α-decaying excited states in carbon and boron isotopes

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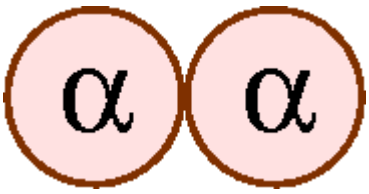
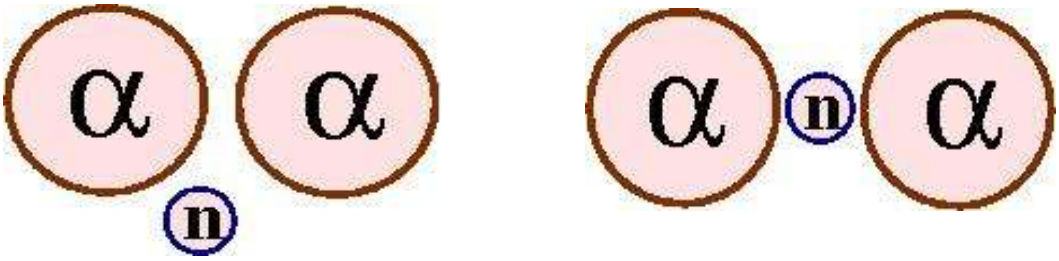
Introduction

- light nuclei: variety of structural properties from spherical shell model structure to clustering
- α-particle: basic unit in cluster structures
- beryllium isotopes: good evidence for well developed cluster structure in ^{8,9,10}Be, tentative evidence in ^{11,12,14}Be
- sharing of the neutron(s) between two α-cores ⇒ α+Xn+α structure ⇒ nuclear molecules

^{8}Be

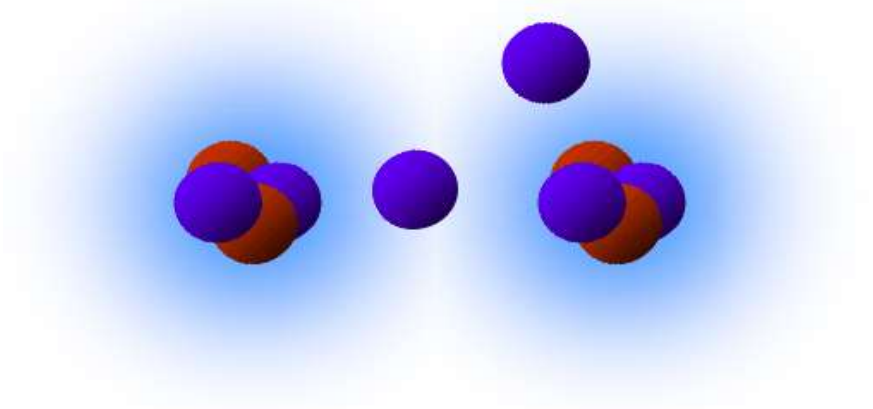


^{9}Be

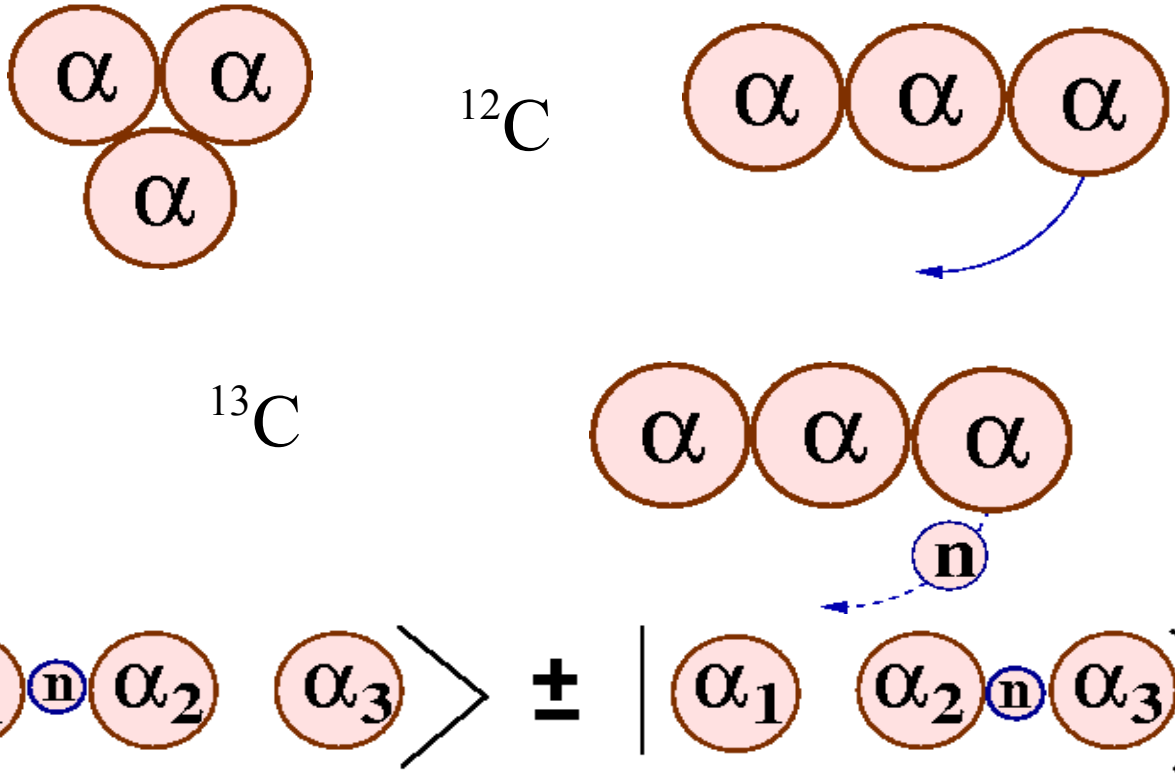


- valence neutron around α-particle is in p-type orbit ⇒ π and σ-type orbits in Be isotopes

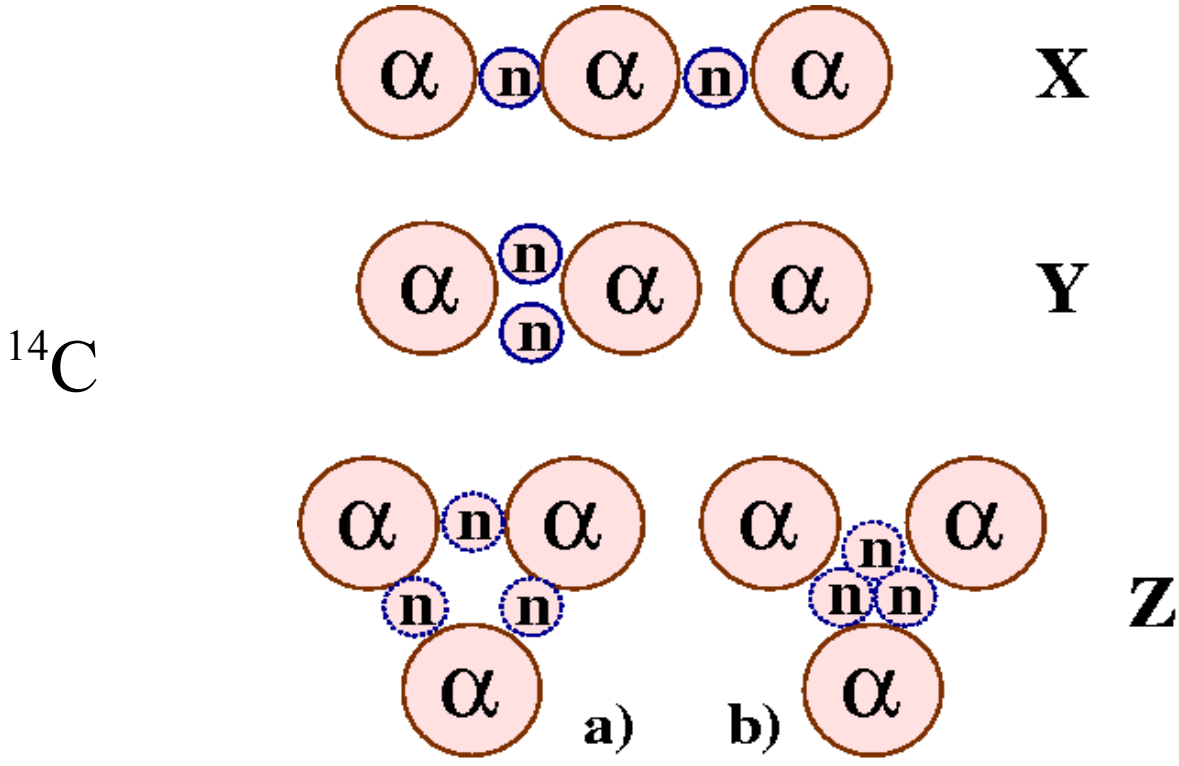
^{10}Be



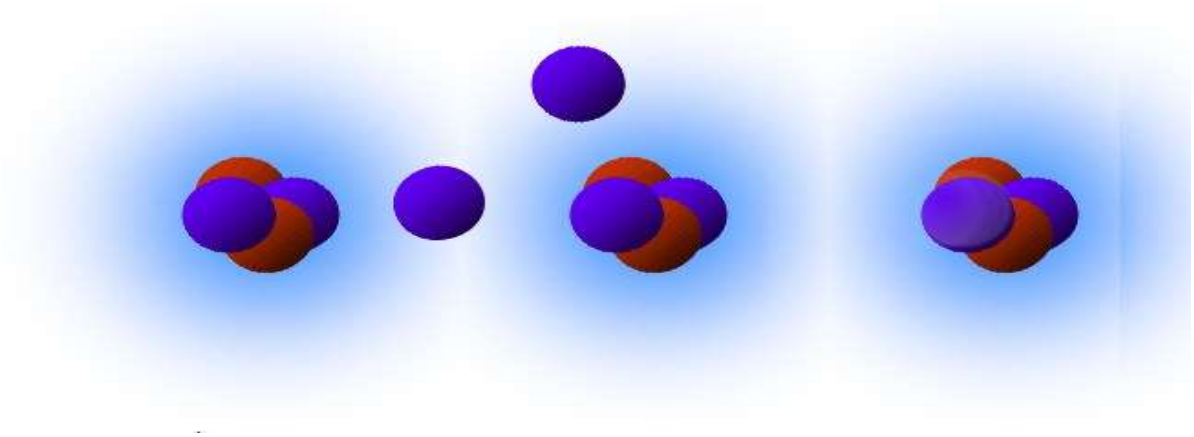
- carbon nuclei: 3α cluster structure in $^{12}C \Rightarrow$ an extension to the three-centre system



- intrinsic asymmetry of the 3α+n structure $\Rightarrow$ two rotational bands with opposite parity



^{14}C ?



