Cluster Dscay of the High-lying Excited States in ^{14}C

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Outline

I. Some background

II. The experiment

III. Preliminary results

IV. Summary

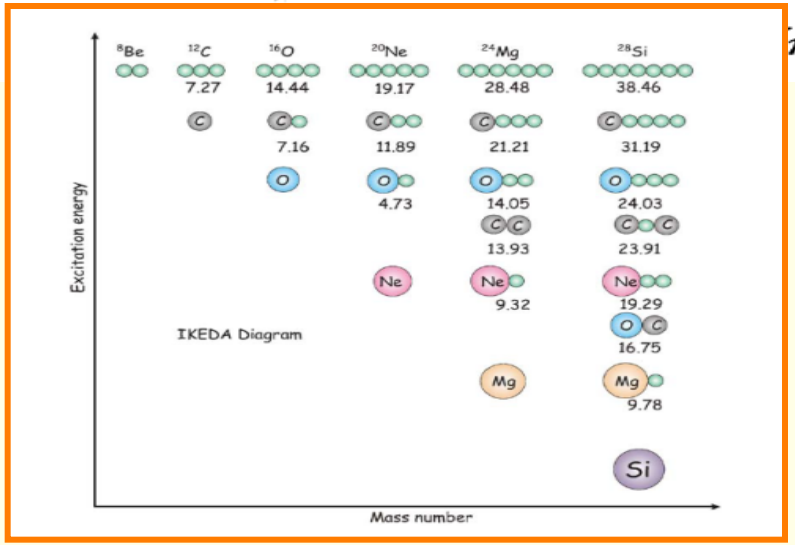
The threshold rule in cluster formation

464 Supplement of the Progress of Theoretical Physics, Extra Number, 1968

The Systematic Structure-Change into the Molecule-like Structures in the Self-Conjugate 4*n* Nuclei

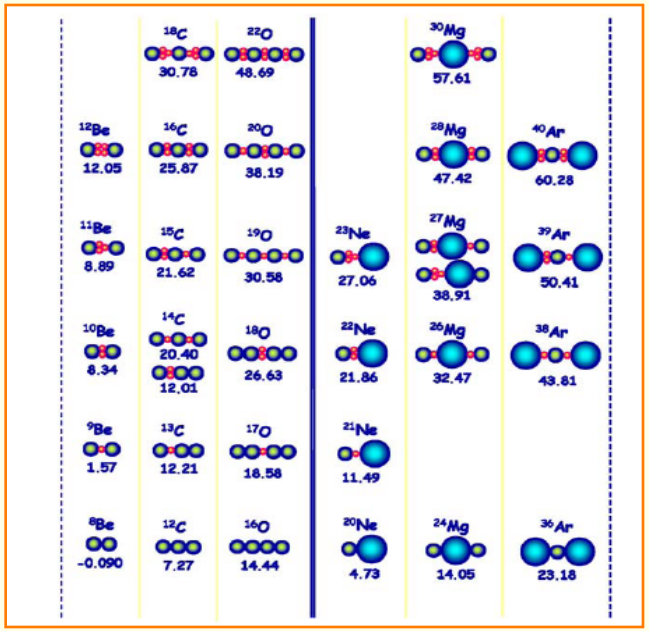
Kiyomi IKEDA,*) Noboru TAKIGAWA and Hisashi HORIUCHI

niversity of Tokyo, Tokyo



"Ikeda diagram"

