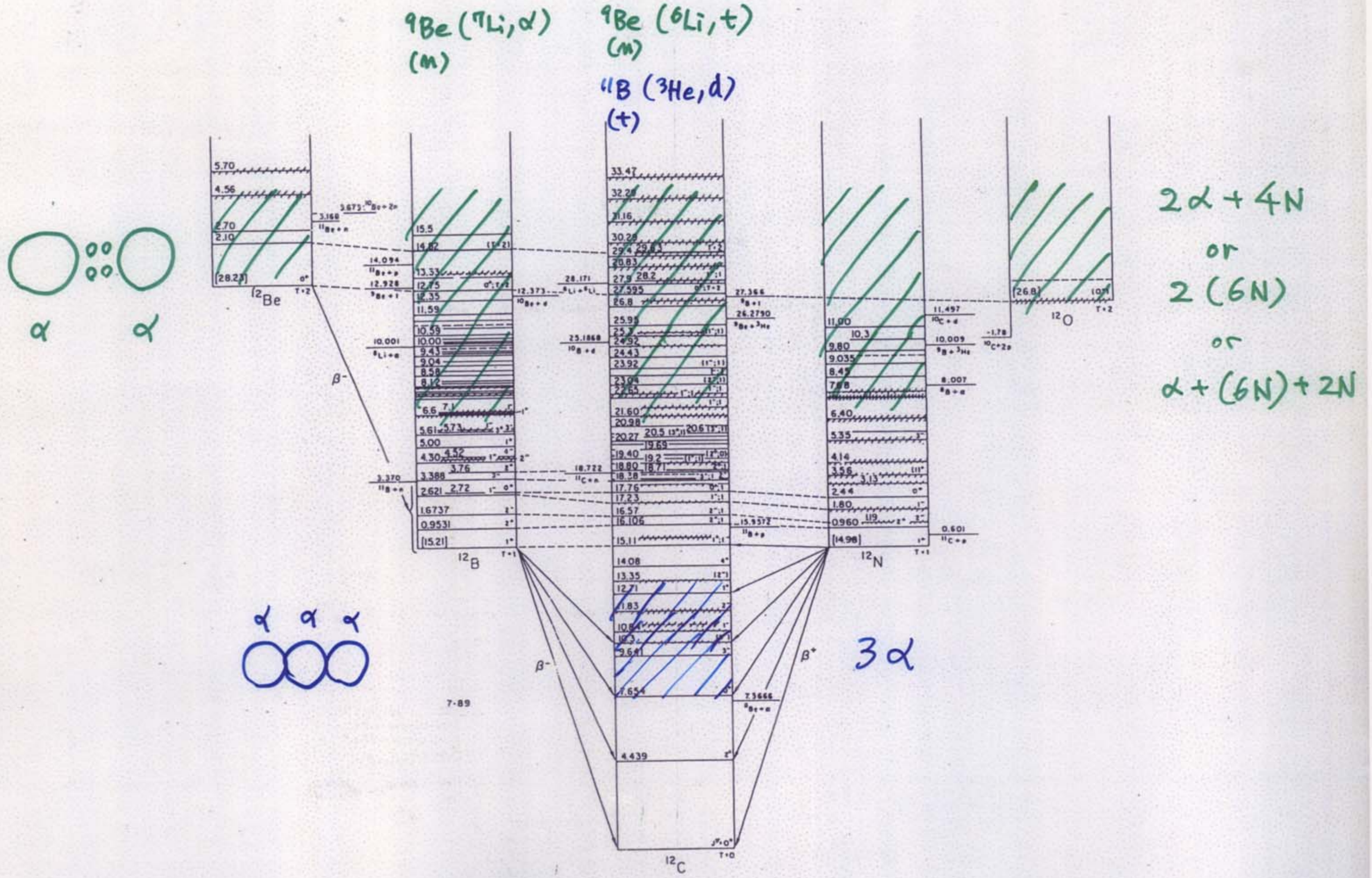
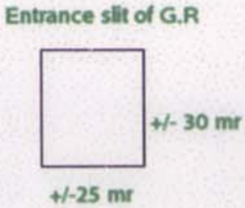


Fig. 9. Isobar diagram, $A = 12$: for notation see fig. 4.