- boron isotopes: does α-clustering influence their structure, do they fit to that picture ?
- two- or three-centre systems ?
- ^{11}B: α+α+t three-centre structure
- heavier B isotopes: α+α+t+Xn ?

- theory: the antisymmetrized molecular dynamics framework (Y. Kanada-En'yo et al), molecular orbit model (N. Itagaki et al)
- reproduce well the properties of Be and C isotopes and suggest that clustering has a determining role in the structural properties of the heavier neutron-rich isotopes

- experimental signatures for excited states with molecular 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)

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

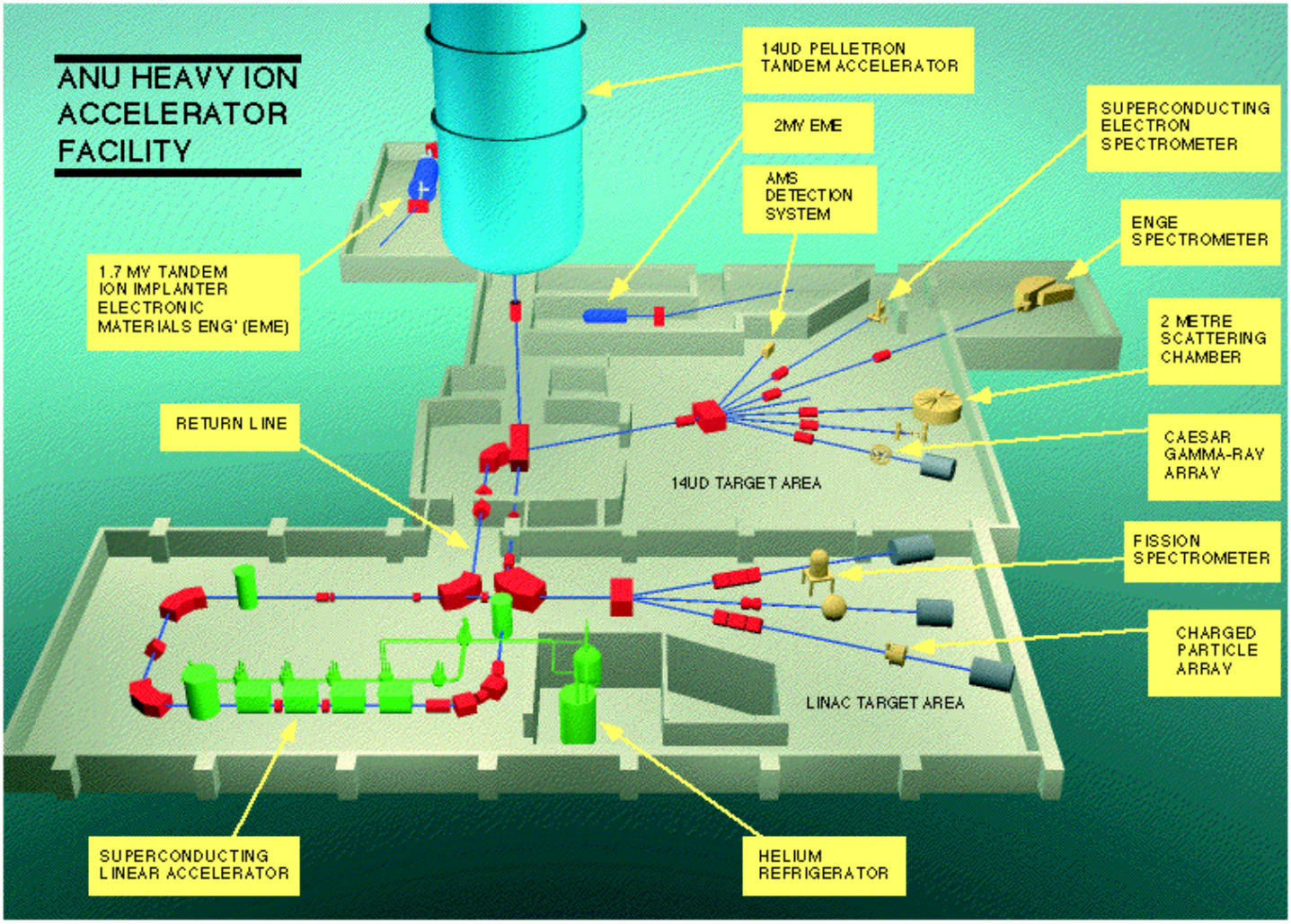
d) strong γ-transitions between states in the rotational band

- boron and carbon nuclei have been studied intensively but the experimental evidence for molecular states is rather scarce

- here presented the results of experimental studies which probe cluster structure of $^{11,13,14}C$ and $^{11,12}B$ via strong α-decay of their excited states

Experimental details

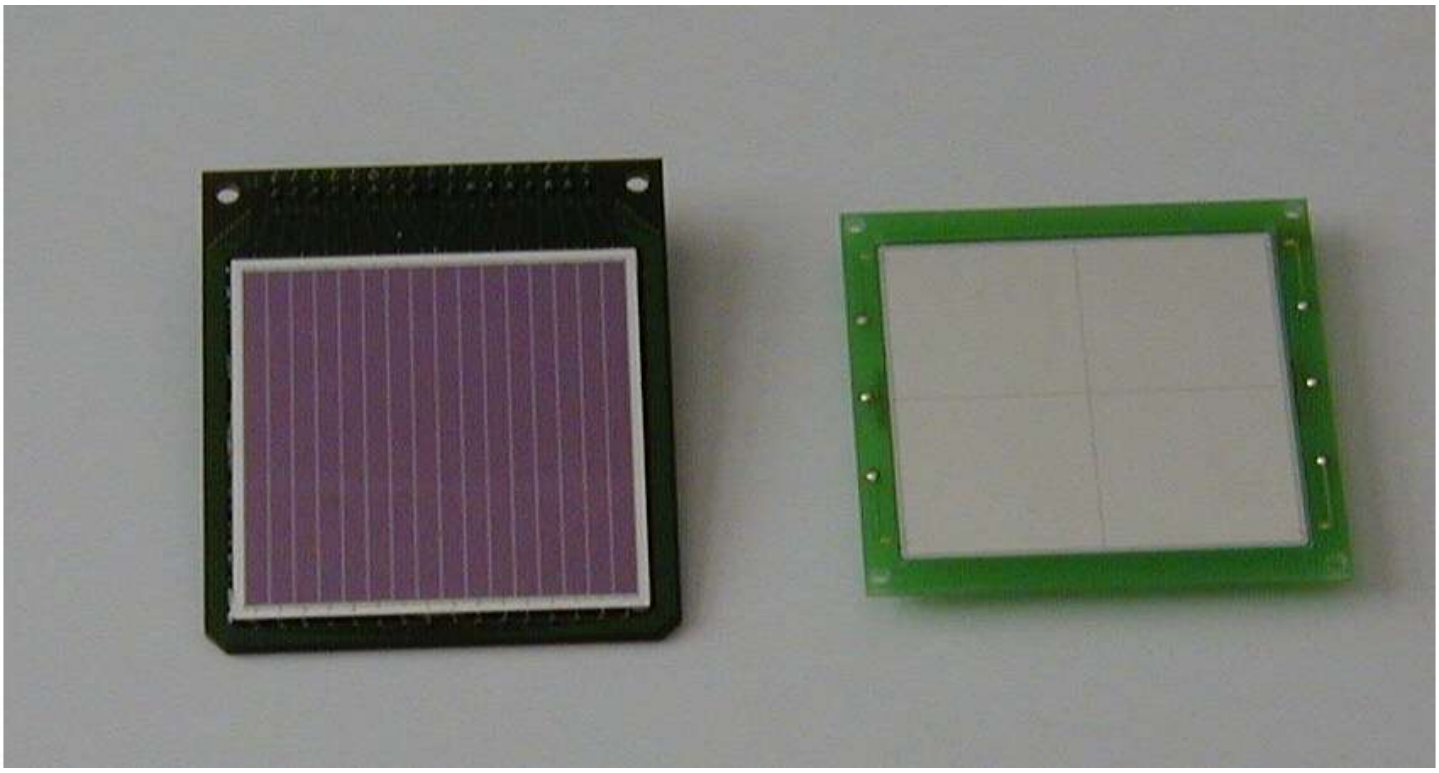
- the measurements were performed at the Australian National University's 14UD tandem accelerator facility, Canberra, Australia



- beam: 70 MeV ^{9}Be, intensity ~ 3enA
- target: Li_2O_3 foil, 100 μg/cm^2
- four detector telescopes for charged particles ⇒ particle identification

- 2 telescopes at 17.3° and 17.8° (~7° - ~28°), 2 at 28.6° and 29.7° (~20° - ~38°) in a cross-like arrangement

- very thin (~70 μm) 5 x 5 cm^2 silicon detectors segmented into four squares, position – sensitive strip detectors with the same active area divided into 16 strips, 2.5 cm thick CsI detectors ⇒ provided charge and mass resolution from protons to beryllium isotopes