Clustering in unstable nuclei – a new area



W.Von Oerttzen et al., Phys. Report 432(06)43

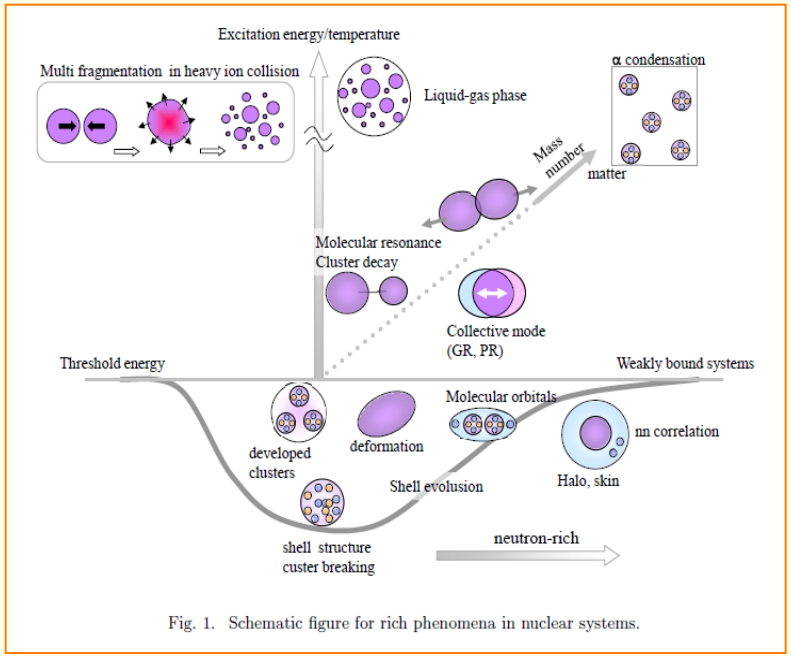
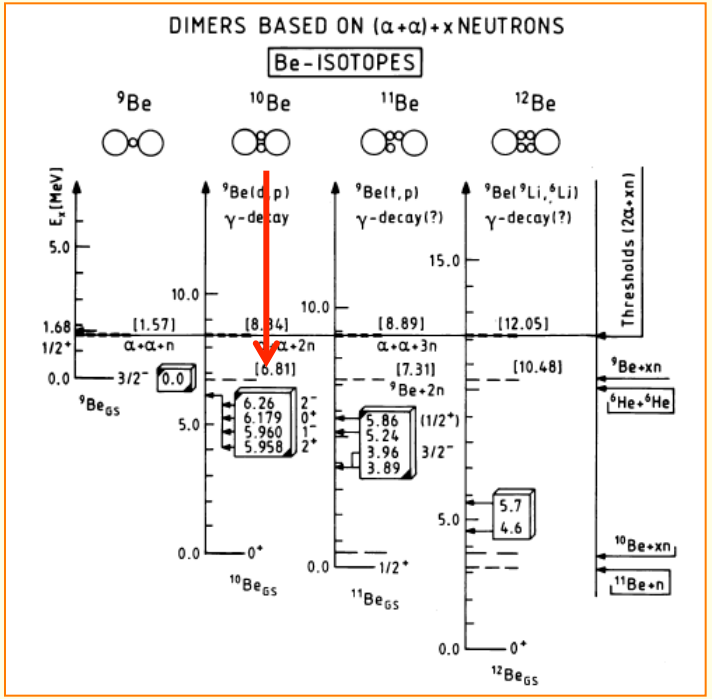