Experimental Procedure



Beam : ^{3}He, 450 MeV (a few tens nA)

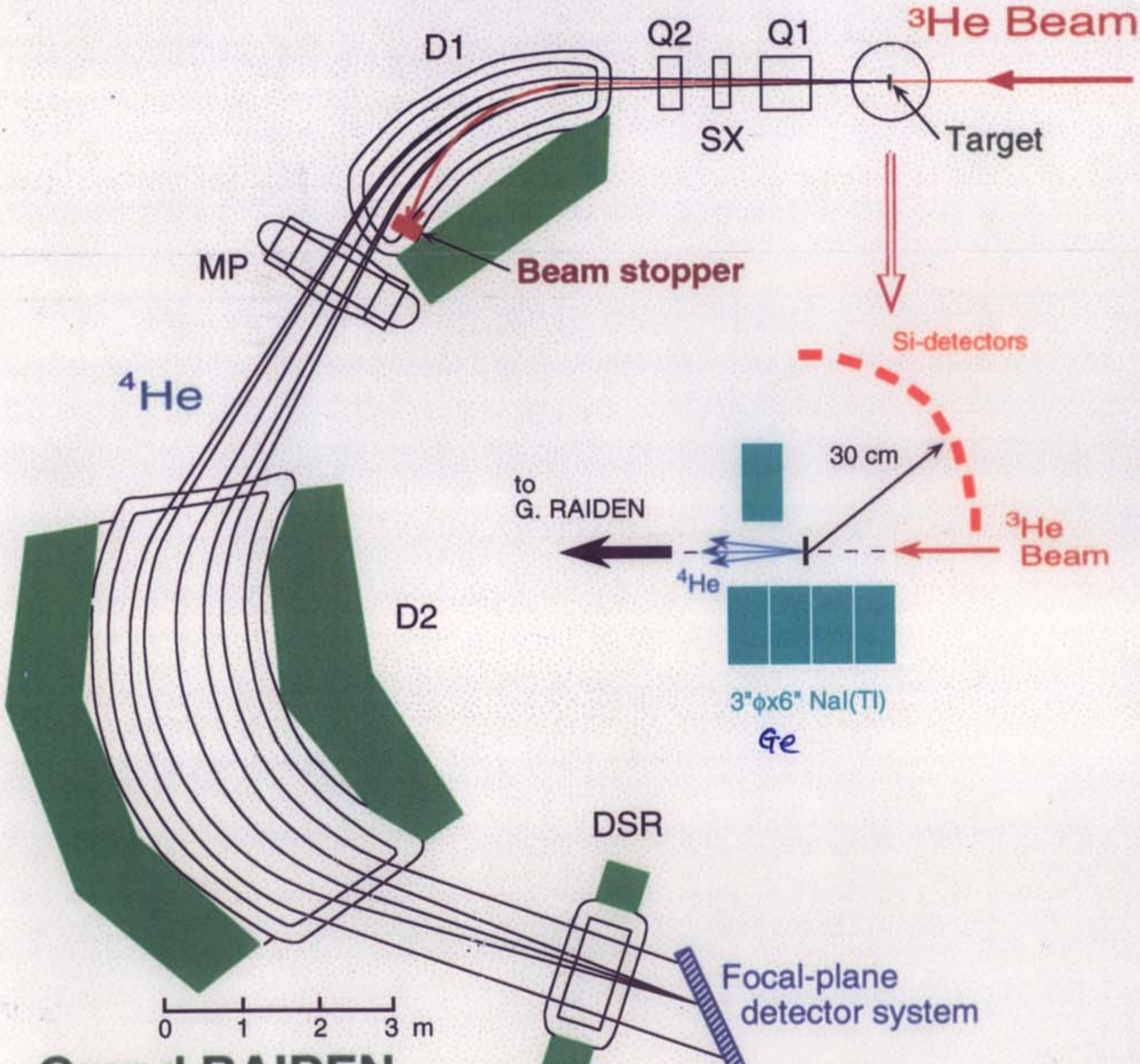
Targets : ^{7}Li, ^{12}C