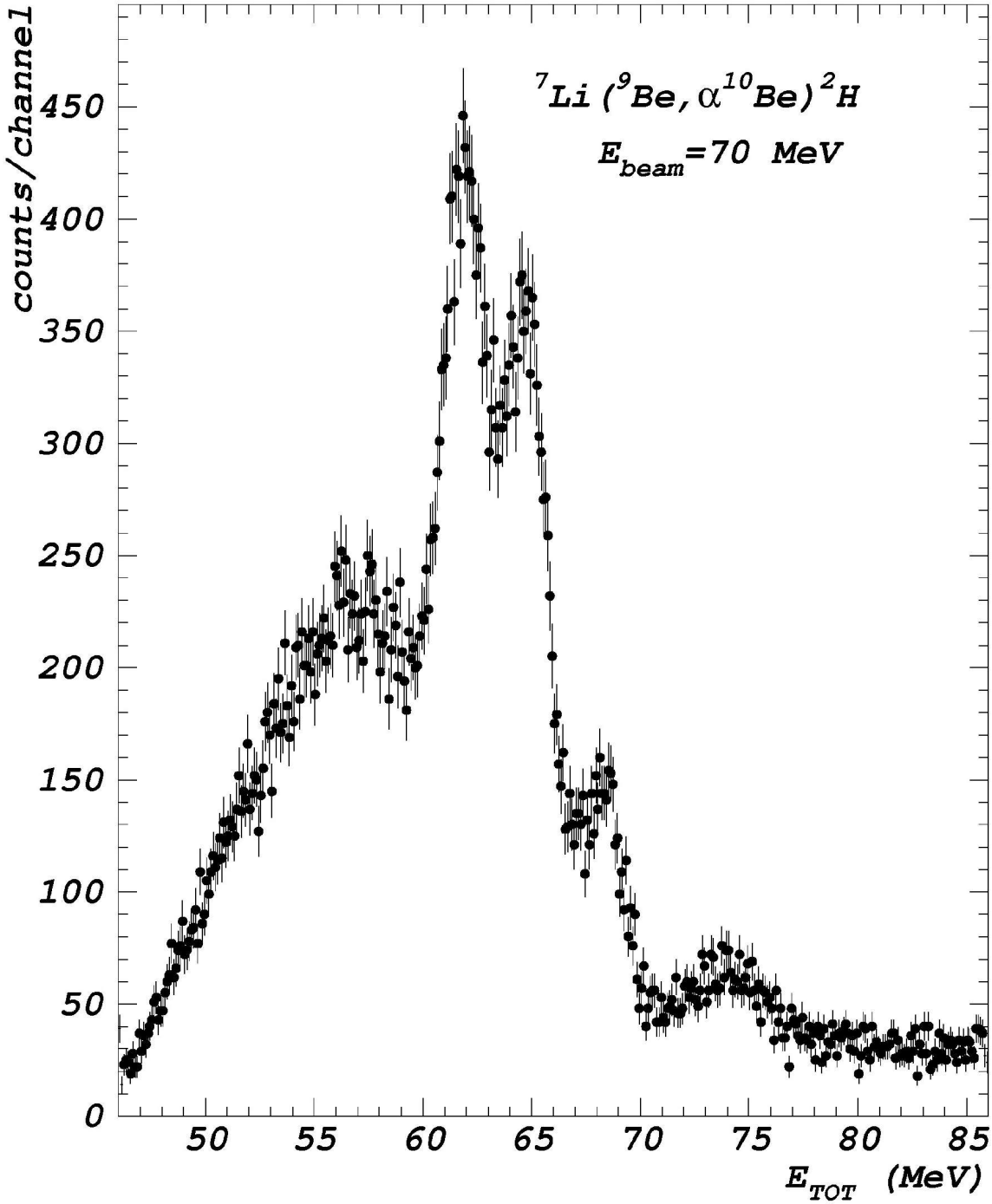


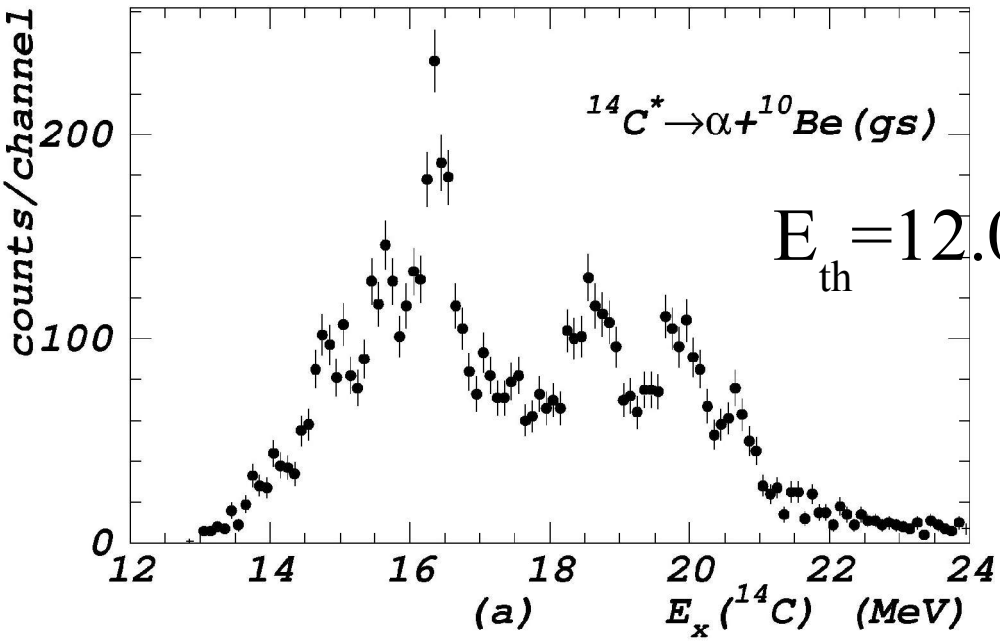
- kinematically complete measurements of the three-body reactions: determination of the momentum of each particle in coincident events ⇒ complete determination of the reaction kinematics

Results: ^{14}C

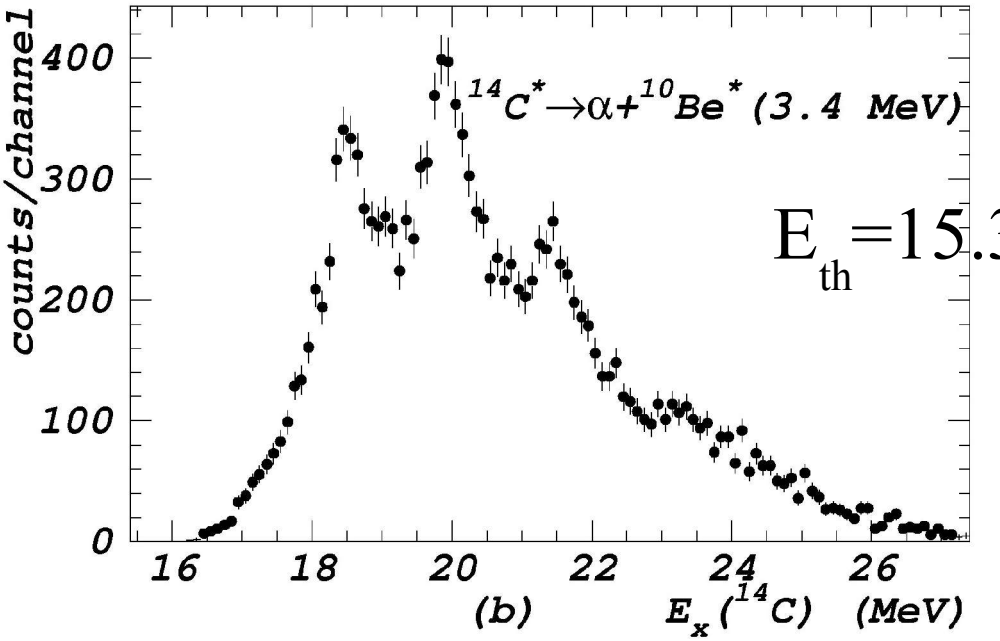
$^{7}Li(^{9}Be,^{14}C^{*}\rightarrow {}^{10}Be+\alpha)^{2}H$