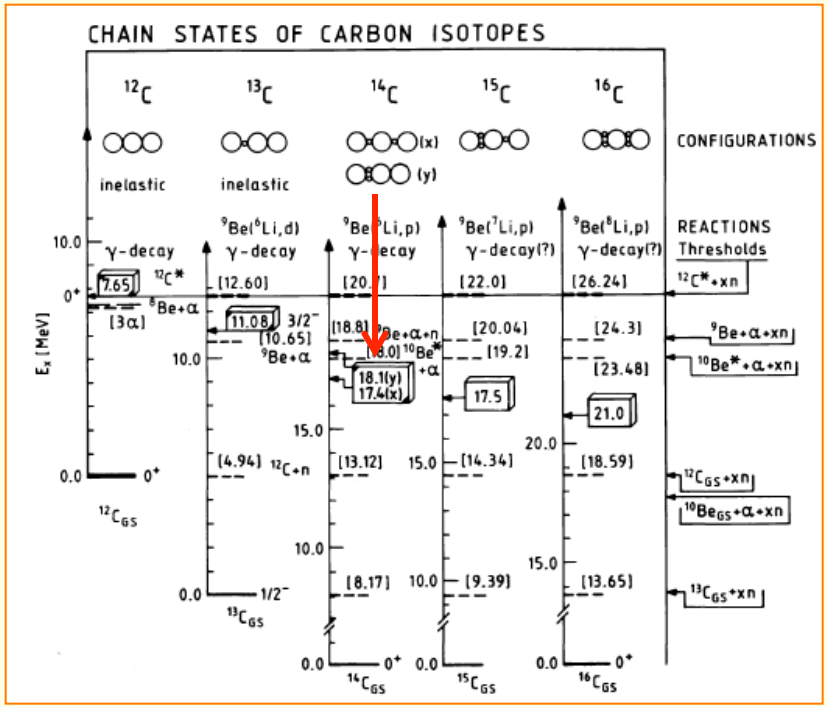
Fig. 1. Schematic figure for rich phenomena in nuclear systems.

Y. Kanada-En'yo et al., Prog. Theor. Exp. Phys., 2012, 01A202

Possible chain states based on α-cores

^{8}Be(2α)





W.Von Oerttzen et al., Z. Phys. A357(97)355.

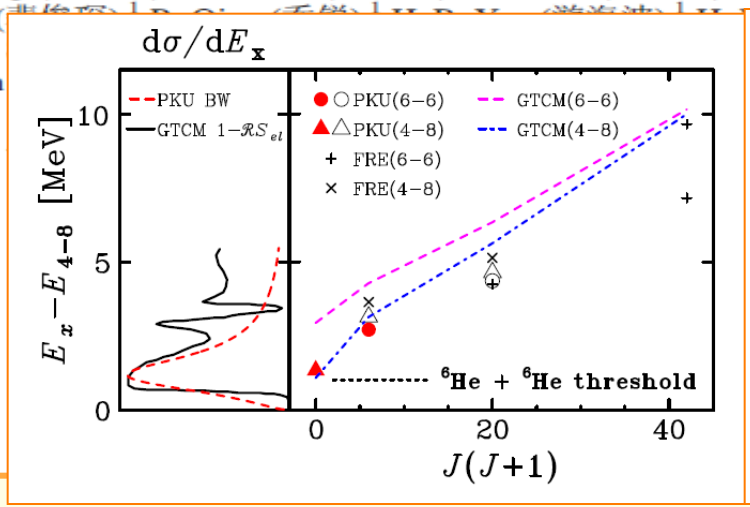
Example of studies for ^{x}Be

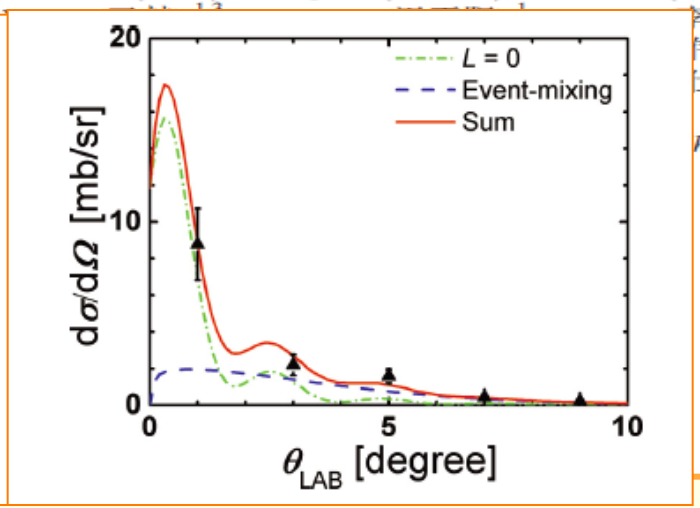
PRL 112, 162501 (2014) PHYSICAL REVIEW LETTERS week ending 25 APRIL 2014