α : Grand RAIDEN at $\theta < 5^{\circ}$

charged particles

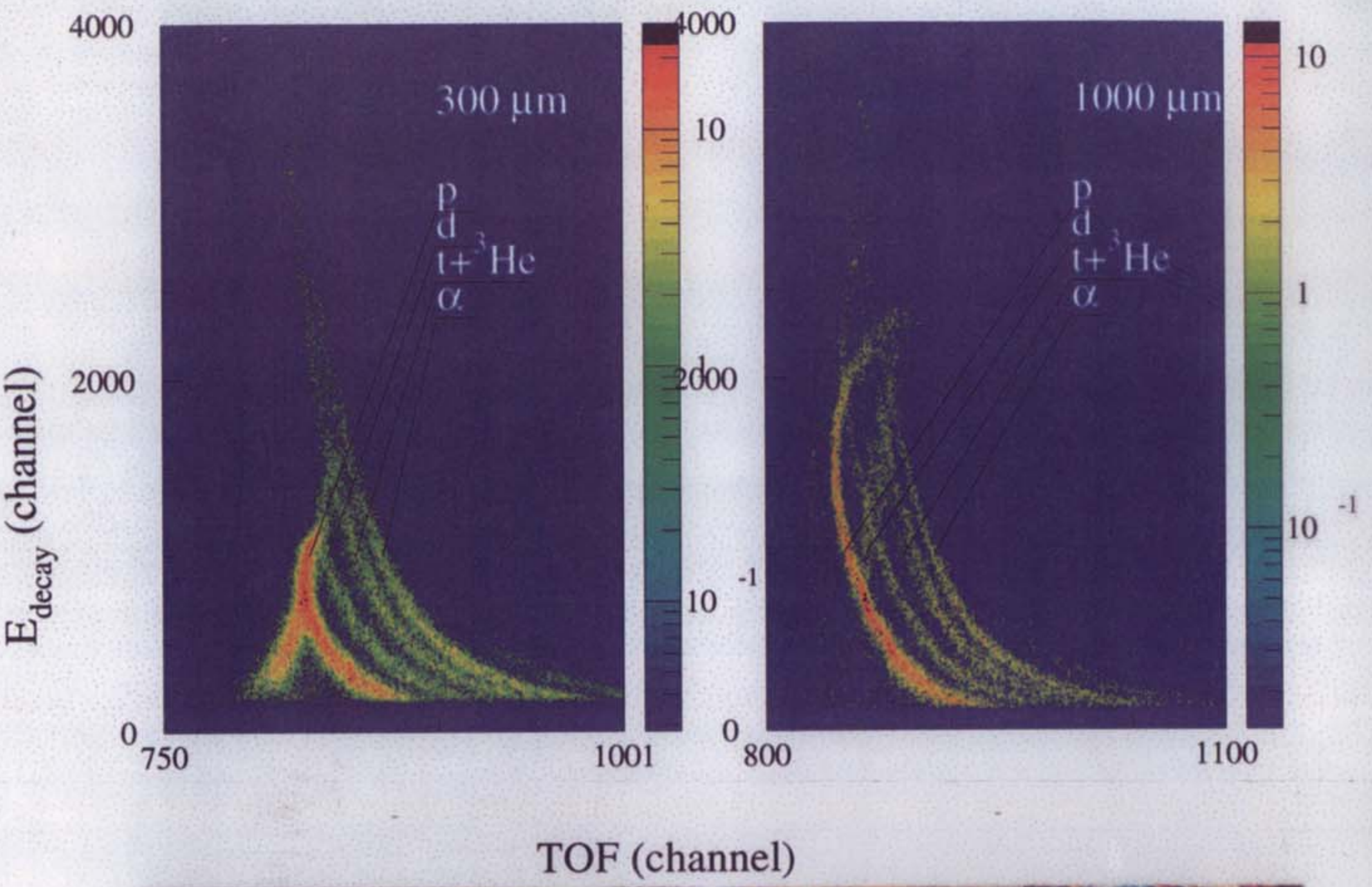
: Si-detectors at $\theta = 90^{\circ} \sim 170^{\circ}$

