Three-Centre Cluster Structure in ^{11}C and ^{11}B

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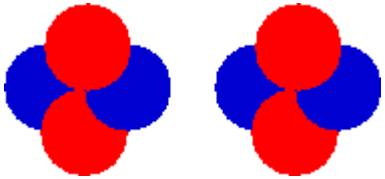
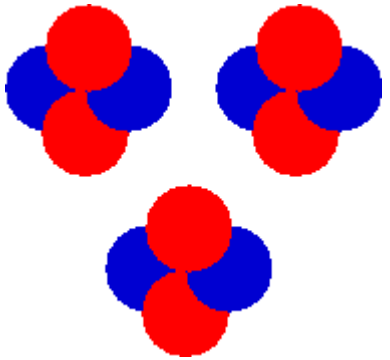
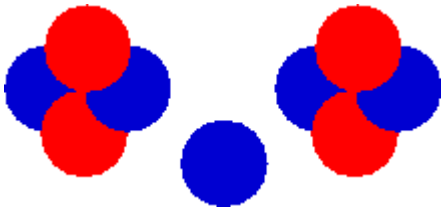
INTRODUCTION

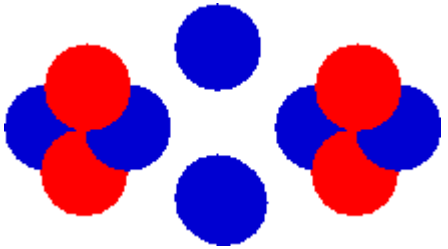
- many light nuclei possess a prominent cluster structure
- α-particle: basic unit in cluster structures

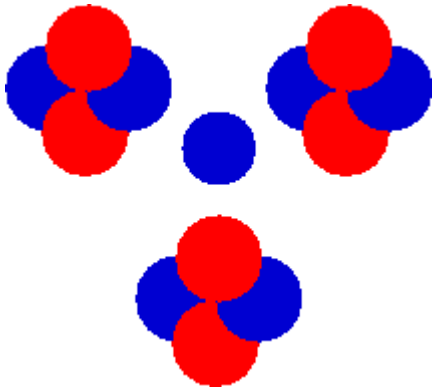
^{8}Be 

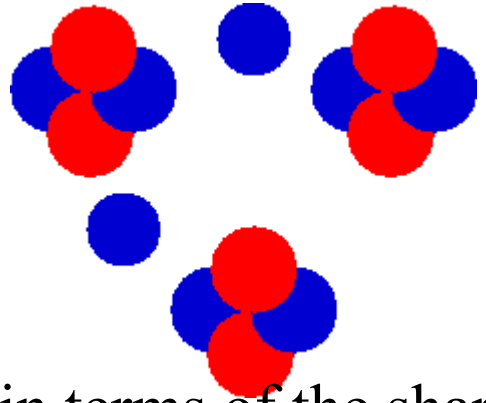
^{12}C 

- attention has focused on neutron-rich Be and C nuclei: Nα+Mn structure

^{9}Be 

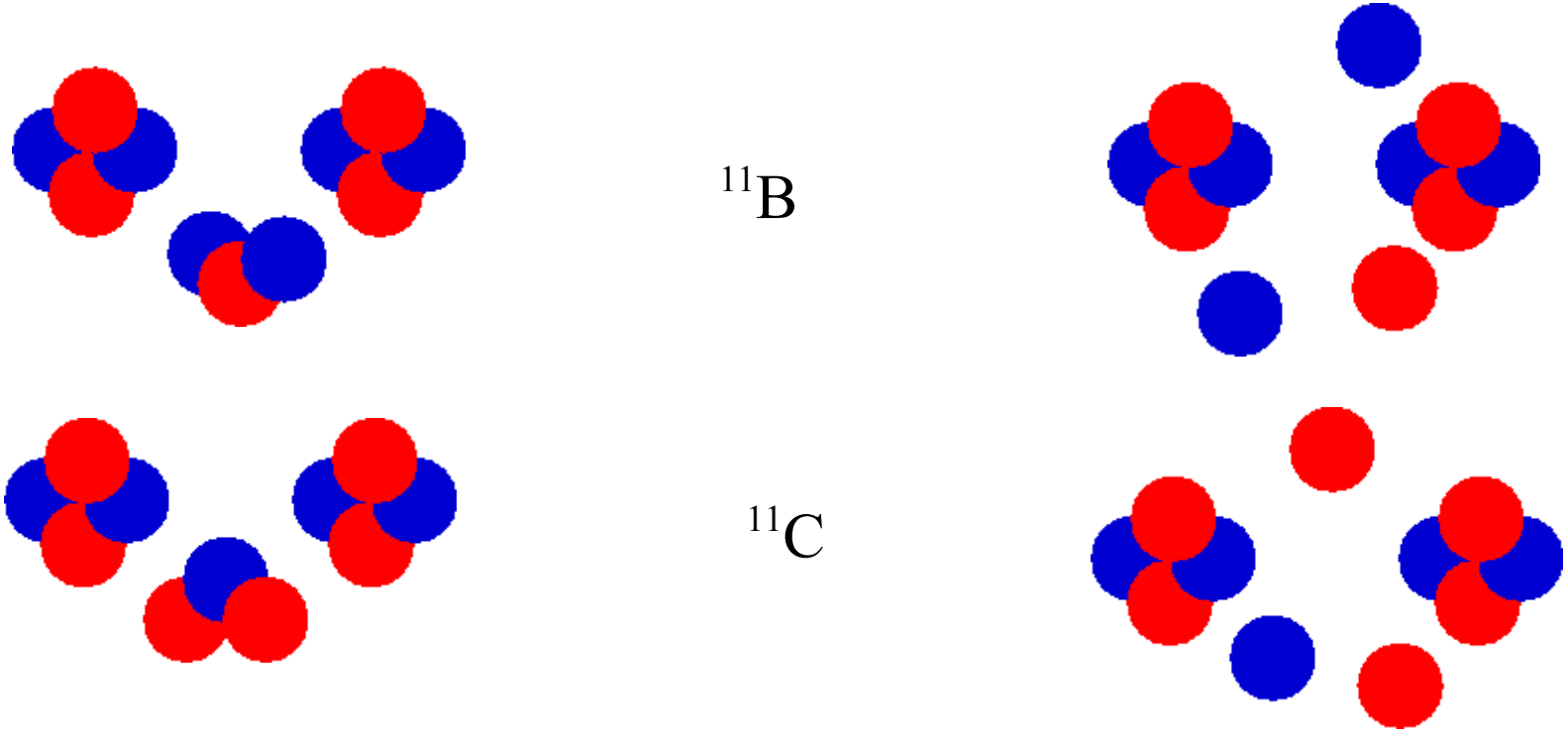
^{10}Be 

^{13}C 

^{14}C 

- properties of Be and C nuclei may be described in terms of the sharing of the valence neutrons between the α-cores – nuclear molecules

- interesting issue: influence of α-clustering on the structure of neutron deficient ^{11}C and also on boron isotopes, particulary ^{11}B
- are these mirror nuclei two- or three-centre systems ?



- example of the 3-centre systems where are holes rather than particles being exchanged between α-particles
- knowledge of their structure may help in understanding of the molecular nature of light nuclei and its evolution from 2- to 3-centre structure

- astrophysical interest: $^{7}Be(\alpha,\gamma)^{11}C$ reaction is starting point of the hot pp chain and $^{7}Li(\alpha,\gamma)^{11}B$ may bypass A=8 gap in the big-bang nucleosynthesis

- experimental signatures for excited states with developed cluster structure:
a) reaction mechanism by which the states are populated
b) large population/decay probability for the channel associated with cluster structure and suppressed single-nucleon population/decay probability
c) rotational band associated with large deformation (moment of inertia I)

$$E_{exc} \sim \frac{\hbar}{(2I)} * [J(J+1)]$$

d) strong γ-transitions between states in the rotational band

- ^{11}C and ^{11}B have been studied extensively but the experimental evidence for cluster structures is rather scarce
- here presented the results of experimental studies which probe cluster structure of ^{11}C and ^{11}B via the α-decay of their excited states
- ^{11}C states: the ^{16}O(^{9}Be,α^{7}Be)^{14}C reaction
- ^{11}B states: the ^{7}Li(^{9}Be,α^{7}Li)^{5}He and ^{7}Li(^{9}Be,ααt)^{5}He reactions
- resonant particle spectroscopy technique
- two-nucleon transfer processes onto the 2α+n cluster nucleus ^{9}Be provide a mechanism by which the multi-centre cluster structures may be populated

EXPERIMENTAL DETAILS

-measurements performed at the Australian National University's 14UD tandem accelerator facility, Canberra, Australia

- beam: 70 and 55 MeV ^{9}Be, intensity ~3 enA

- target: Li_2O_3 foil, 100 μg/cm^2

- detector array: four telescopes for charged particles in a cross-like arrangement