Observation of Enhanced Monopole Strength and Clustering in ^{12}Be

Z. H. Yang (杨再宏),[1] Y. L. Ye (叶沿林),[1,*] Z. H. Li (李智焕),[1] J. L. Lou (楼建玲),[1] J. S. Wang (王建松),[2] D. X. Jiang (江栋兴),[1] Y. C. Ge (葛愉成),[1] Q. T. Li (李奇特),[1] H. Hua (华辉),[1] X. Q. Li (李湘庆),[1] F. R. Xu (许甫荣),[1] J. C. Pei (裴俊辉),[1] R. Qiao (乔锴),[1] H. B. Yu (俞海波),[1,3] 李阔昂),[1] Y. L. 伟),[1] C. Wen 仕纶),[2]

[1]State hina





PHYSICAL REVIEW C 91, 024304 (2015)

Helium-helium clustering states in ^{12}Be

SCIENCE CHINA
Physics, Mechanics & Astronomy
September 2014 Vol. 57 No. 9: 1613–1617

^{x}C: triangle, and π-bond or σ-bond linear-chain states

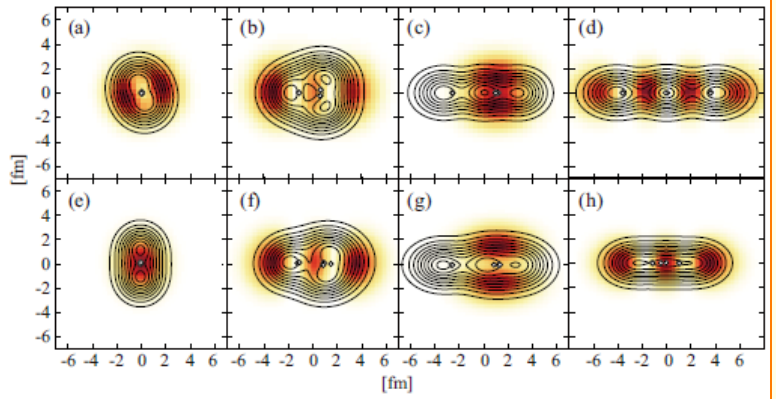
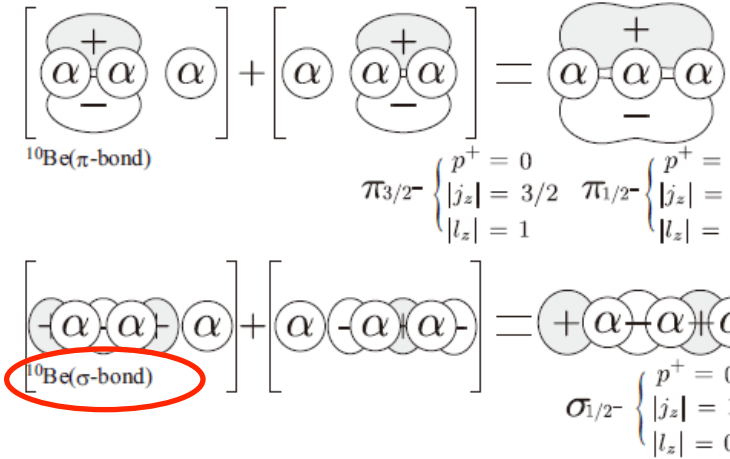


FIG. 2. (color online) The density distribution of (a)-(d) the positive states and (e)-(h) negative parity states. The contour lines show the proton density distributions. The color plots show the single particle orbits occupied by the most weakly bound neutron. Open boxes show the centroids of the Gaussian wave packets describing protons.