γ - rays : 3"φx6" NaI(Tl) , Ge

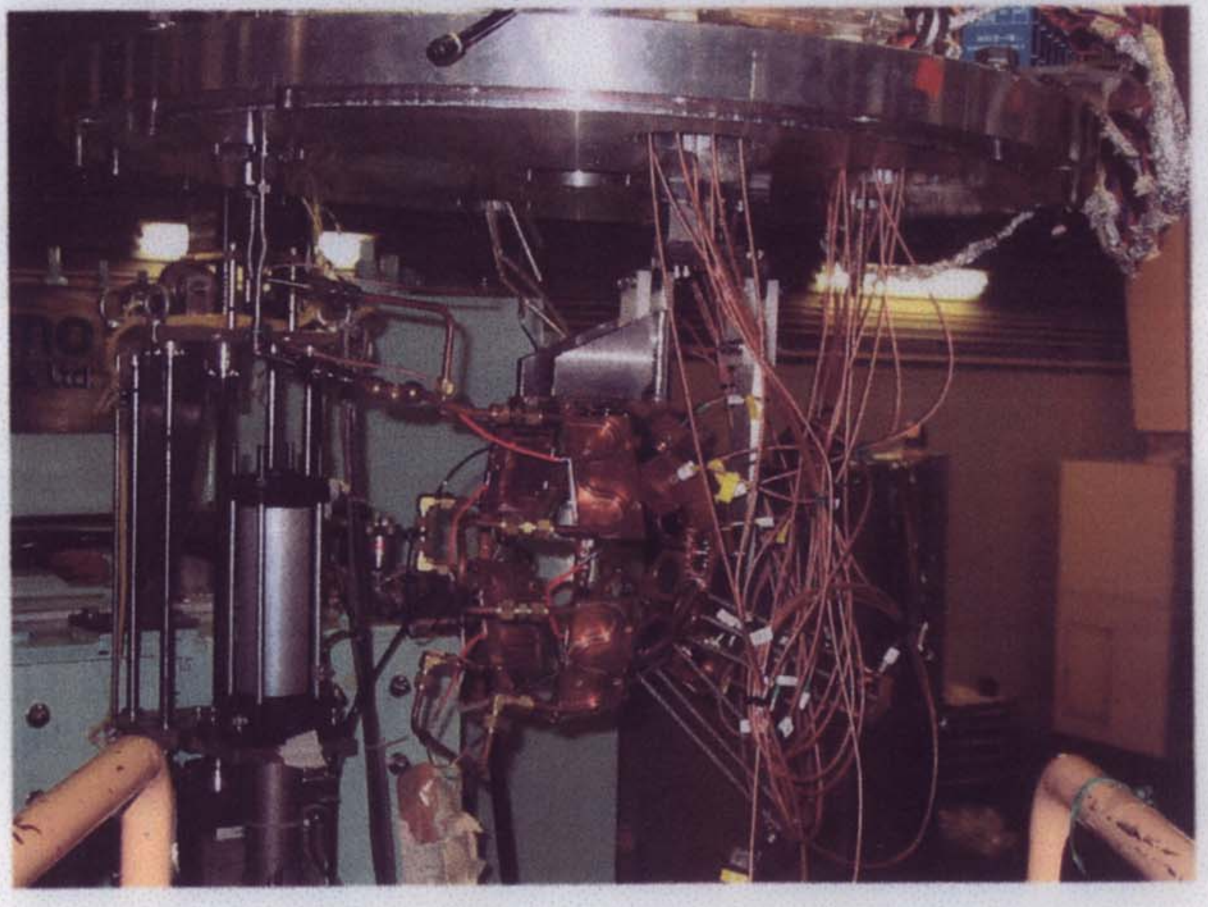


Grand RAIDEN

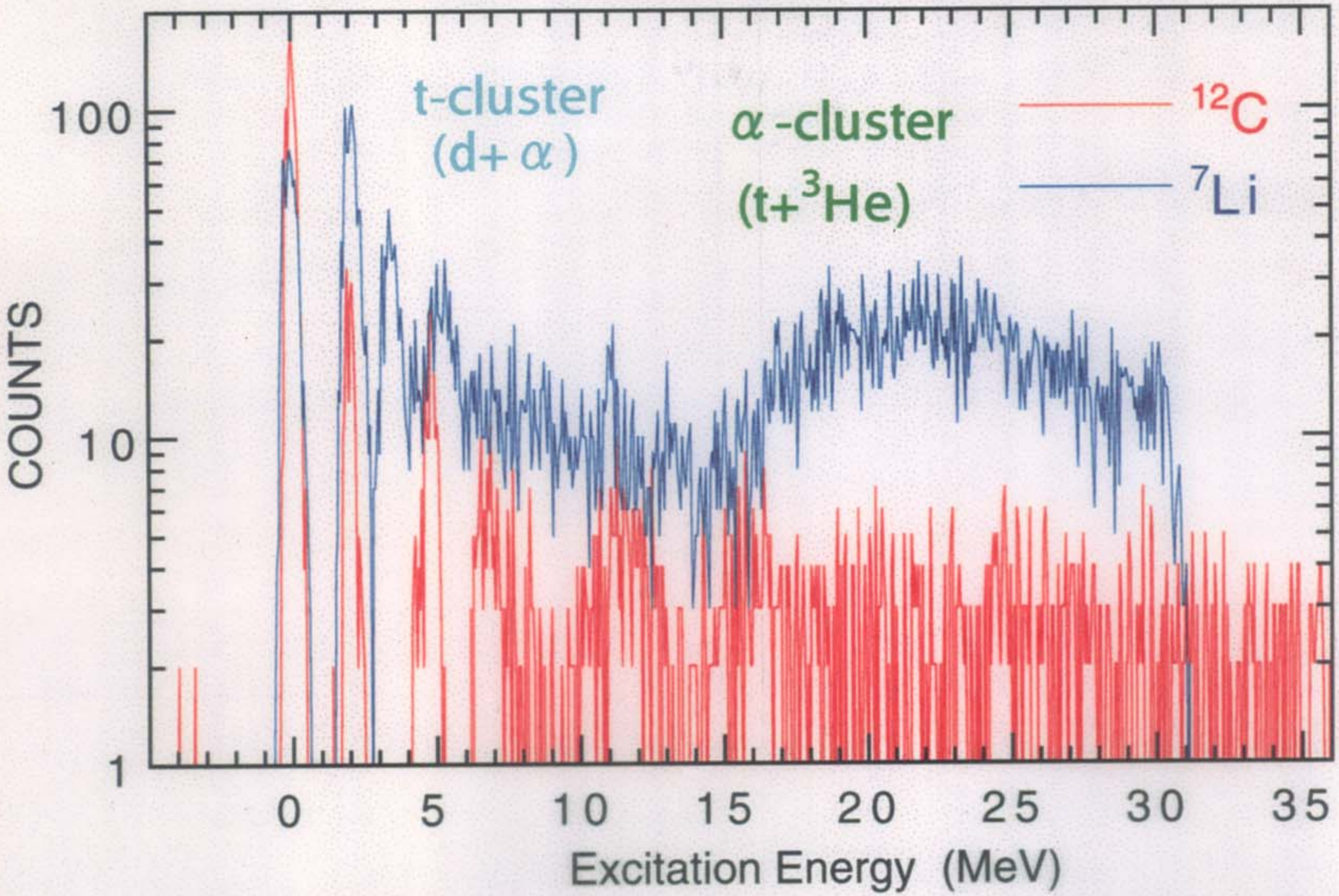
$^7Li(^3He,t)$