N. Soić et al, Phys. Rev. C **68** (2003) 014321

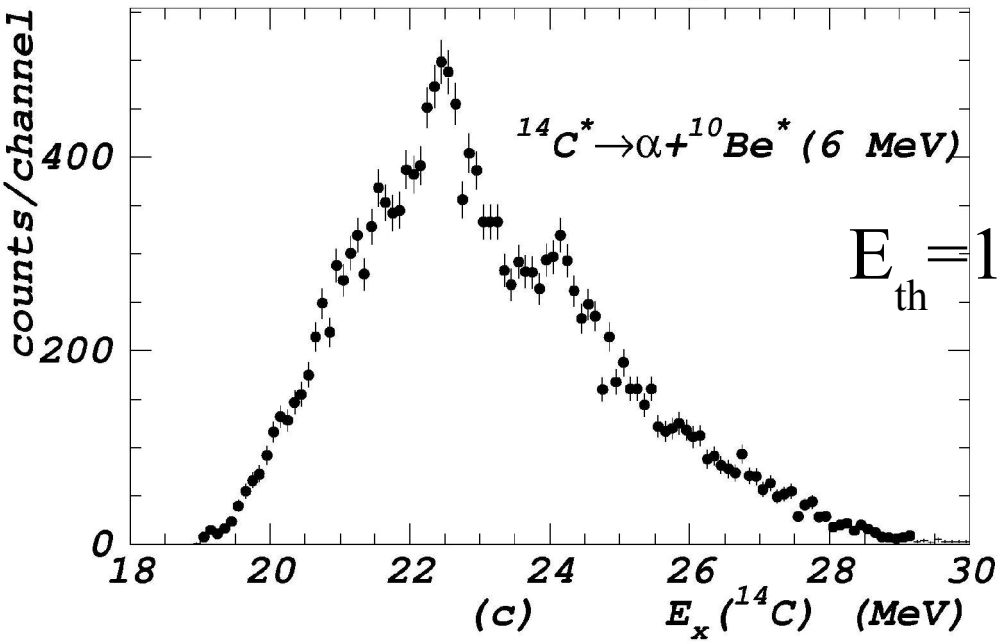




E_{th}=12.012 MeV



E_{th}=15.380 MeV



E_{th}=18.0 MeV

Excitation energies of ^{14}C α-decaying states

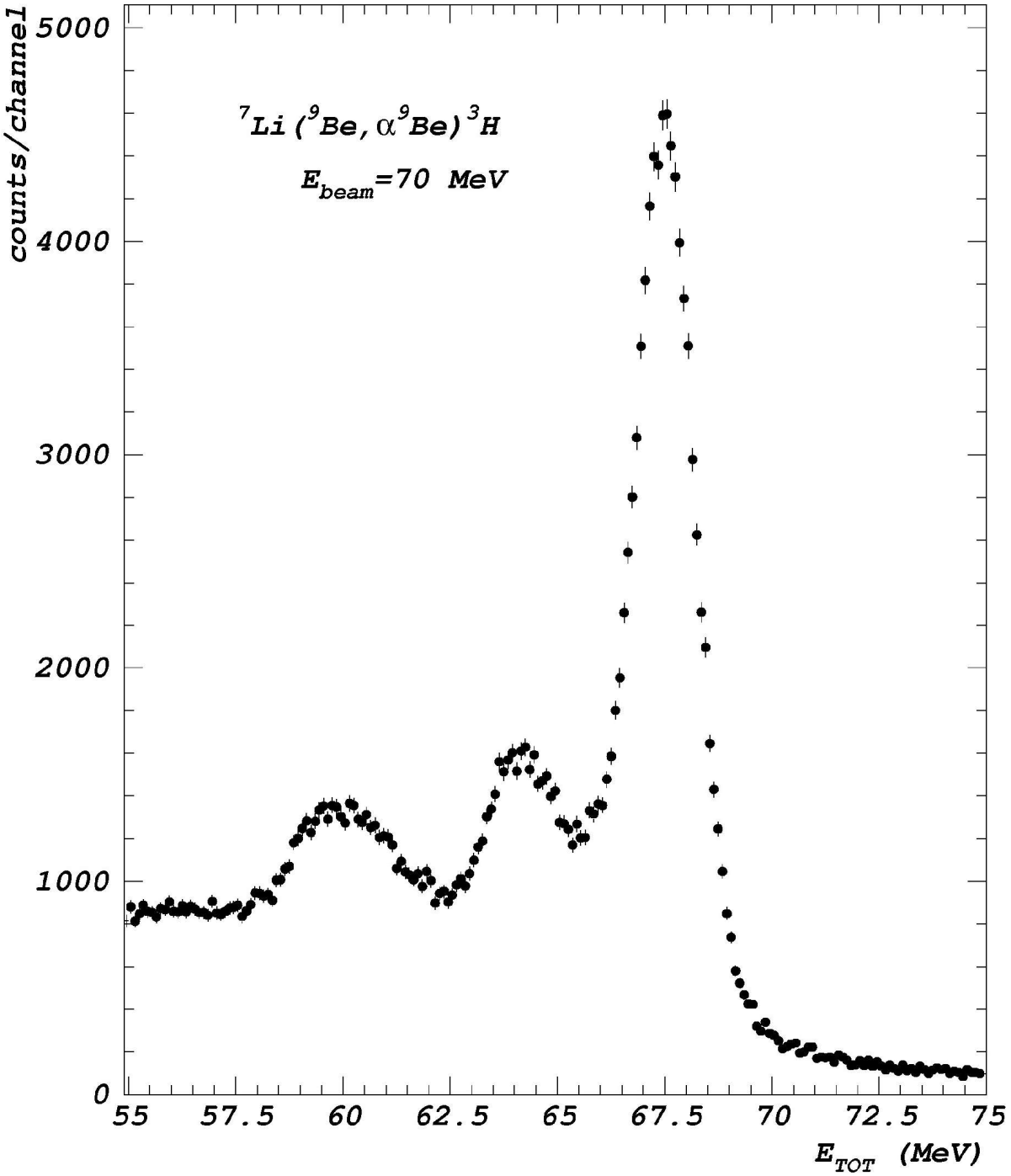
$^{10}Be_{gs}$+α	^{10}Be(2$^+$)+α	^{10}Be(6 MeV)+α	previous
14.7			14.667(4$^+$)
15.5			15.44(3$^-$)
16.4			16.43
18.5	18.5		18.5
	(19.1)		
19.8	19.8		
20.6			20.4
	21.4		(21.4)
		22.4	22.1(2$^-$,T=2)
	(23.2)		23.288
		24.0	24.4(4$^-$,T=2)

- no α-decaying states observed before, our results are the first evidence for α-decay in ^{14}C
- the states which decay to the ground and the first 2$^+$ state are the same, while a distinct set of states decay to the 6 MeV states ⇒ that could reflect their different structure (π and σ neutrons)
- measurements of the spins of these states are required for understanding of their structure

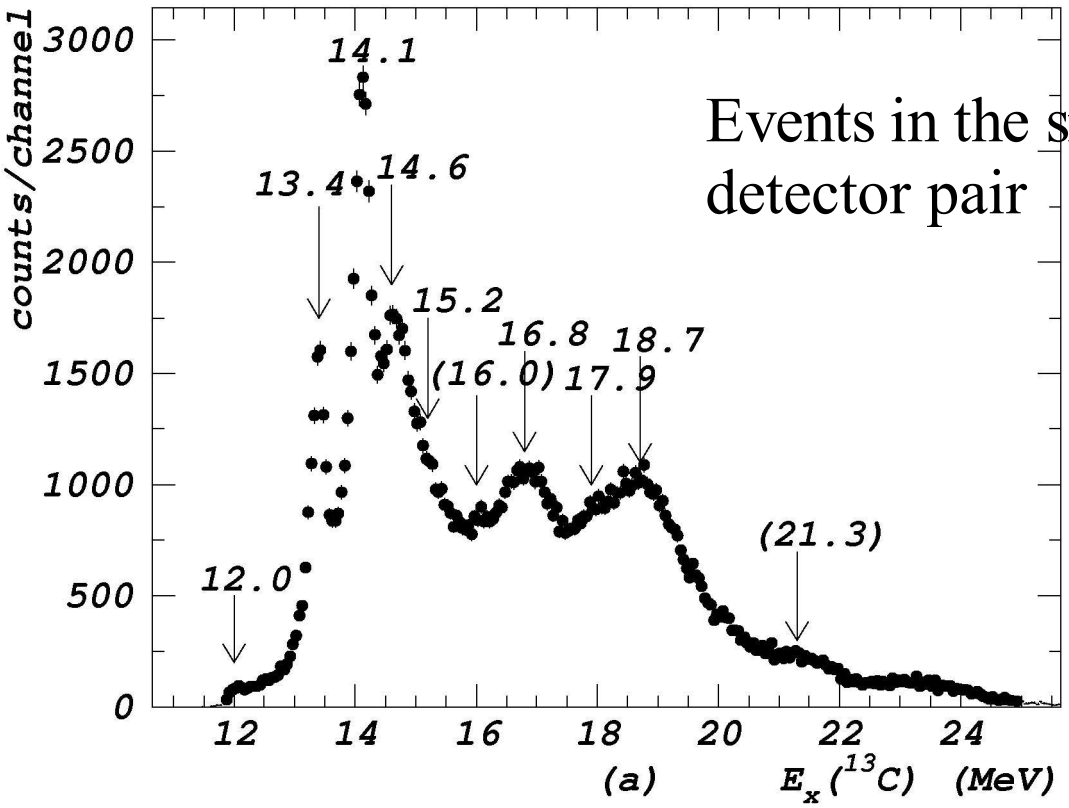
Results: ^{13}C

$^{7}Li(^{9}Be,^{13}C^{*}\rightarrow {}^{9}Be+\alpha)^{3}H$

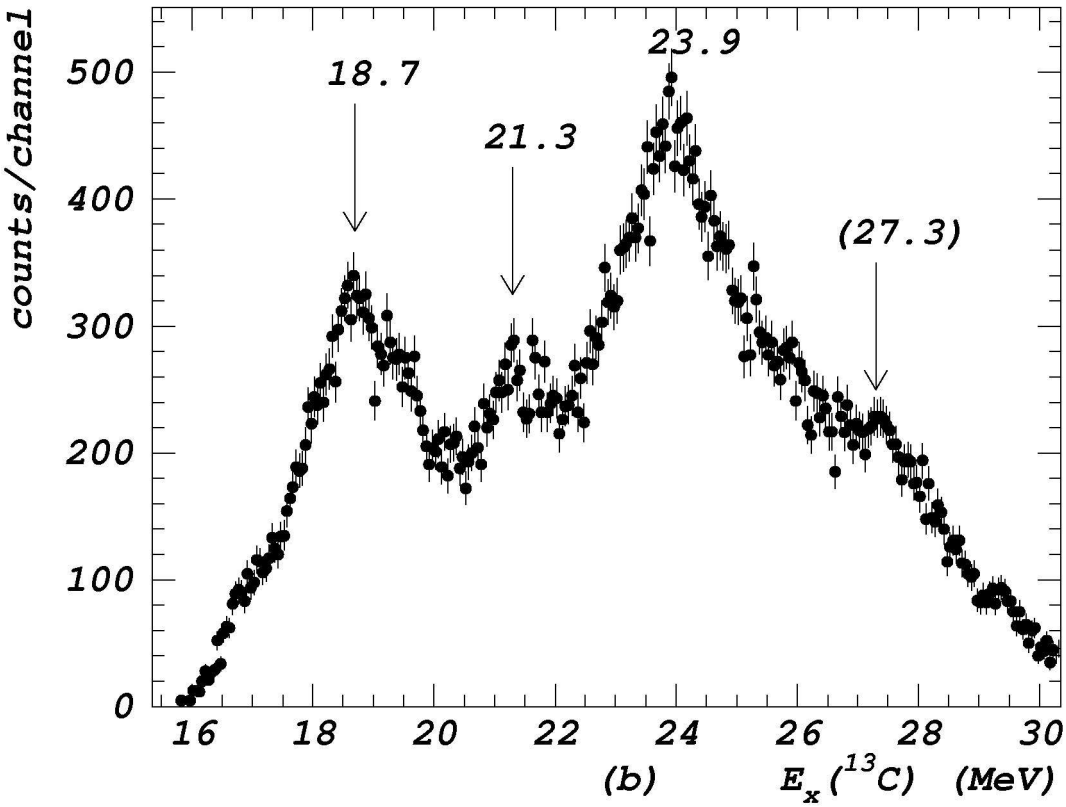
N. Soić et al, Nucl. Phys. A **728** (2003) 12



E_{th}=10.648 MeV



Events in the small angle detector pair



Events in the larger angle detector pair

Excitation energies and widths of α-decaying states

Present	Lee et al, PRC 58 (1998) 1005		Ajzenberg-Selove, NPA 523 (1991) 1		
	5 levels at 10.768-11.711				
	11.841	46	11.848	68	$7/2^+$
12.0	11.96	240	11.95	500	$5/2^+$
			12.106	540	$3/2^+$
			12.13	80	$5/2^-$
			12.14	430	$1/2^+$
	12.8	1000	13.0	broad	
	13.28	310	(13.28)	(340)	
13.4	13.30	33	13.41	35	$(9/2^-)$
	(13.53)	(65)	13.57	620	$7/2^-$
	13.73	77	13.76	300	
	13.92	100			
14.1	14.08	160	14.13	150	$3/2^-$
	14.36	115	14.39	280	
14.6			14.58	230	
(15.2)			15.27		$9/2^+$
(16.0)			16.08	150	$(7/2^+)$
16.8	310		16.95	330	
(17.9)			(17.92)		
18.7	570		18.699	100	
21.3	530		21.28	159	
23.9	1100		24.0	4000	
(27.3)			27.5	1000	