π-bond or σ-bond



most exotic one: σ-bond linear-chain state

T. Baba and M. Kimura arXiv:1605/05567v1

Latest AMD calculations for ^{14}C

T. Baba and M. Kimura arXiv:1605/05567v1

Major improvements:

- Gogny D1S force to better describe E_x;
- Projected single particle wave function for valence neutrons to distinguish the π-bond or σ-bond states;
- core excitation included and the reduced decay-width deduced accordingly.

$$E'^{\pi} = \frac{\langle \Phi^{\pi} | H | \Phi^{\pi} \rangle}{\langle \Phi^{\pi} | \Phi^{\pi} \rangle} + v_{\beta}(\langle \beta \rangle - \beta_0)^2 + v_{\gamma}(\langle \gamma \rangle - \gamma_0)^2$$

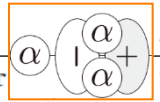
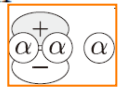
$$\widetilde{\phi}_s = \sum_{\alpha=1}^{A} f_{\alpha s} \widetilde{\varphi}_{\alpha}.$$

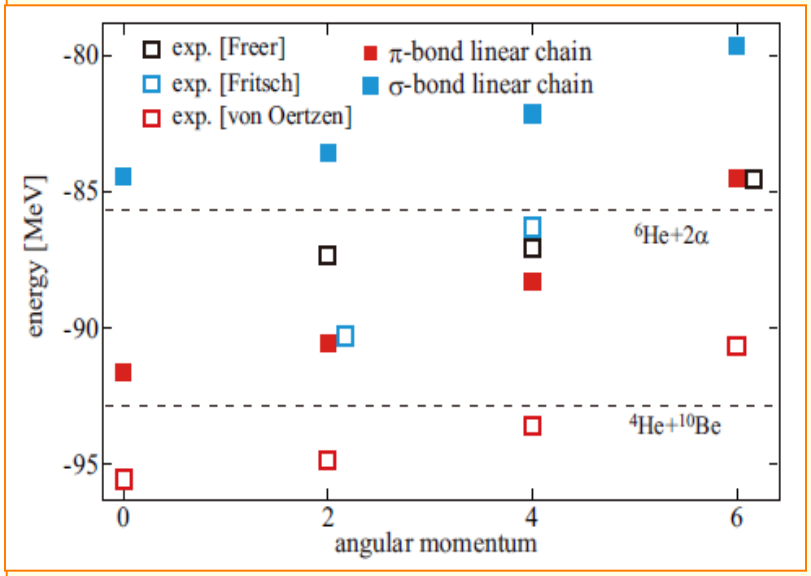
$$j(j+1) = \langle \widetilde{\phi}_s | \hat{j}^2 | \widetilde{\phi}_s \rangle, \quad |j_z| = \sqrt{\langle \widetilde{\phi}_s | \hat{j}_z^2 | \widetilde{\phi}_s \rangle},$$

$$l(l+1) = \langle \widetilde{\phi}_s | \hat{l}^2 | \widetilde{\phi}_s \rangle, \quad |l_z| = \sqrt{\langle \widetilde{\phi}_s | \hat{l}_z^2 | \widetilde{\phi}_s \rangle},$$