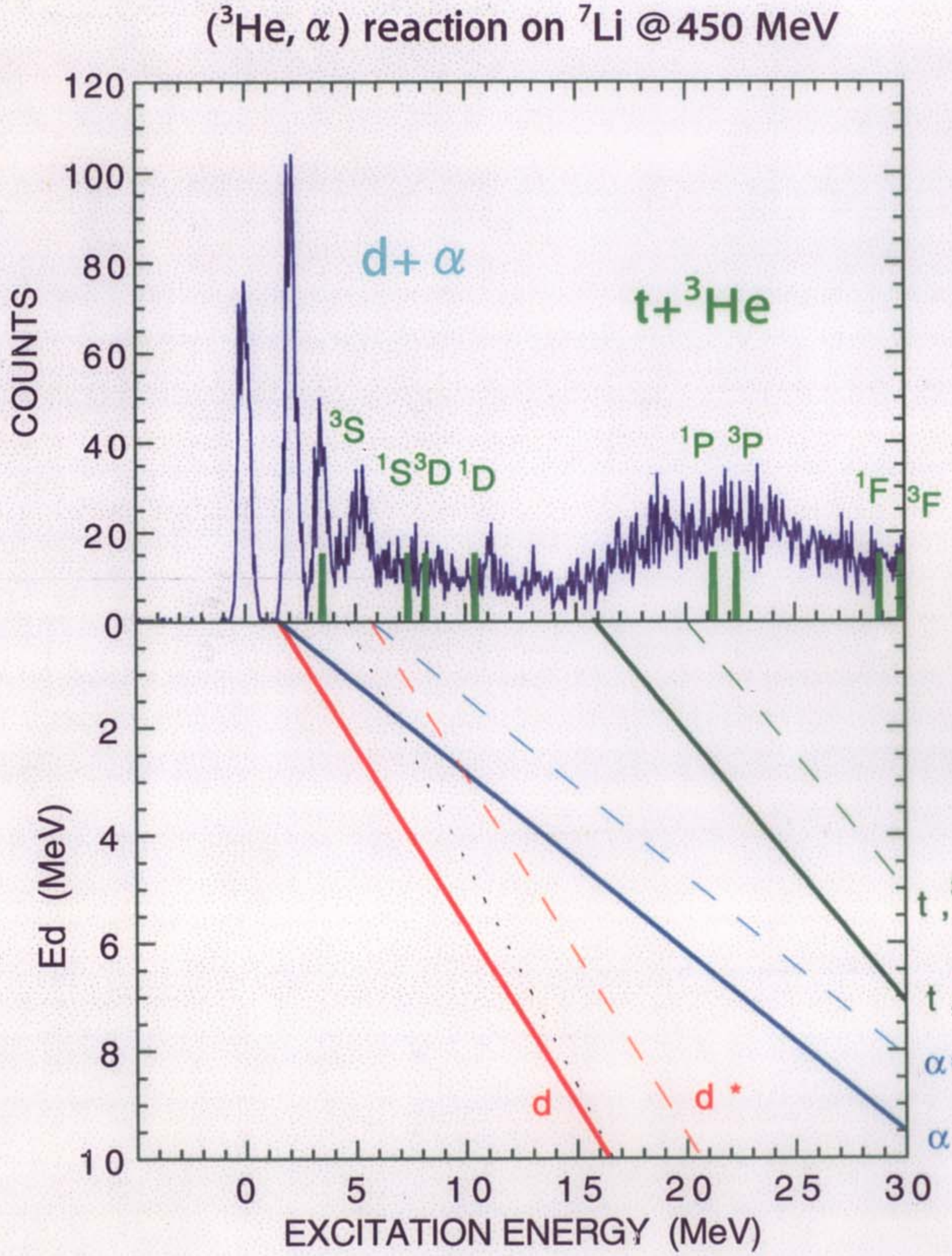


300 µm
1000 µm
p
d
t+^{3}He
α
4000
2000
0
750
1001
800
1100
10
1
10^{-1}
E_{decay} (channel)
TOF (channel)