T1: 17.3° ϕ=0°

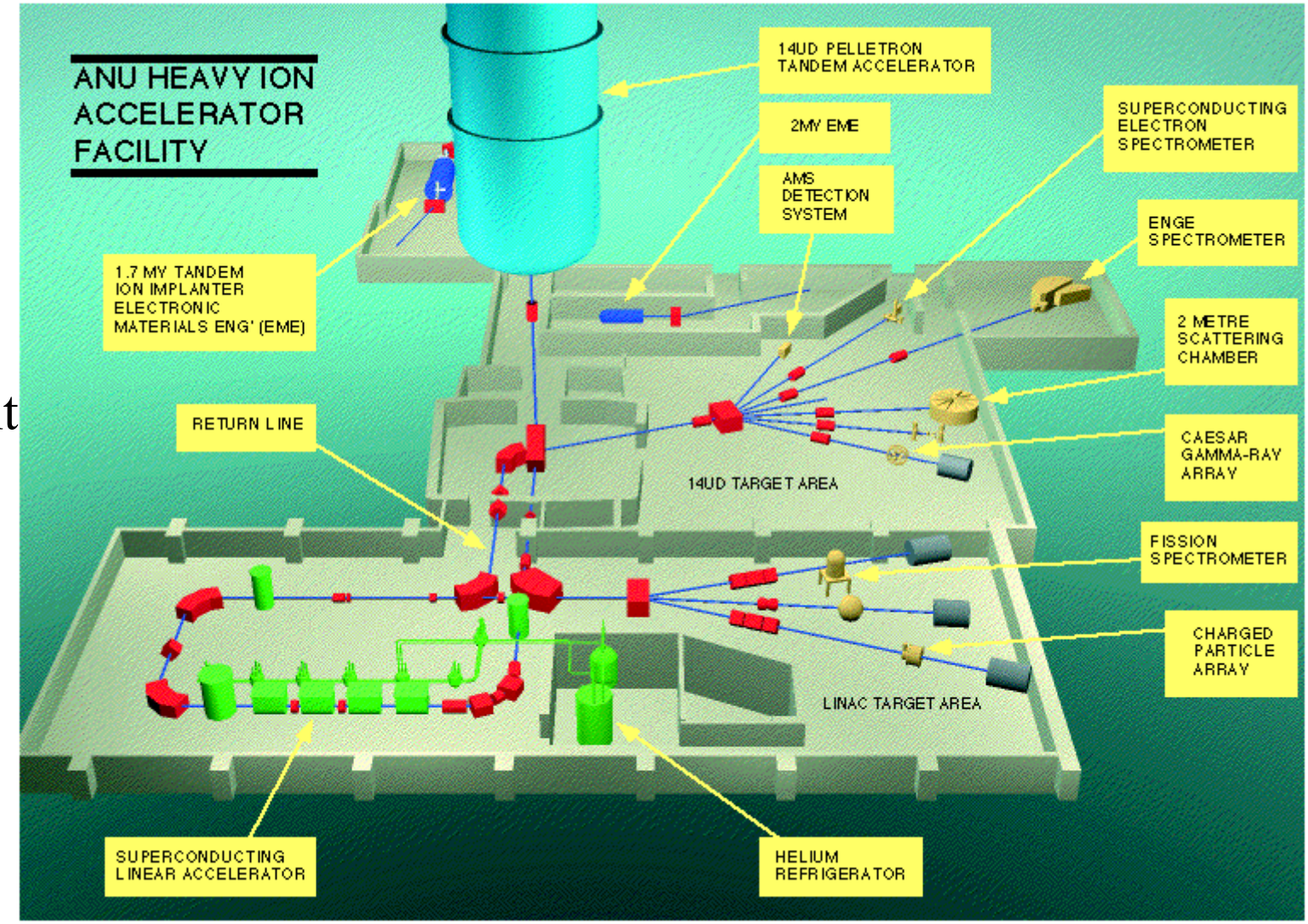
T2: 17.8° ϕ=180°

Θ = ~7°- ~28°

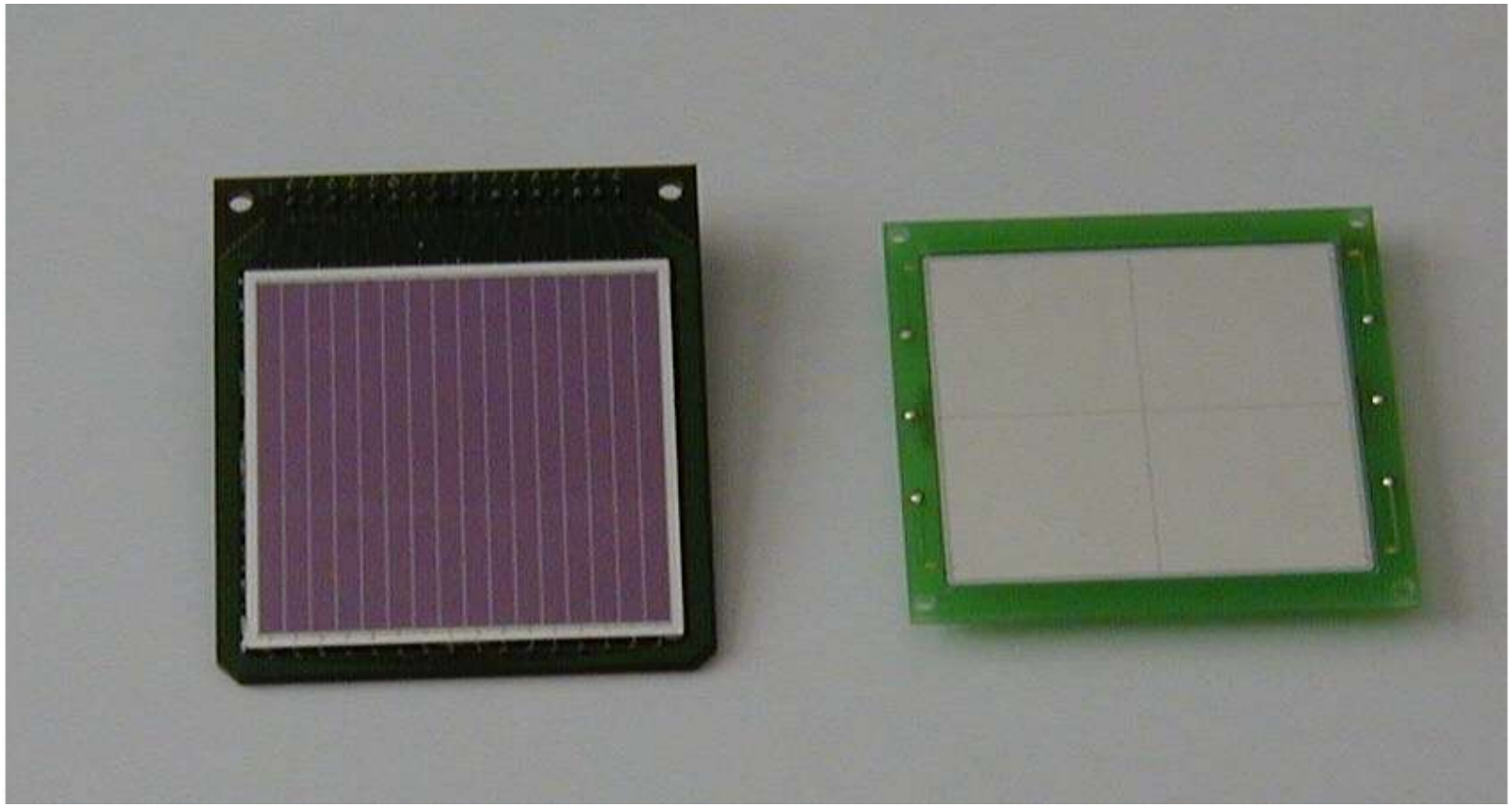
T3: 28.6° ϕ=90°

T4: 29.7° ϕ=270°

Θ = ~20°- ~38°

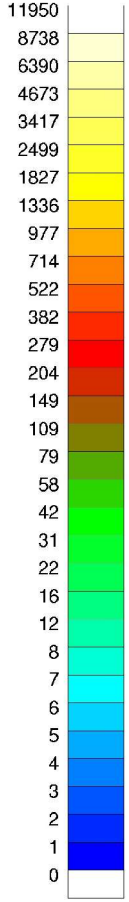


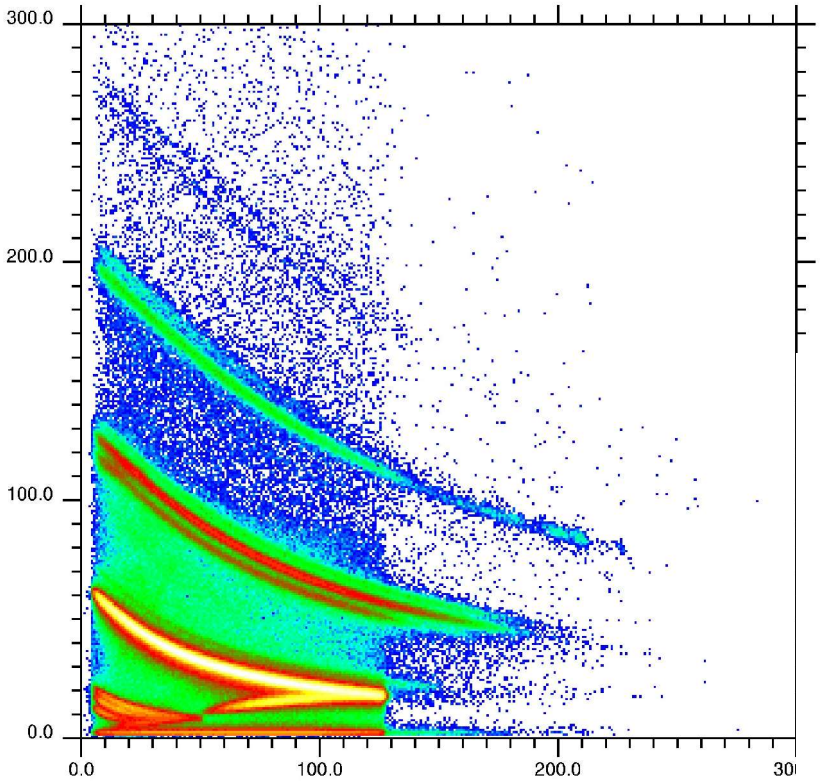
- telescopes contained 3 elements: 70 μm 5x5 cm^2 silicon detectors segmented into four squares, 500 μm 5x5 cm^2 silicon strip detectors divided into 16 position-sensitive strips, 2.5 cm thick CsI detectors