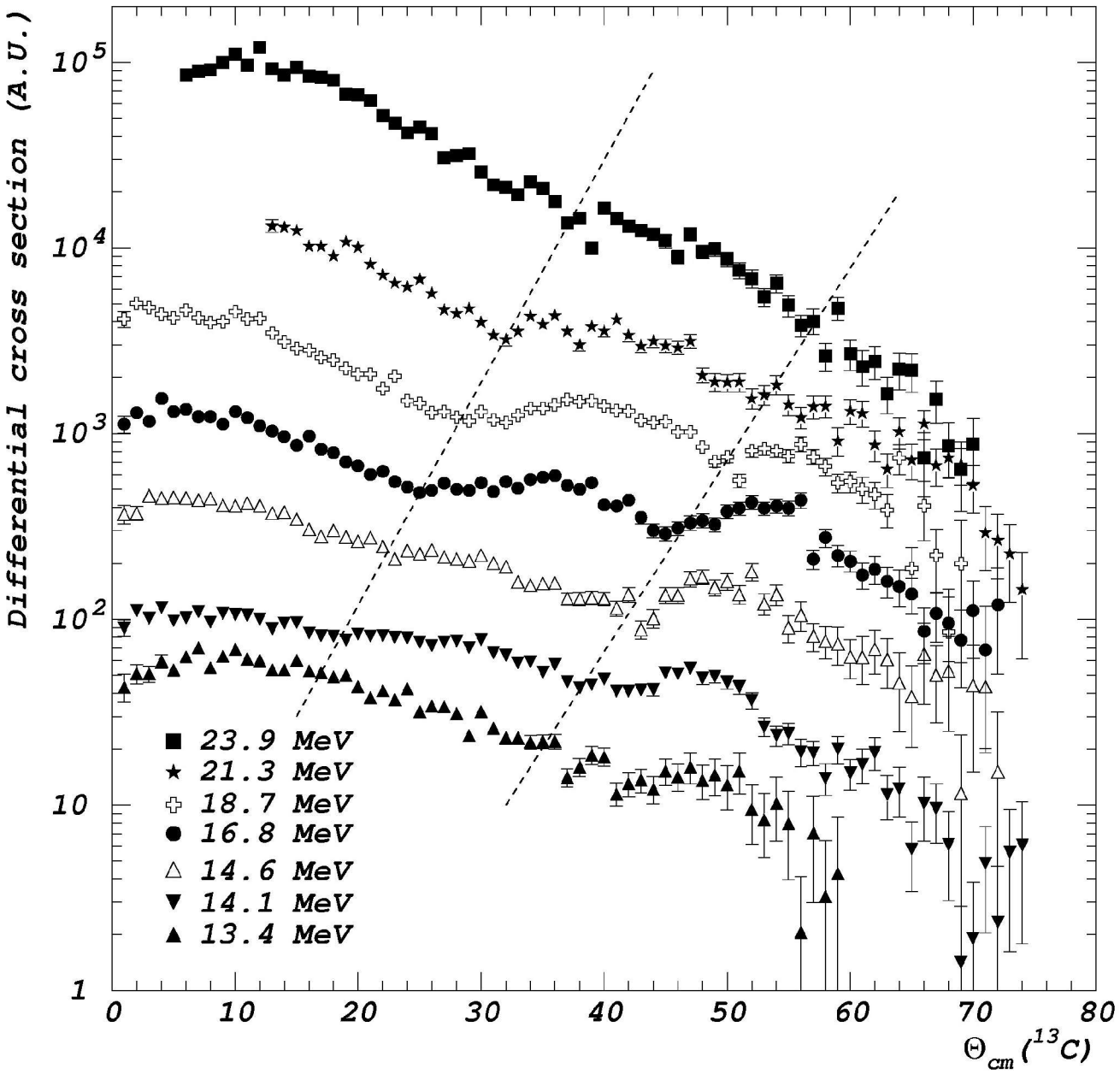
- from the difference in the widths of the states at 18.7, 21.3 and 23.9 MeV $\Rightarrow$ probably new resonances which may possess a structural link with those at lower excitations

Proposed rotational bands in M. Milin, W. von Oertzen, Eur. Phys. J. A 14 (2002) 295

3α+n chain structure

K=3/2$^-$		K=3/2$^+$	
3/2$^-$	9.897	3/2$^+$	11.080
5/2$^-$	10.818	5/2$^+$	11.950
7/2$^-$	12.438	7/2$^+$	13.41
9/2$^-$	14.13	9/2$^+$	15.28
11/2$^-$	16.08	11/2$^+$	16.95

- parity splitting is the consequence of the reflection asymmetric shape
- very large moment of inertia