(^3He, α) reactions on ^7Li and ^{12}C @450 MeV

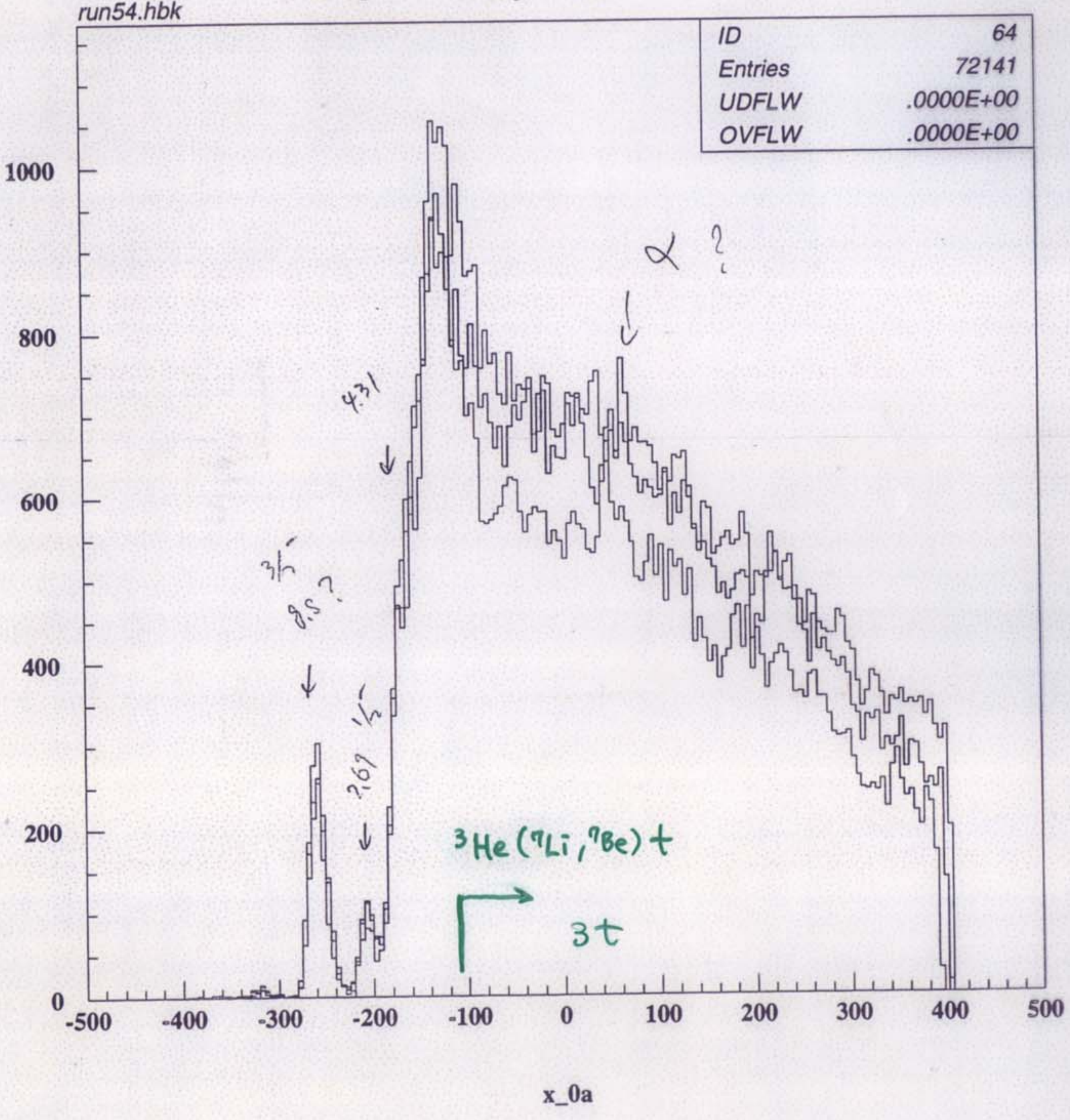




(³He, α) reaction on ⁷Li @ 450 MeV
COUNTS
d+ α
t+³He
³S
¹S ³D ¹D
¹P ³P
¹F ³F
Ed (MeV)
t , ³He*
t , ³He
α*
α
d
d *
EXCITATION ENERGY (MeV)