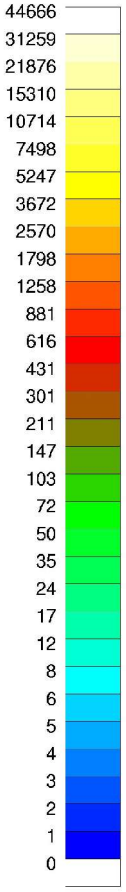


- charge and mass resolution from hydrogen to beryllium isotopes

- kinematically complete measurements of the reactions with 3 and 4 particles in the exit channel: determination of the momentum of each particle in the coincident events
- the reaction kinematics fully reconstructed

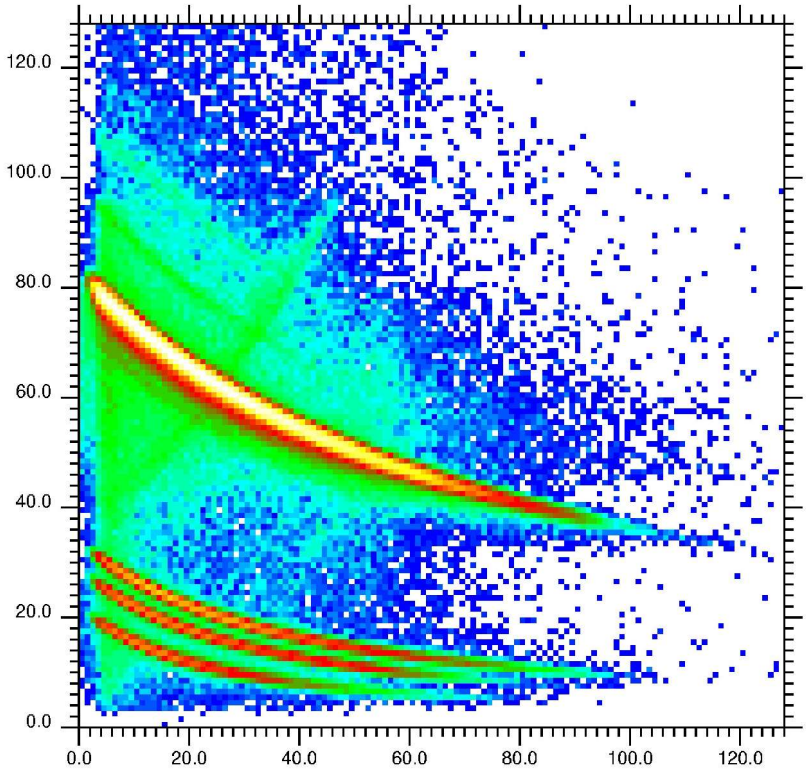






Si – Si matrix

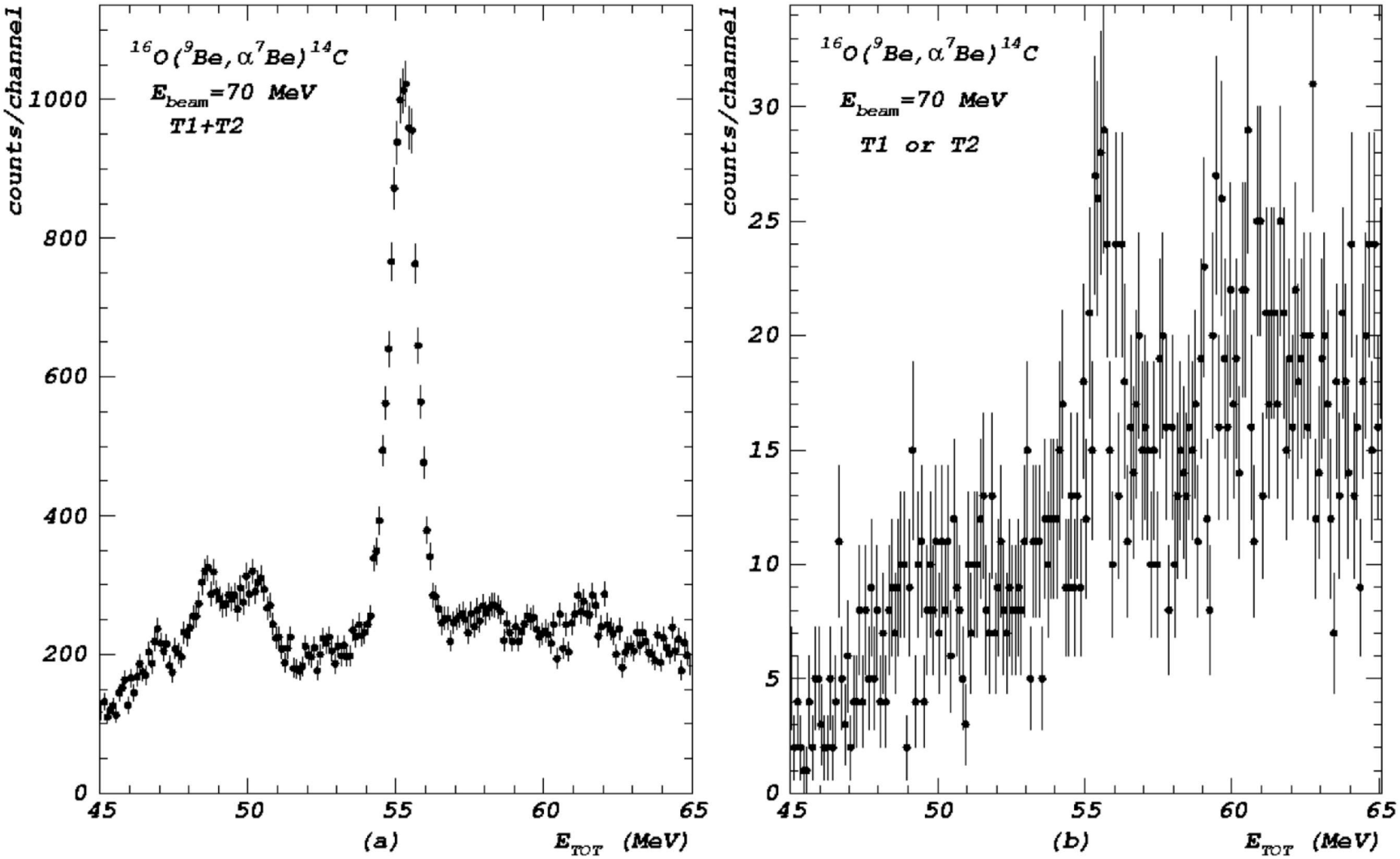
Si – CsI matrix



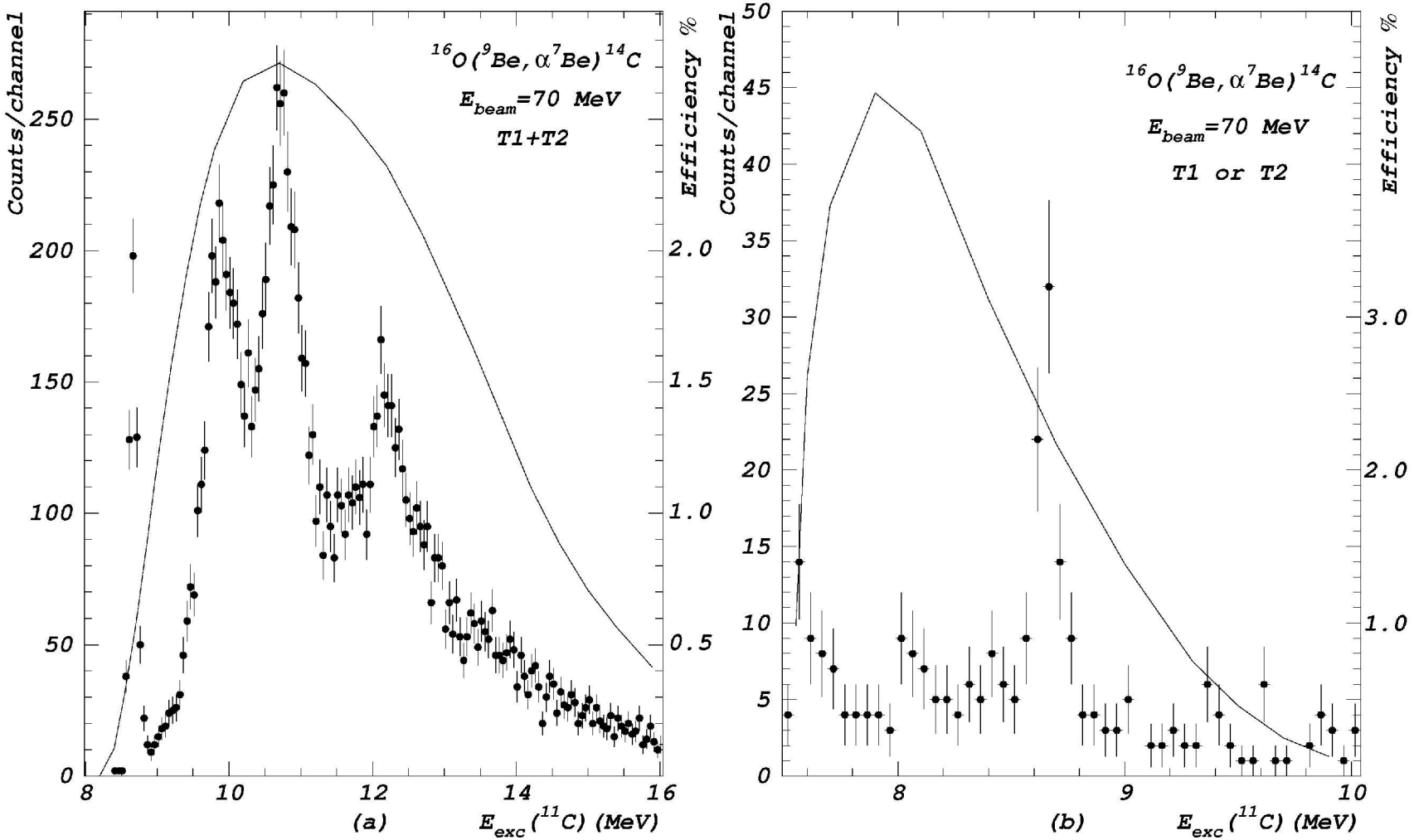
RESULTS: ^{11}C

$^{16}O(^{9}Be,^{11}C^{*}\rightarrow{}^{7}Be+\alpha)^{14}C$, Q = -14.602 MeV

- total energy spectra from 70 MeV data: peak at 55.4 MeV, resolution 1.3 MeV
- contributions from the ^{7}Be g.s. and the 1st excited state (429 keV) unresolved