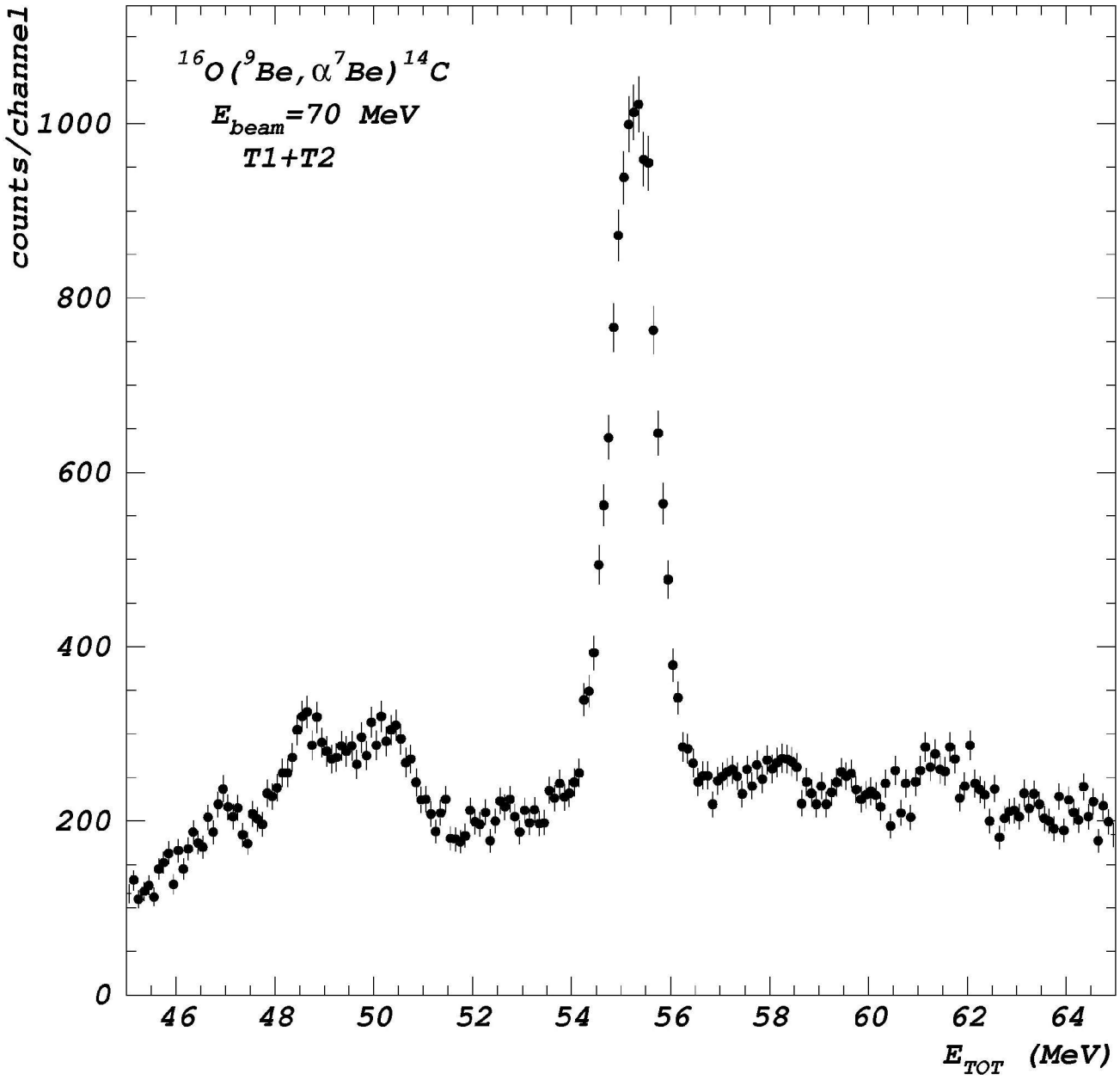


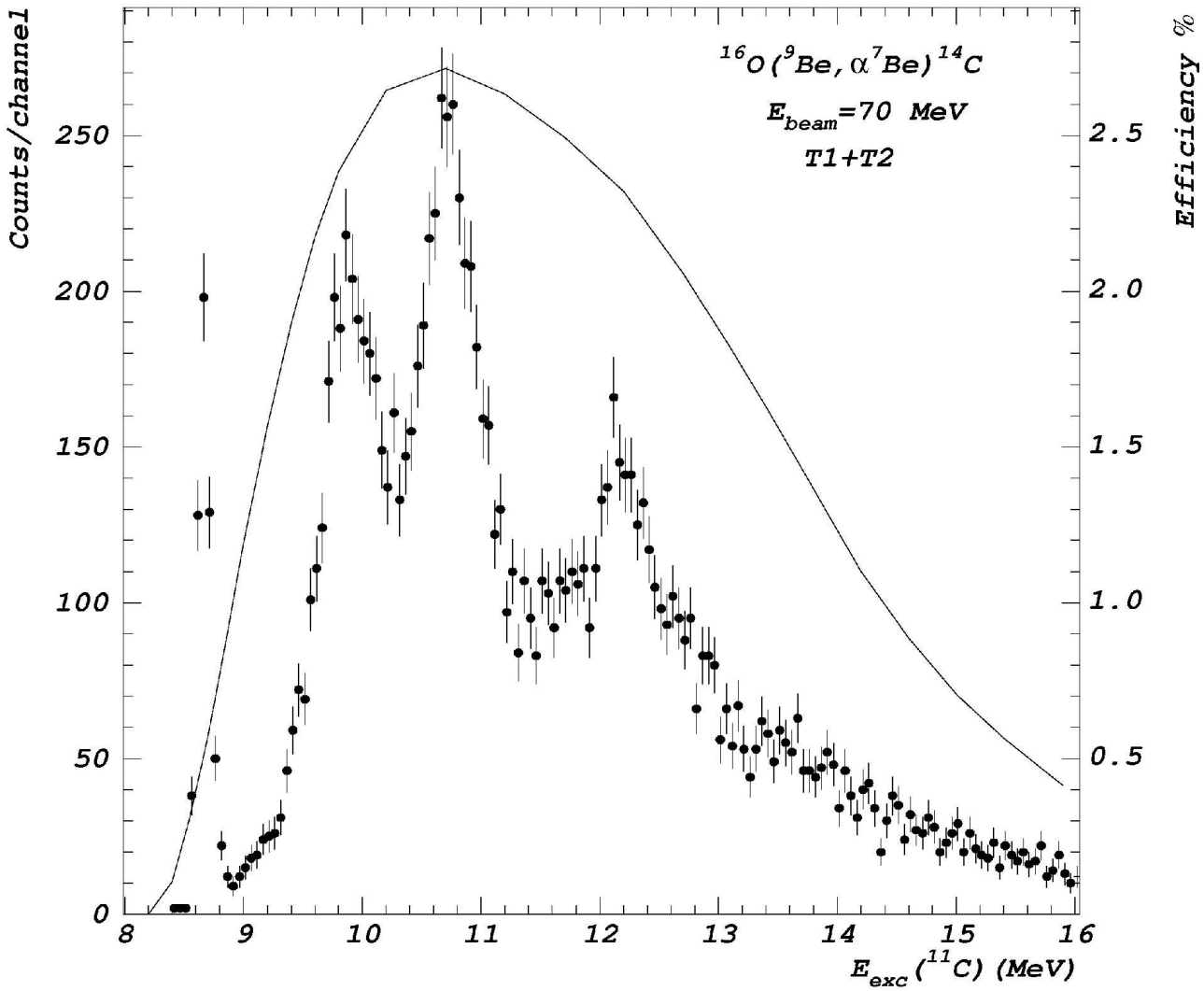
- the angular distributions of the ^{13}C* prior to breakup reconstructed from the measured momenta of the α+^{9}Be are not highly structured
- the minima shift with energy systematically
- indication that the 14.1-21.3 MeV states correspond to the α-transfer to a common orbital
- spin determinations are imperative

Results: ^{11}C

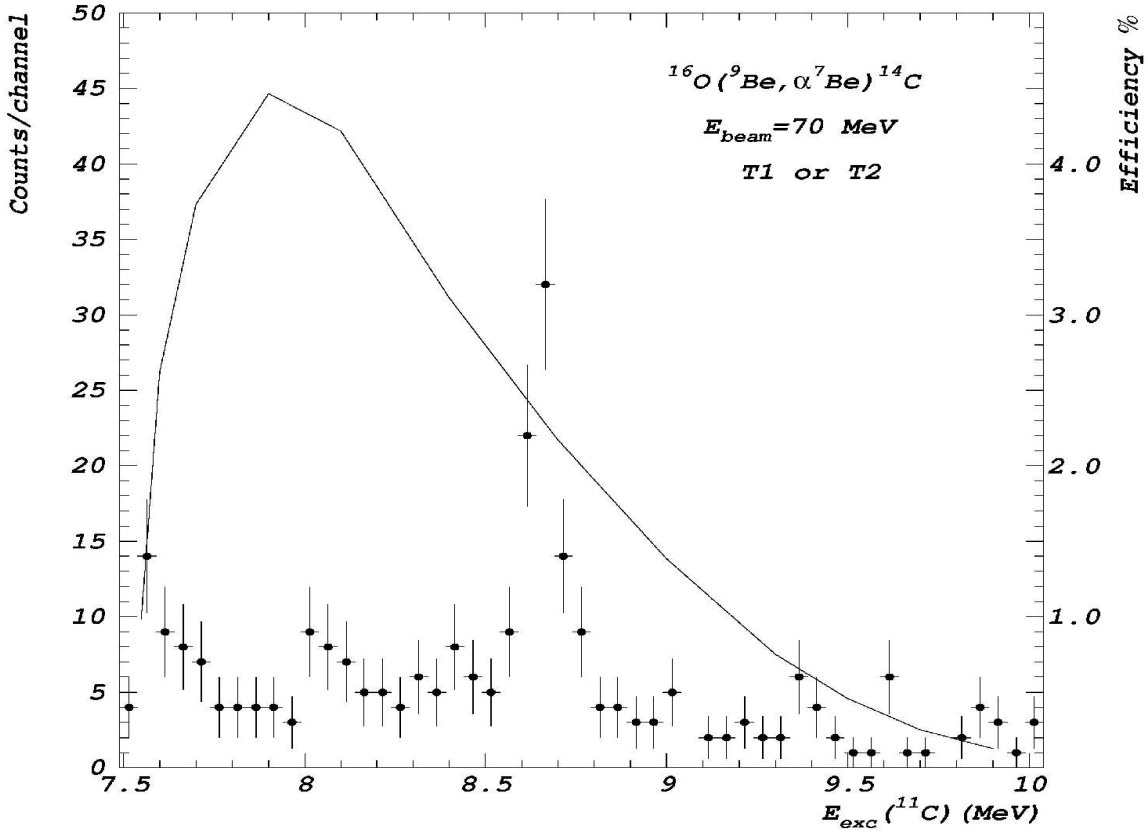
$^{16}O(^{9}Be,^{11}C^{*}\rightarrow {}^{7}Be+\alpha)^{14}C$

- two proton pickup to ^{9}Be




$^{16}O(^{9}Be,\alpha^{7}Be)^{14}C$
E_{beam}=70 MeV
T1+T2
Counts/channel
Efficiency %
$E_{exc}(^{11}C)$ (MeV)

$E_{th} = 7.543$ MeV


$^{16}O(^{9}Be,\alpha^{7}Be)^{14}C$
E_{beam}=70 MeV
T1 or T2
Counts/channel
Efficiency %
$E_{exc}(^{11}C)$ (MeV)

Excited states in ^{11}C decaying into $\alpha+^{7}Be_{gs}$

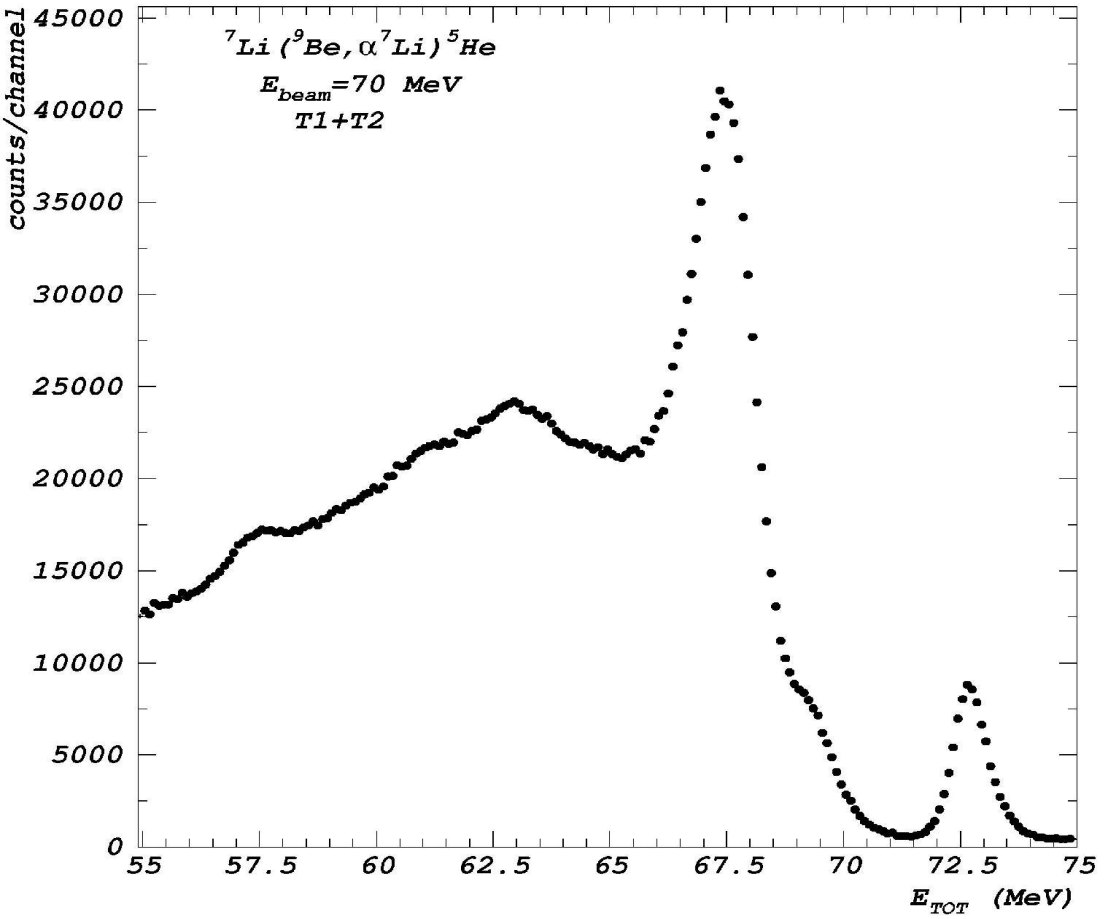
Present	$^{6}Li(^{10}B,\alpha^{7}Be)$ Lee et al, PRC 58 (1998) 1005	Ajzenberg-Selove, NPA 506 (1990) 1		
	8.10	8.1045	11 eV	$3/2^-$
	8.42	8.420	15 eV	$5/2^-$
8.65	8.655	8.655	≤5 keV	$7/2^+$
		8.699	15	$5/2^+$
		9.65	210	$(3/2^-)$
9.85		9.78	240	$(5/2^-)$
		9.97	120	$(7/2^-)$
		10.083	230	$7/2^+$
10.7		10.679	200	$9/2^+$
12.1		12.16	270	T=3/2