$^9Be(^7Li,^7Be)^9Li$

2001/12/12 13.04



$^9Be \rightarrow \alpha + {}^5He$

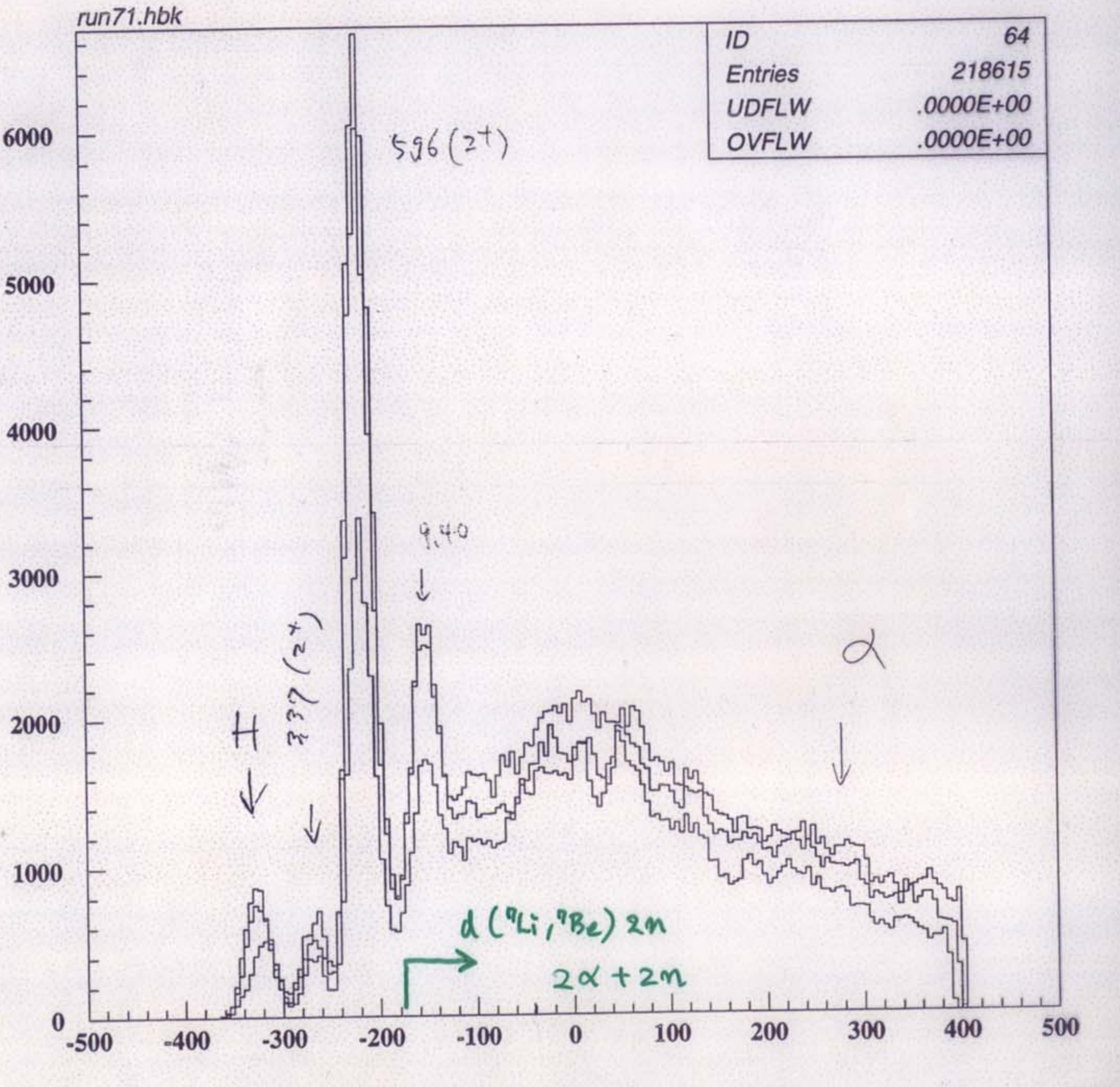
$\rightarrow {}^6Li + t$

$\rightarrow {}^3He + {}^6He$

$^9Li \rightarrow {}^6He + t$ $Q = 7.588$ MeV

$^{10}B(^{7}Li, ^{7}Be)^{10}Be$

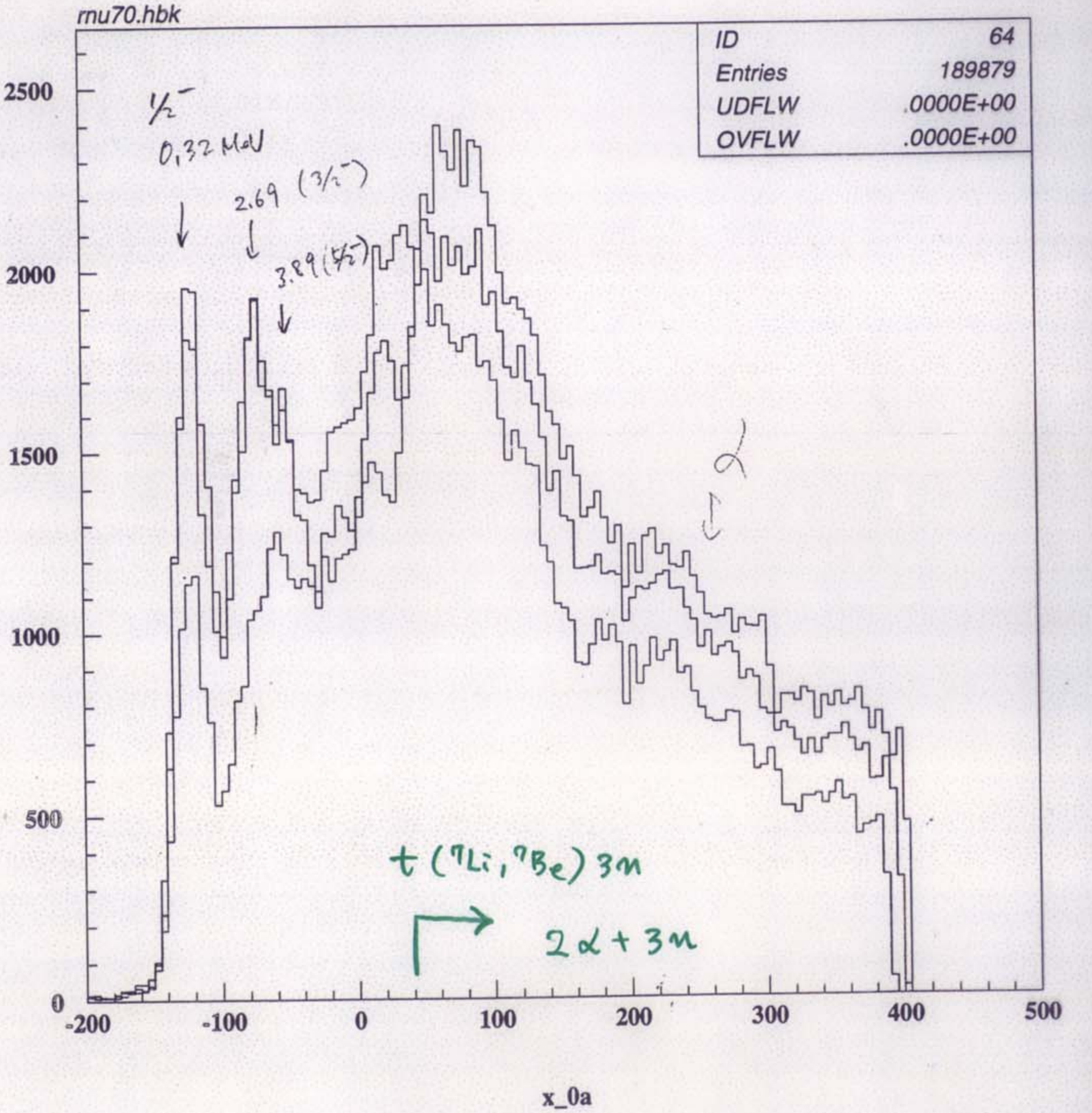
2001/12/12 13.00



$^{10}Be \rightarrow \alpha + {}^{6}He \quad Q = 7.41$ MeV

$^{11}B(^7Li, ^7Be)^{11}Be$

2001/12/12 12.55



$^{11}Be \rightarrow \alpha + {}^6He + n \quad Q = 7.915$ MeV

5. まとめ

―― 原子核のクラスター構造 ――

- Li 原子核中のクラスター励起

(^{7}Li,^{7}Be) reaction at 65*A* MeV

Δ S=0, Δ S=1 spectra

Δ L (angular distributions)

α, d, ^{3}He-cluster excitation

α : formation of exotic cluster structure

(^{2}H -^{4}H, ^{3}H -^{4}H)

d : candidate for a soft-dipole resonance

^{3}He : ^{6}Li (t+^{3}He; $^3S_1$) → ^{6}He (t+t ; $^3P_1$ or $^1P_1$)

- クラスター分子構造の励起

CEX, pick-up, stripping reactions

cluster excitation

x(3N)+yN, x α +yN, exotic-cluster 分子構造

粒子-γ 同時計数測定