- ^{11}C excitation energy reconstructed from the relative velocity of the fragments
- no contributions from the $^{18}O \rightarrow \alpha + ^{14}C$ and $^{21}Ne \rightarrow ^{7}Be + ^{14}C$ decays
- detection efficiency calculations performed using Monte Carlo simulations
- uncertainty in the excitation energy 100 keV, resolution 200-300 keV
- data show evidence for only $\alpha + ^{7}Be(gs)$ decay, E_{thrs}=7.543 MeV



- reaction cross section decreases rapidly with increasing $^{11}C^*$ emission angle => main reaction mechanism was two-proton pickup to ^{9}Be

^{11}C excited states decaying into $\alpha+^{7}Be(gs)$

Present	Ajzenberg-Selove,NPA506(1990)		
	8.1045	11 eV	$3/2^-$
	8.420	15 eV	$5/2^-$
8.65	8.655	5 keV	$7/2^+$
	8.699	15 keV	$5/2^+$
	9.20	500	$5/2^+$
	9.65	210	$(3/2^-)$
9.85	9.78	240	$(5/2^-)$
	9.97	120	$(7/2^-)$
	10.083	230	$7/2^+$
10.7	10.679	200	$9/2^+$
	11.03	300	
	11.44	360	
12.1	12.16	270	T=3/2
	12.4	1-2 MeV	
	12.51	490	$1/2^-;3/2$
(12.6)	12.65	360	$(7/2^+)$
	(13.01)		
	13.33	270	
(13.4)	13.4	1100	

$^{11}C^*$ decays threshold (MeV)

$\alpha+^{7}Be$	7.543
$p+^{10}B$	8.6896
$^{3}He+2\alpha$	9.131
$^{3}He+^{8}Be$	9.223
$n+^{10}C$	13.120

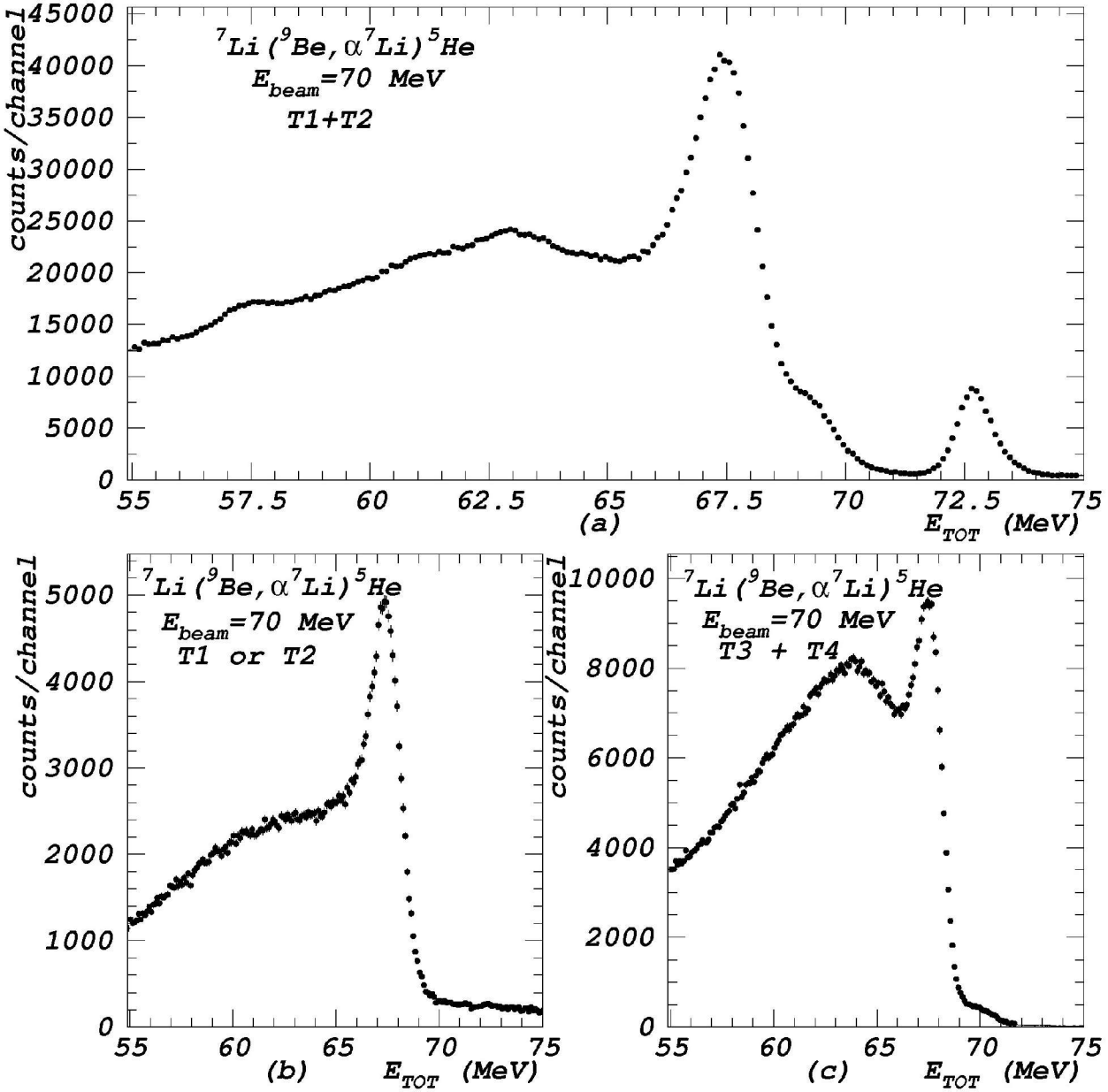
- both data sets, taken at E_{beam}=70 and 55MeV, give the same states

- the first direct observation of α-decay for states above 9 MeV

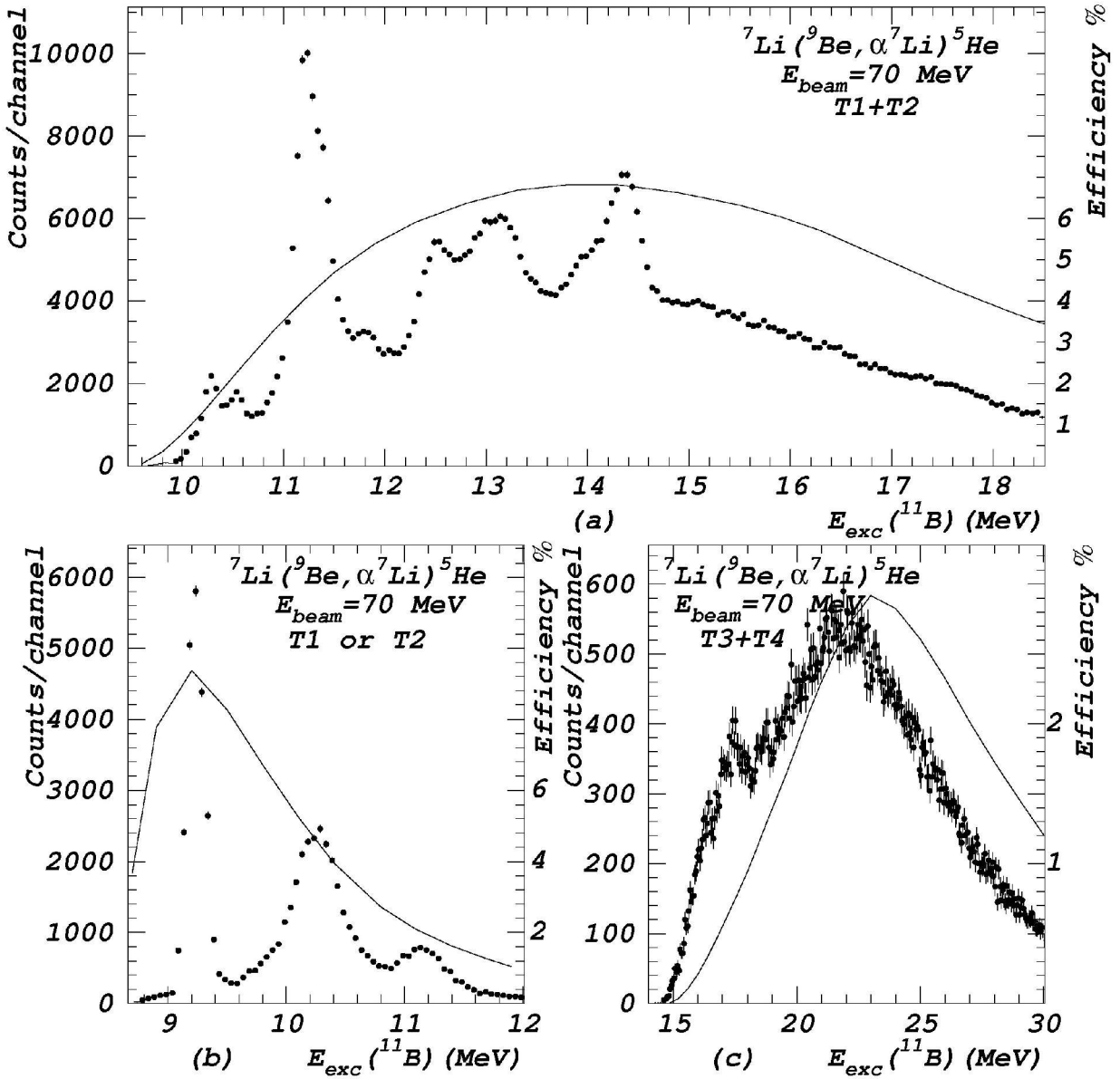
- observed strong α-decay of the 12.1 MeV state which is proposed to be the isobaric analog of the ^{11}Be ground state