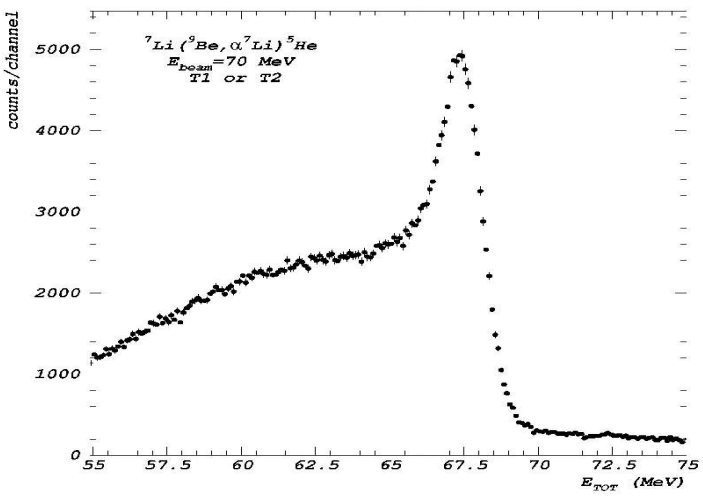
- 12.1 MeV state is proposed to be the isobaric analogue state of the ^{11}Be ground state, but we observe here its strong $\alpha+^{7}Be_{gs}$ decay $\Rightarrow$ it has mixed isospin

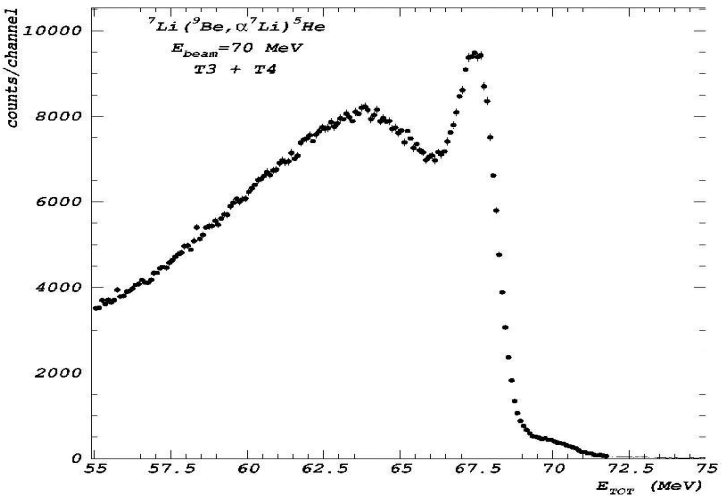
Results: ^{11}B

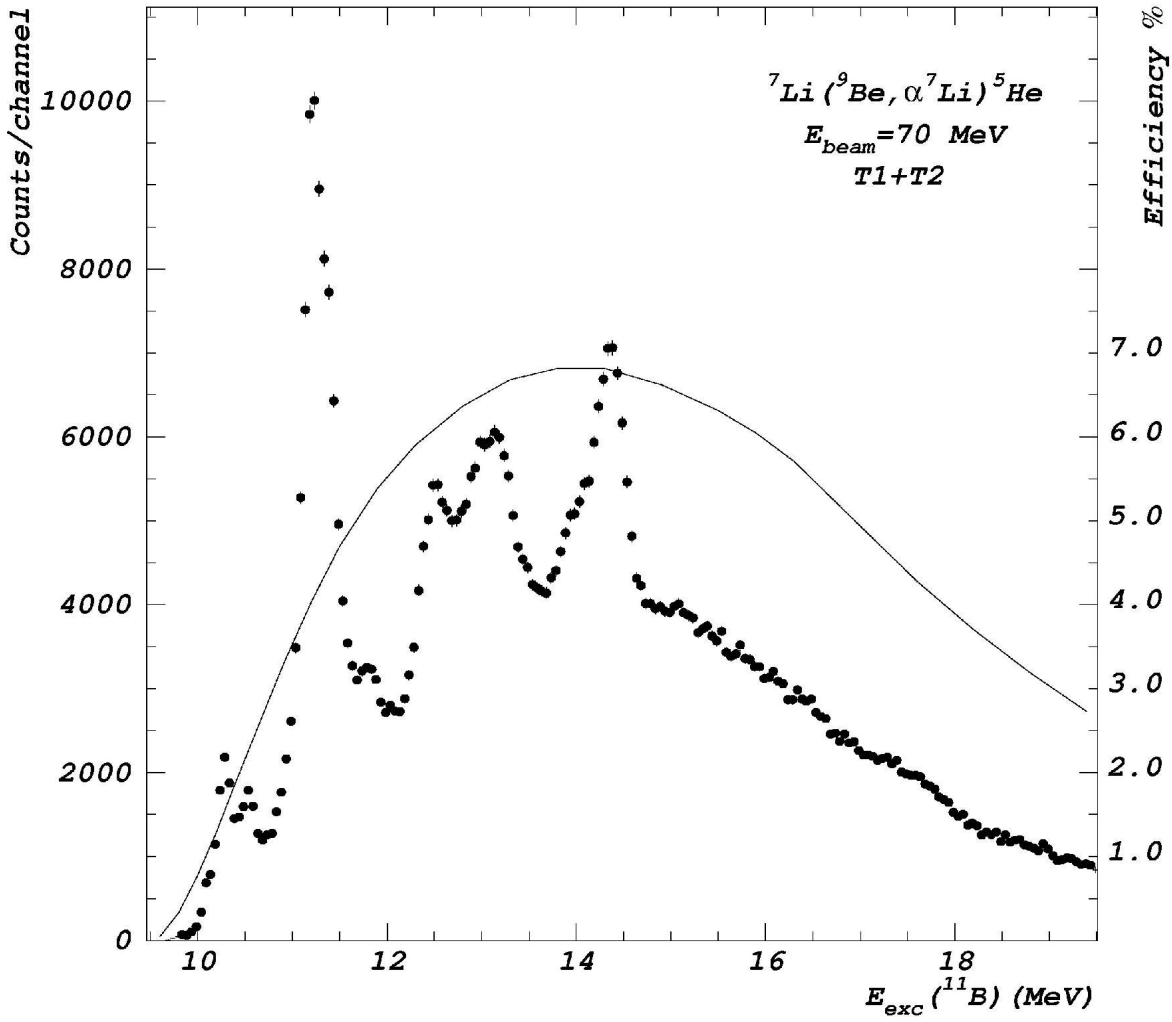
^{7}Li(^{9}Be,^{11}B*→ ^{7}Li+α)^{5}He

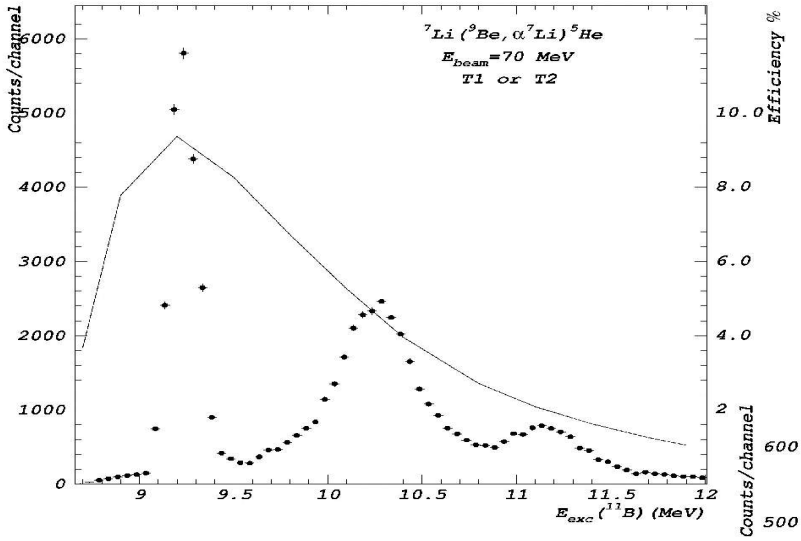
- d pickup to ^{9}Be, α knockout to ^{7}Li



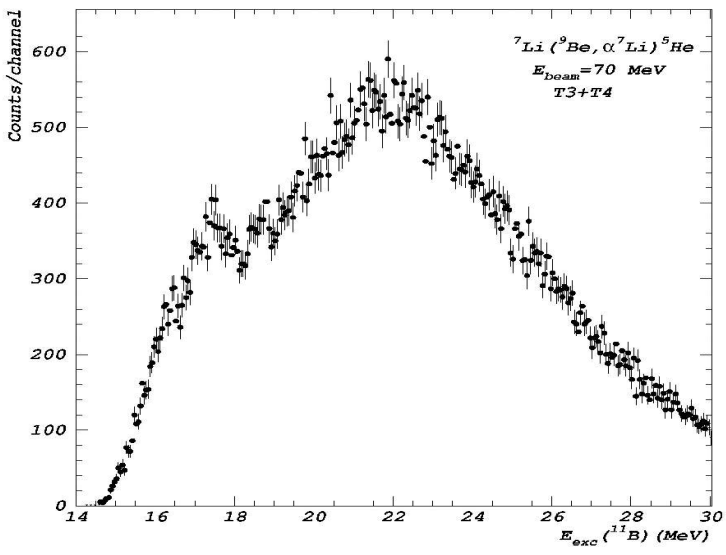





^{7}Li(^{9}Be,α^7Li)^{5}He
E_{beam}=70 MeV
T1+T2
Counts/channel
Efficiency %
E_{exc}(^{11}B) (MeV)


^{7}Li(^{9}Be,α^7Li)^{5}He
E_{beam}=70 MeV
T1 or T2
Counts/channel
Efficiency %
E_{exc}(^{11}B) (MeV)

E_{th}=8.664 MeV


^{7}Li(^{9}Be,α^7Li)^{5}He
E_{beam}=70 MeV
T3+T4
Counts/channel
E_{exc}(^{11}B) (MeV)