RESULTS: ^{11}B

$^{7}Li(^{9}Be,^{11}B^{*}\rightarrow{}^{7}Li+\alpha)^{5}He$, Q = -2.4 MeV



- total energy spectra from 70 MeV data, peak at 67.5 MeV, resolution 2MeV
- width of the ^{5}He gs 600keV
- contributions from the ^{7}Li gs and the 1st excited state (478 keV) unresolved



- no evidence for the ^{12}B→ ^{7}Li+^{5}He decay, ^{9}Be→α+^{5}He decay observed only in T3+T4 data (its contribution removed from the spectrum)
- uncertainty in the excitation energy is 100 keV, resolution 200 – 300 keV
- data give evidence for only ^{11}B→α+^{7}Li(gs) decay, E_{thrs} = 8.664 MeV
- analysis of the angular distributions suggests deutron pickup from ^{7}Li to ^{9}Be, small contribution of the α-transfer from ^{9}Be to ^{7}Li possible at larger ^{11}B* angles

- observed α+^{7}Li(gs) resonances extend the ^{11}B excitation energy range for this decay channel ; the same states oberved at E_{beam}=70 and 55 MeV

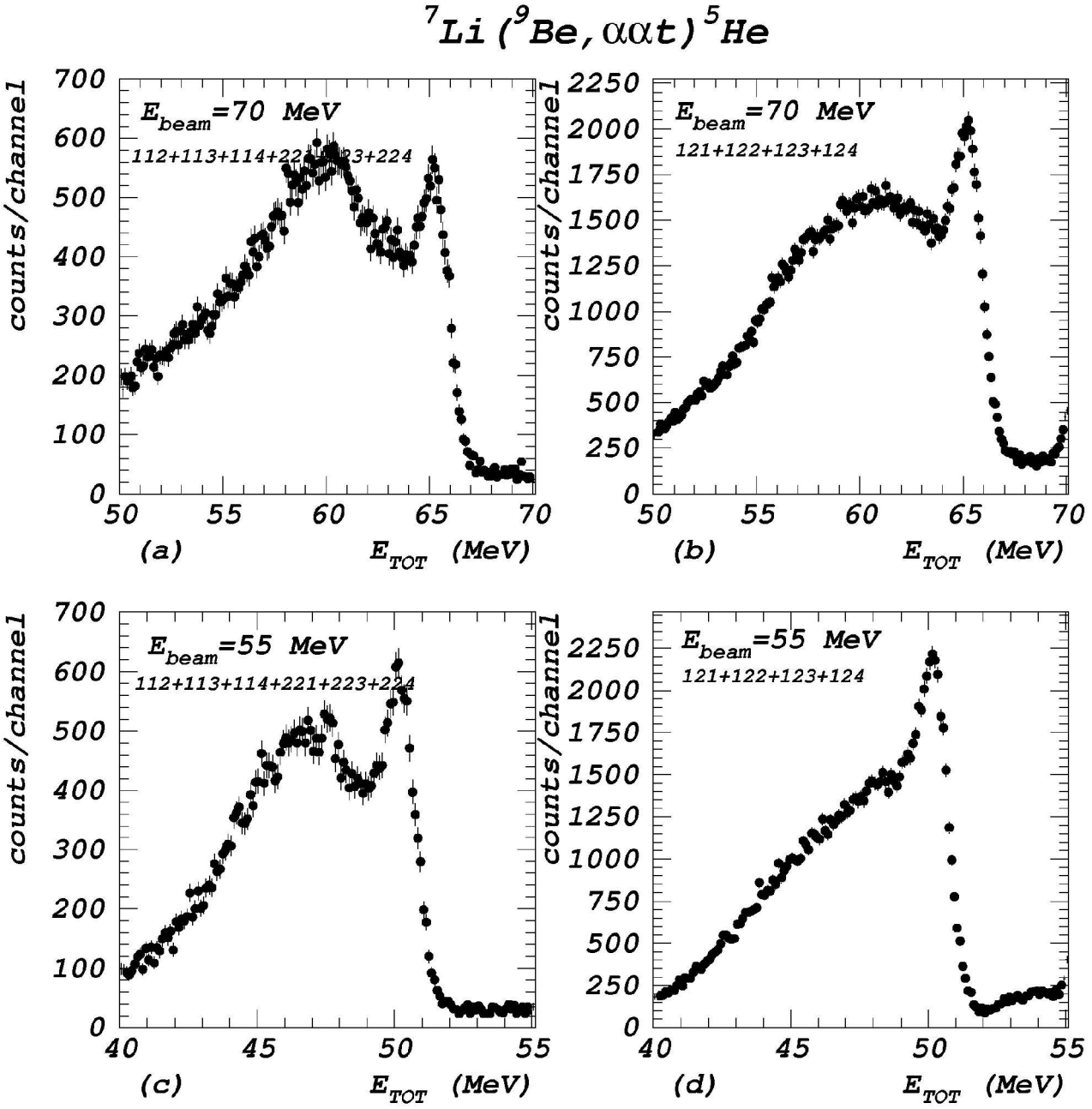
Present	Ajzenberg-Selove,NPA506(1990)		
	8.9202	4.37 eV	$5/2^-$
9.2	9.1850	2 eV	$7/2^+$
	9.2744	4 keV	$5/2^+$
	9.82		$(1/2^+)$
	9.876	110 keV	$3/2^+$
10.3	10.26	150	$3/2^-$
	10.33	110	$5/2^-$
10.55	10.597	100	$7/2^+$
	10.96	4500	$5/2^-$
11.2	11.265	110	$9/2^+$
(11.4)	11.444	103	
	11.6	170	$5/2^+$
11.8	11.886	200	$5/2^-$
	12.0	1000	$7/2^+$
12.5	12.557	210	$1/2^+$;T=3/2
(13.0)	12.916	200	$1/2^-$;3/2
13.1	13.137	426	$9/2^-$
	13.16	430	$(5/2,7/2)^+$
(14.0)	14.04	500	$11/2^+$
14.35	14.34	254	$5/2^+$;3/2
	14.565	30	
	15.29	250	$(3/2,5/2,7/2)^+$;3/2
	16.437	30	T=3/2
	17.33	1000	
17.4	17.43	100	T=3/2
	18.0	870	T=3/2
(18.6)	18.37	260	$(1/2,3/2,5/2)^+$

^{11}B excited states decaying into $\alpha+^7$Li(gs)

^{11}B* decays	threshold (MeV)
$\alpha+^7$Li	8.664
$t+2\alpha$	11.131
$t+^8$Be	11.223
$p+^{10}$Be	11.228
$n+^{10}$B	11.454
$d+^9$Be	15.815

- four states observed here (T=1/2) coincide with states proposed to be the isobaric analogue states of the ^{11}Be states (T=3/2)

$^{7}Li(^{9}Be,^{11}B^{*}\rightarrow t+\alpha+\alpha)^{5}He$, Q = -4.9 MeV



- total energy spectra at E_{beam} = 70 and 55 MeV

- peaks at 65.1 and 50.1 MeV, resolution 1.5 -2.0 MeV

- similar spectra for other telescope combinations

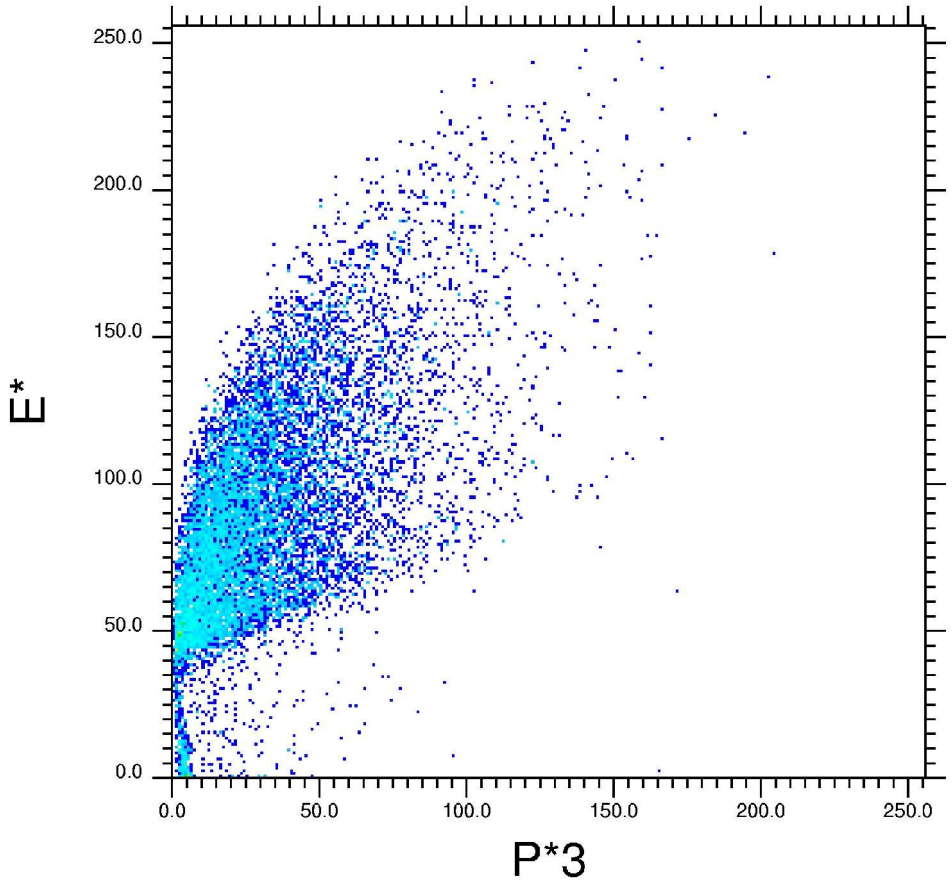
- reaction identification: 3 detected particles of 4 in the exit channel

$$\tilde{P} = [\overrightarrow{p_{beam}} - \vec{p}_1 - \vec{p}_2 - \vec{p}_3]^2 / (2 \times amu)$$