Excited states in ^{11}B decaying into $\alpha+^{7}Li_{gs}$

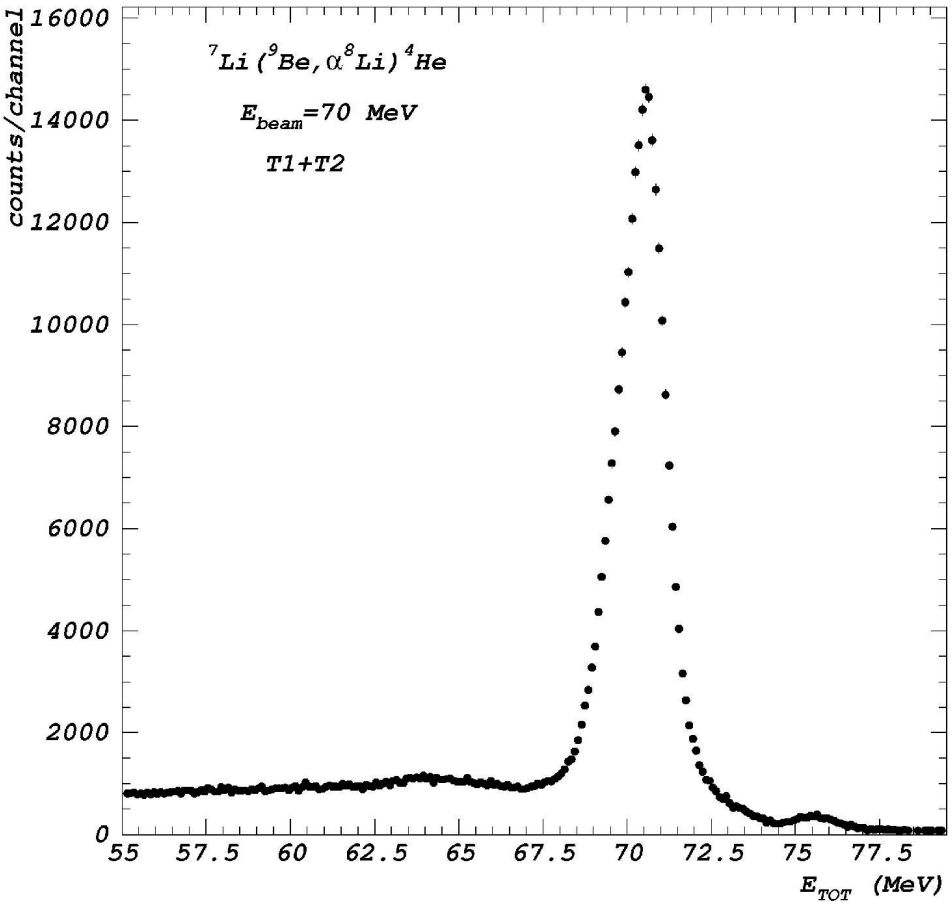
Present	Ajzenberg-Selove, NPA 506 (1990) 1			
9.27	9.1850	2 eV	$7/2^+$	
	9.2744	4 keV	$5/2^+$	
10.25	10.26	150	$3/2^-$	
	10.33	110	$5/2^-$	
10.55	10.597	100	$7/2^+$	
11.2	11.265	110	$9/2^+$	
(11.4)	11.444	103		
11.8	11.886	200	$5/2^-$	
12.5	12.557	210	$1/2^+$	T=3/2
(13.0)	12.916	200	$1/2^-$	T=3/2
13.15	13.137	426	$9/2^-$	
	13.16	430	$5/2^+,7/2^+$	
(14.0)	14.04	500	$11/2^+$	
14.35	14.34	254	$5/2^+$	T=3/2
(17.45)	17.43	100	T=3/2	

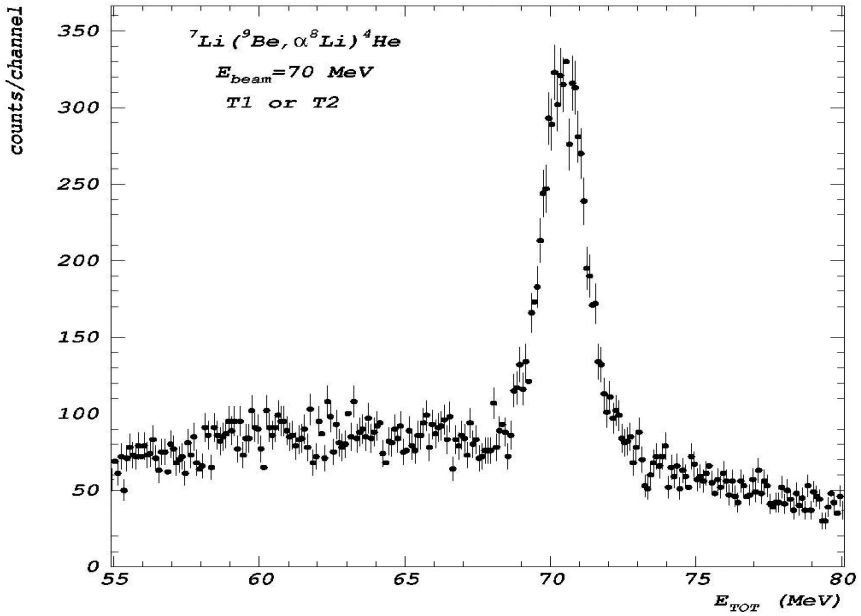
- all of these states are tabulated as α-decaying
- four states observed here proposed to be the isobaric analogue states of the ^{11}Be states $\Rightarrow$ these states have mixed isospin
- we have the same series of states excited in ^{11}B and ^{11}C $\Rightarrow$ the same cluster structure ?

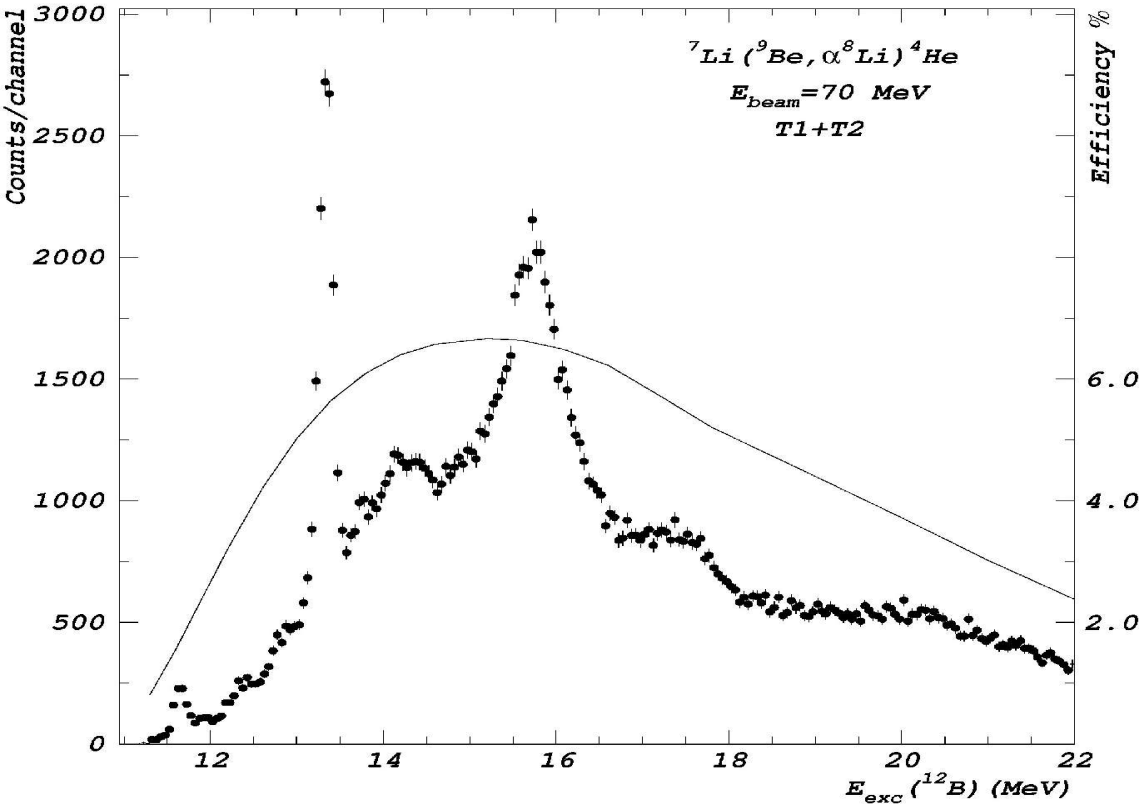
Results: ^{12}B

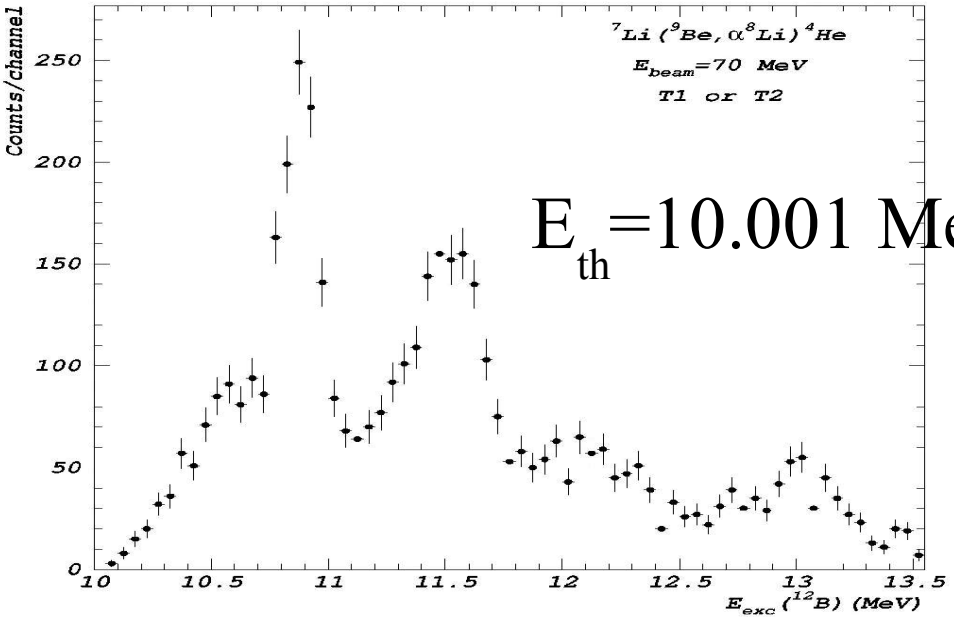
^{7}Li(^{9}Be,^{12}B*→ ^{8}Li+α)^{4}He

- t pickup to ^{9}Be, α+n knockout to ^{7}Li









E_{th}=10.001 MeV

- observed states at 10.9, 11.6, 13.4, (14.1), 15.7 and (17.4) MeV
- the same states observed in the first report on α-decaying states in ^{12}B (N.Soić et al, Europhys. Lett. **63** (2003) 524)
- spin determination !

Summary and Future Prospects

- it was demonstrated that breakup studies provide an effective spectroscopic tool, particularly for cluster states
- reported experimental results on the α-decay of excited states in ^{11,13,14}C and ^{11,12}B indicate cluster structure in these nuclei
- observed states are good candidates for states with molecular structure based on α-particles
- the determination of the spins and parities as well as partial widths of the observed states are imperative in order to fully understand structure of C and B isotopes
- molecular structures could also appear in nuclei similar to these studied here: heavier Be, B and C isotopes, neutron rich nuclei based on α+^{16}O structure ...
- similar experiments are already performed or planned in the next future to probe the molecular/cluster states in these systems