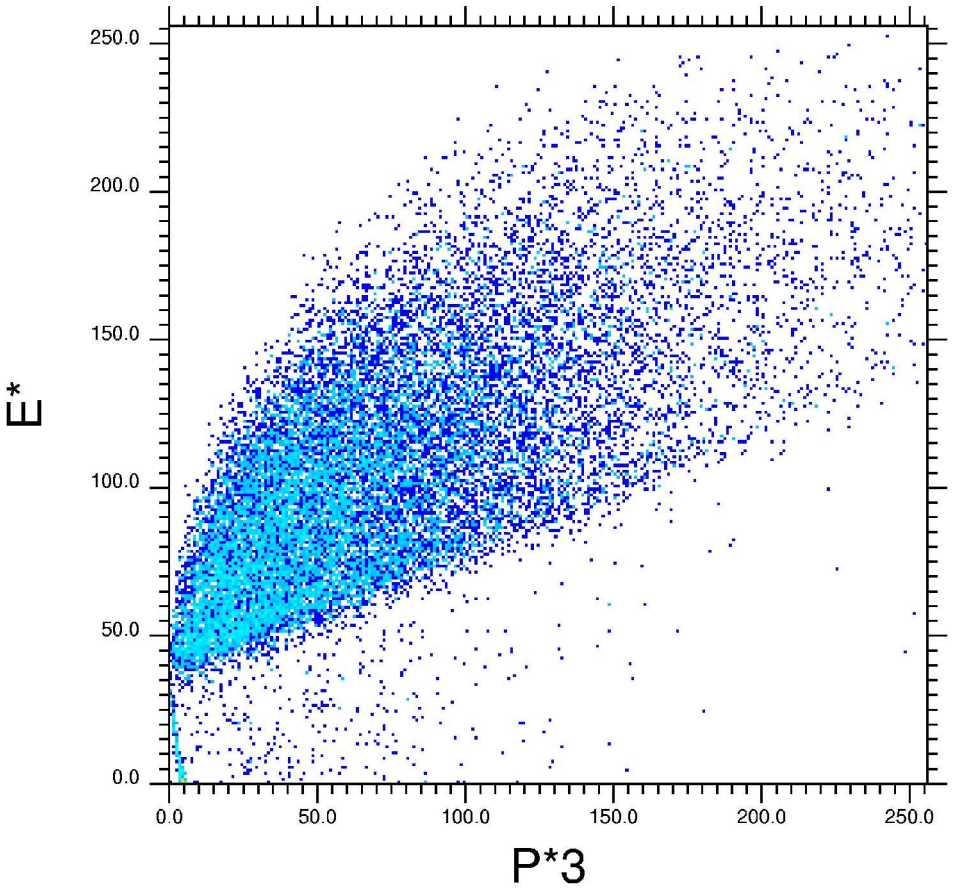
$$\tilde{E} = E_{beam} - E_1 - E_2 - E_3$$

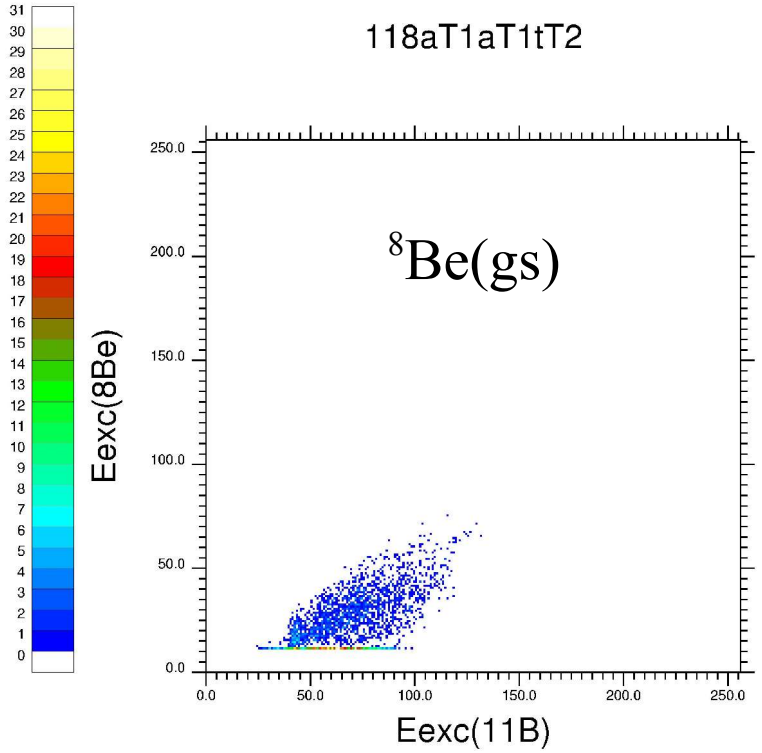
$$\tilde{E} = \tilde{P} / A_{recoil} - Q$$

PEaT1aT2tT1

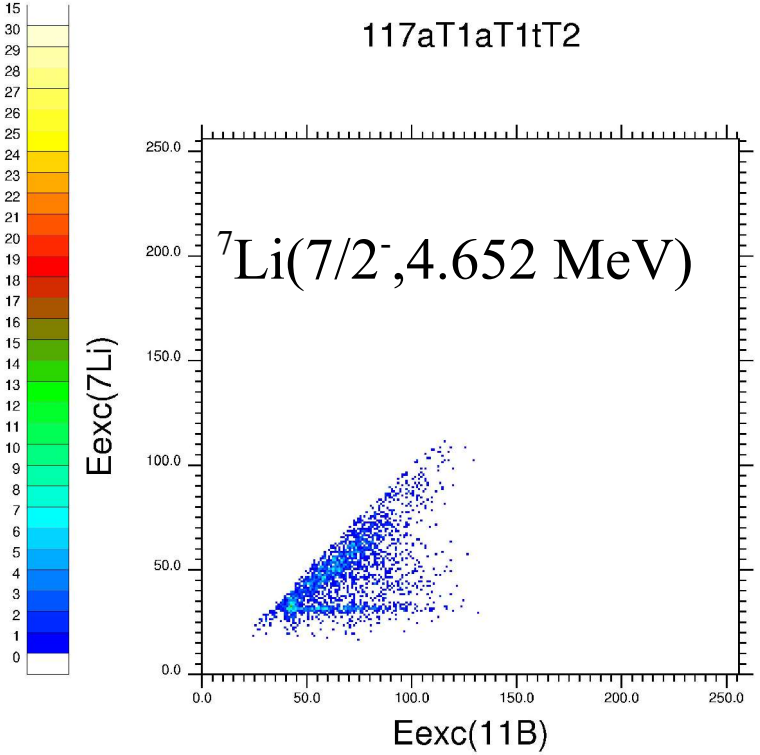


PEaT2aT3tT4

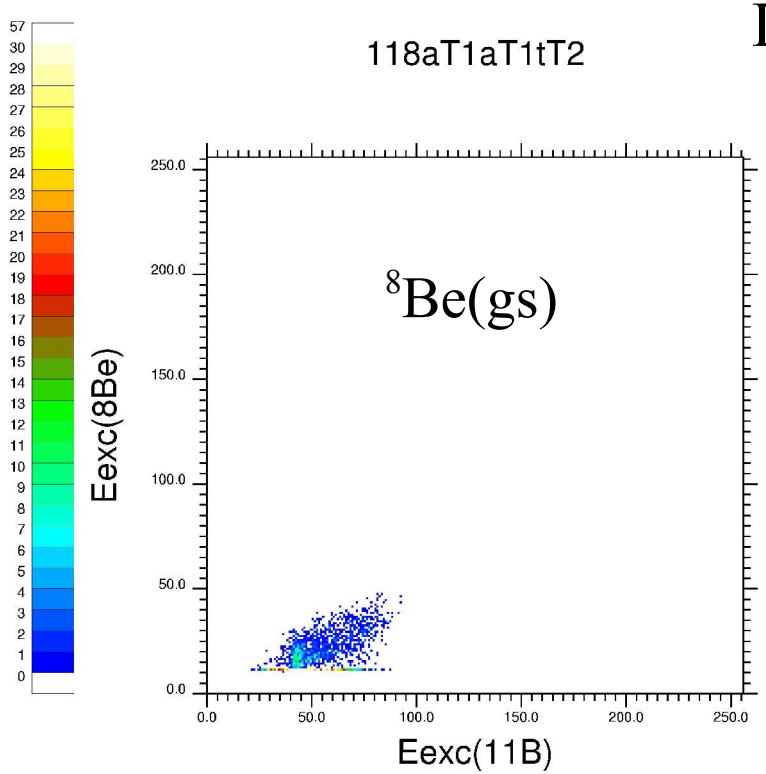




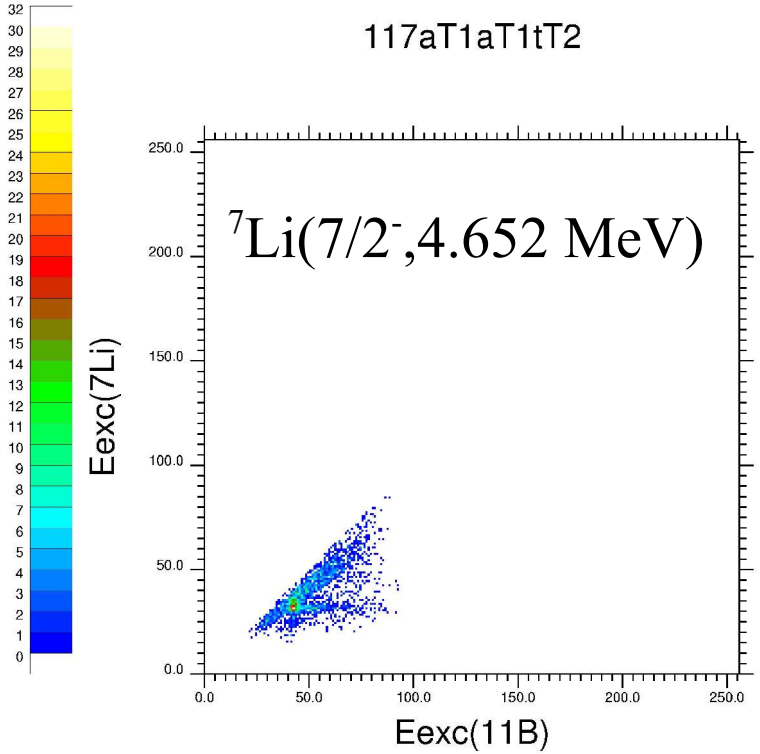
70 MeV



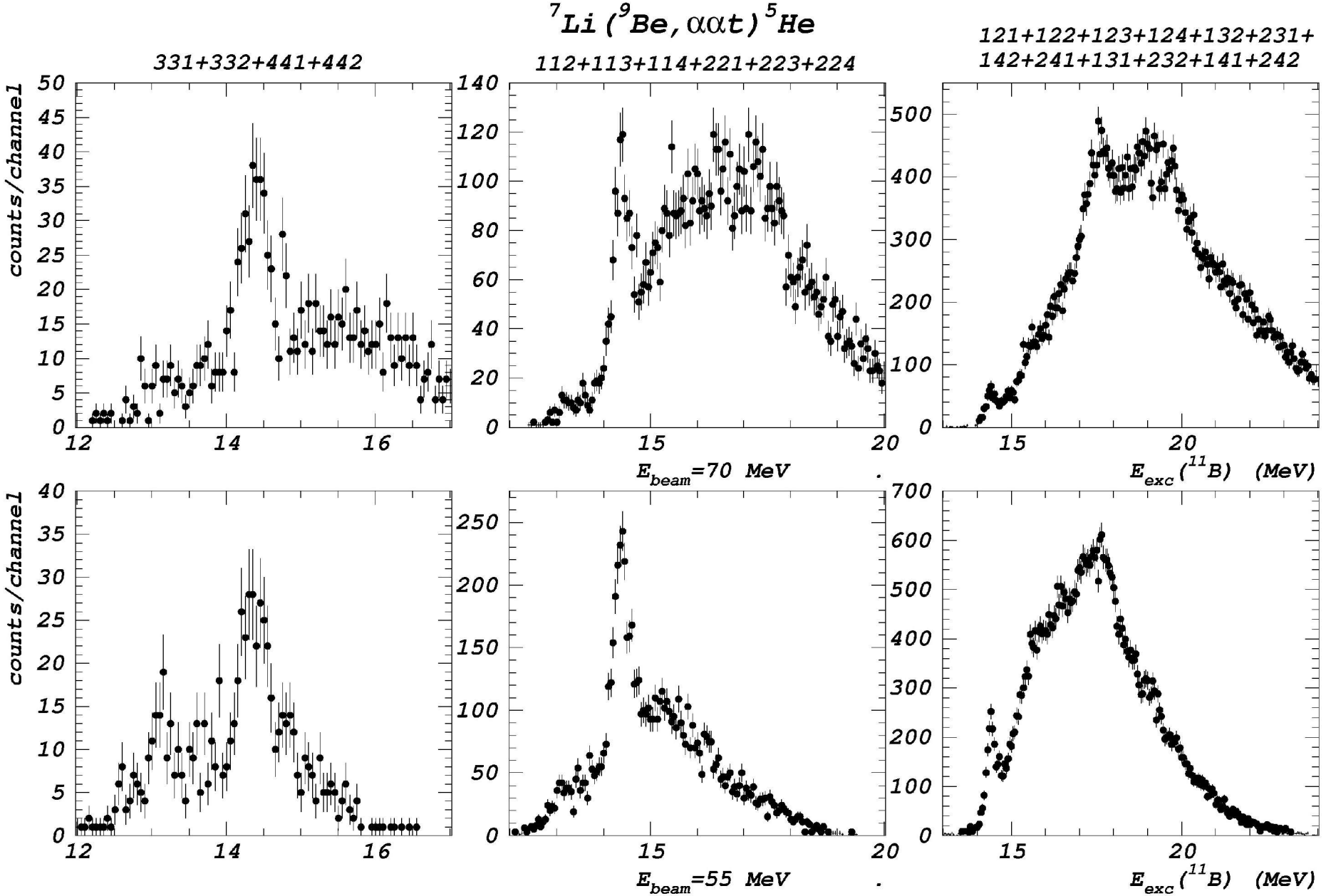
Dalitz plot



55 MeV



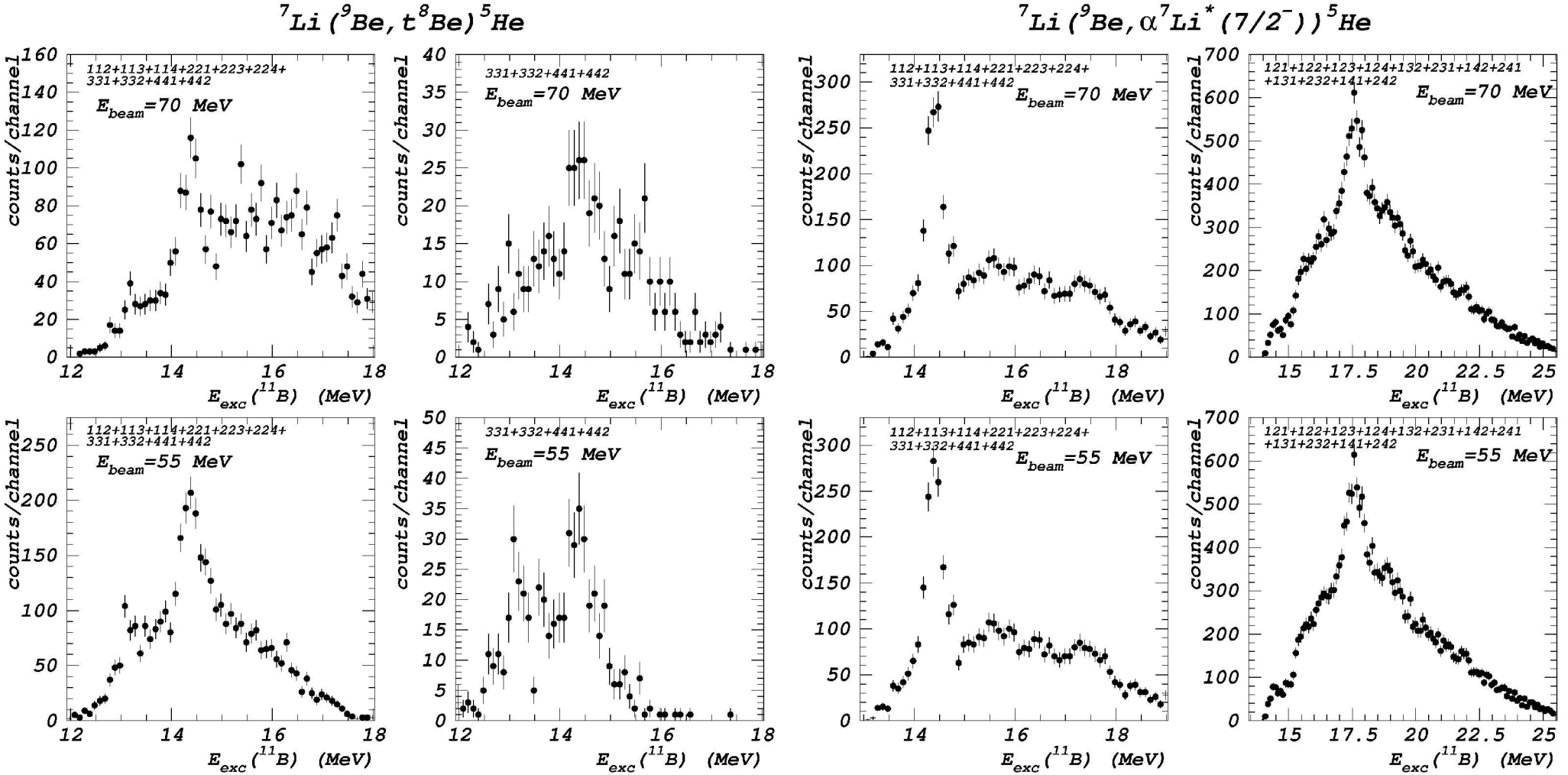
- ^{11}B excitation energy spectra reconstructed from the energies and momenta of 3 detected particles: peaks at 13.1, 14.4 and 17.5 MeV
- resolution 250-350 keV, uncertainty 150 keV



- all possible 2- and 3-body decays were reconstructed and it is clear that there is no contribution in presented spectra from any other decay process

$^{11}B^* \rightarrow t + {}^{8}Be(gs)$ decay
peaks at 13.1 and 14.4 MeV

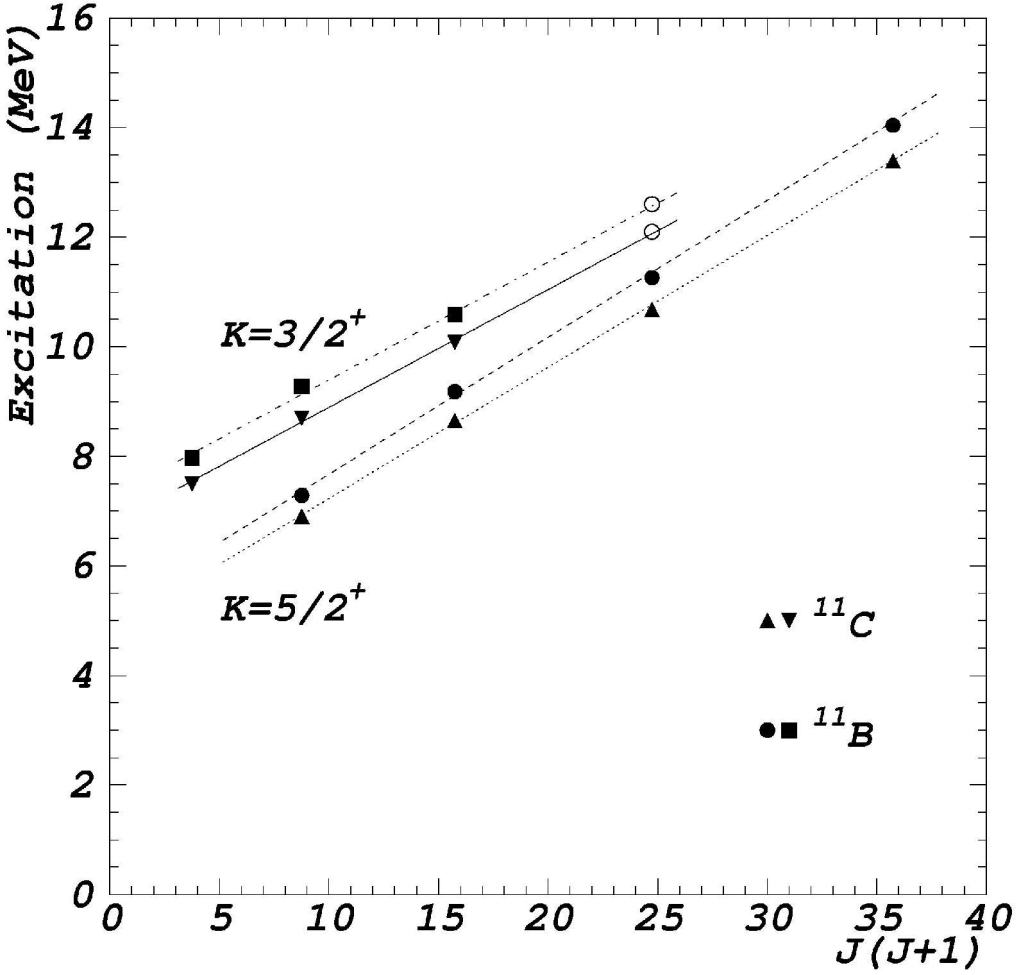
$^{11}B^* \rightarrow \alpha + {}^{7}Li^*(4.652\ MeV)$ decay
peaks at 14.4 and 17.5 MeV



- these results are the first direct evidence for $^{11}B^*$ decays into 3 particles

COMMON FEATURES OF THE ^{11}B AND ^{11}C EXCITED STATES

- the observed ^{11}B states at 12.5, 12.9, 14.4 and 17.5 and ^{11}C state at 12.1 coincide with proposed T=3/2 states (isobaric analogue states of ^{11}Be)
- these states may have large isospin mixing or may be the new states which have a genuine T=1/2 character and may be linked to rotational bands



^{11}B:

K=5/2$^+$: 7.286 9.185 11.265 14.04 MeV

rotational parameter $\hbar^2/2I$ = 0.25 MeV

K=3/2$^+$: 7.978 9.274 10.597 (12.5)

rotational parameter $\hbar^2/2I$ = 0.215 MeV

^{11}C:

K=5/2$^+$: 6.905 8.655 10.679 13.4

rotational parameter $\hbar^2/2I$ = 0.24 MeV

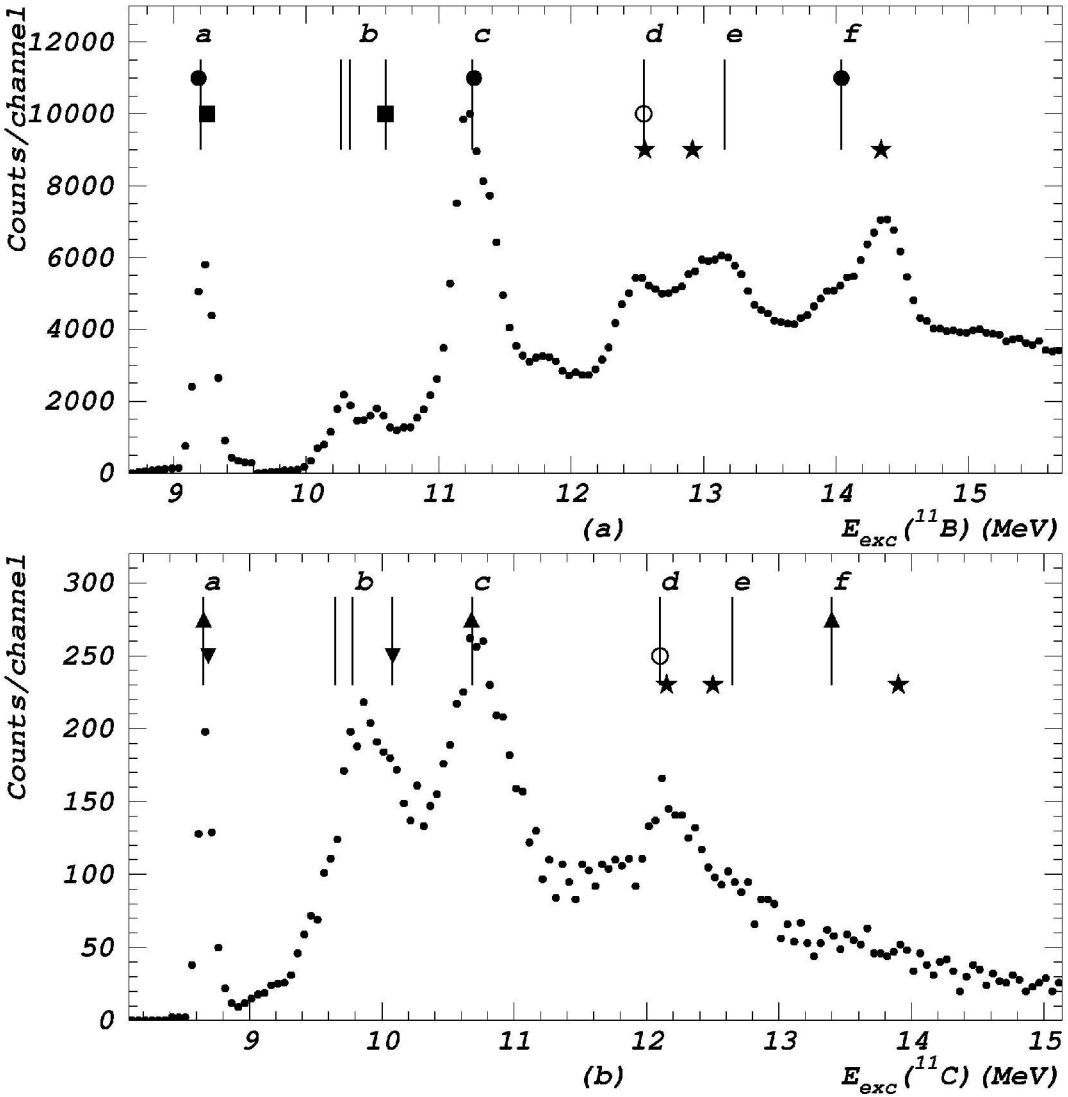
K=3/2$^+$: 7.499 8.699 10.083 (12.1)

rotational parameter $\hbar^2/2I$ = 0.215 MeV

=> very deformed structure

-determination of the spins and parities of the 12.5 and 12.1 MeV states in ^{11}B and ^{11}C is required

- interesting feature of the present spectra: we observe the same series of excited states at the lower excitations in both nuclei
- all states observed in ^{11}C appear also as strong resonances in ^{11}B



- these strongly excited states observed in α-decay of both nuclei should have the same structure

- observed strong α+^{7}Li(^{7}Be) decay of these mirror states produced in the two-nucleon transfer reactions onto ^{9}Be and known α+t(^{3}He) cluster structure of ^{7}Li(^{7}Be) as well as 2α+t decay of ^{11}B states, suggest 2α+t(^{3}He) 3-centre cluster structure of the ^{11}B(^{11}C) excited states

SUMMARY

- performed measurements provide evidence for $\alpha+^{7}$Be(gs) and $\alpha+^{7}$Li(gs), $\alpha+^{7}$Li*(7/2^{-},4.652 MeV), t+^{8}Be(gs) decays of excited states in ^{11}C and ^{11}B
- the nature of the reaction processes, two-nucleon transfer onto the 2α+n nucleus ^{9}Be, the α-decay of excited states at excitations where various decay channels are open and known α+t(^{3}He) structure of ^{7}Li(^{7}Be), as well as observed ^{11}B decays into 2α+t, indicate that these states correspond to the three-centre 2α+t(^{3}He) cluster structure
- this cluster structure appears to be more prominent in the positive-parity states where two rotational bands (K=5/2^{+} and 3/2^{+}) corresponding to very deformed structure are suggested
- the observed structure is probably oblate in character
- indications for mixed isospin of some T=3/2 states were found
- present measurements did not provide information on the spin and parity of these states which is crucial step to understand structure of the observed states
- measurements capable of determining these information have been proposed
- the existing theoretical calculations have not examined 3-centre systems where are holes exchanged between α-particles nor the rotational structures of the proposed 3-centre configurations and such calculations would be extremly useful