$$\gamma^2_{lj^{\pi'}}(a) = \frac{\hbar^2}{2\mu a}[a y_{lj^{\pi'}}(a)]^2$$

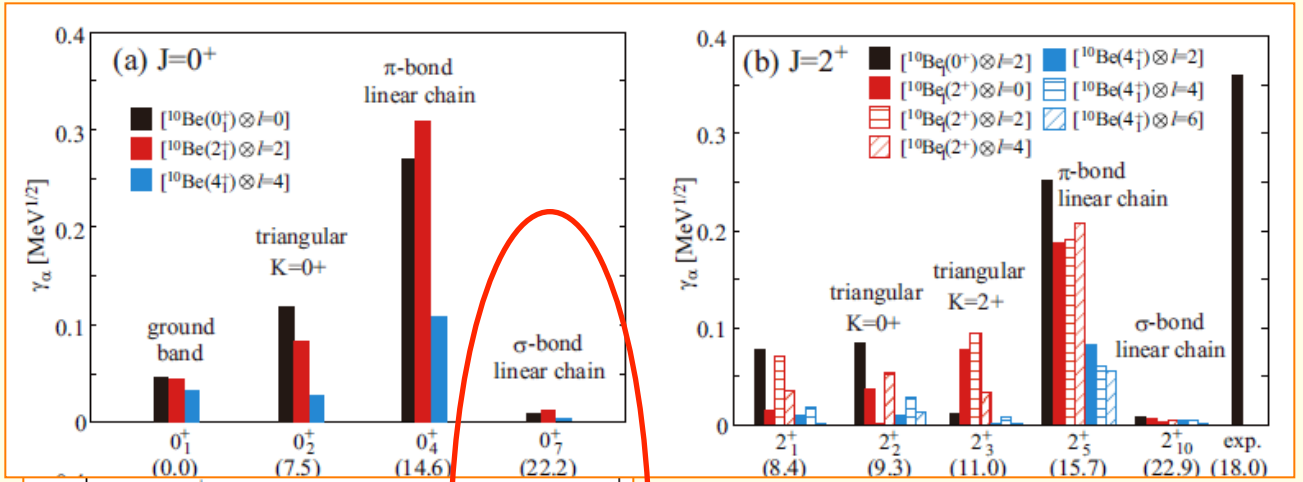
$$y_{lj^{\pi'}}(r) = \sqrt{\frac{A!}{4!(A-4)!}} \langle \phi_{\alpha}[\phi_{\mathrm{Be}}(j^{\pi'}) Y_{l0}(\hat{r})]_{J^{\pi}M} | \Psi^{J^{\pi}}_{Mn} \rangle,$$

band	J^π	E_x	r_p	r_n
ground	0_1^+	0.00	2.53	2.58
	2_1^+	8.41	2.58	2.69
		(7.01)	(2.34)	
triangular	0_2^+	7.49	2.67	2.92
$K^\pi = 0^+$	2_2^+	9.26	2.64	2.83
	4_1^+	12.00	2.65	2.89
triangular	2_3^+	10.99	2.68	2.92
$K^\pi = 2^+$	3_1^+	12.03	2.68	2.92
	4_2^+	13.83	2.68	2.92
π-bond	0_4^+	14.64	3.27	3.20
linear chain	2_5^+	15.73	3.37	3.28
	4_5^+	17.98	3.33	3.24
	6_2^+	21.80	3.39	3.30
σ-bond	0_7^+	22.16	3.91	4.12
linear chain	2_{10}^+	22.93	4.02	4.21
	4_{11}^+	24.30	3.97	4.15



T. Baba and M. Kimura arXiv:1605/05567v1

Decay width is related to the cluster-configuration

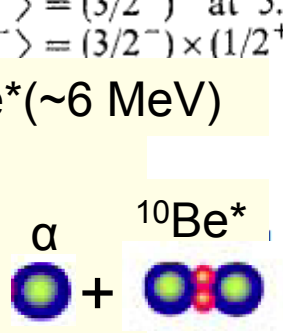


T. Baba and M. Kimura
arXiv:1605/05567v1

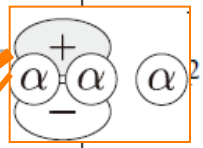
1) $|0^+\rangle = (3/2^-)^2 a + (1/2^+)^2 b$ at 6.179 MeV
2) $|1^-\rangle = (3/2^-) \times (1/2^+)$ at 5.960 MeV
3) $|2^+\rangle = (3/2^-)^2$ at 5.9583 MeV
4) $|2^-\rangle = (3/2^-) \times (1/2^+)$ at 6.263 MeV

^{10}Be*(~6 MeV)

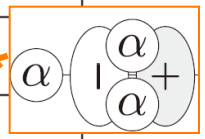
α + ^{10}Be*



σ-bond linear-chain



π-bond linear-chain



triangle

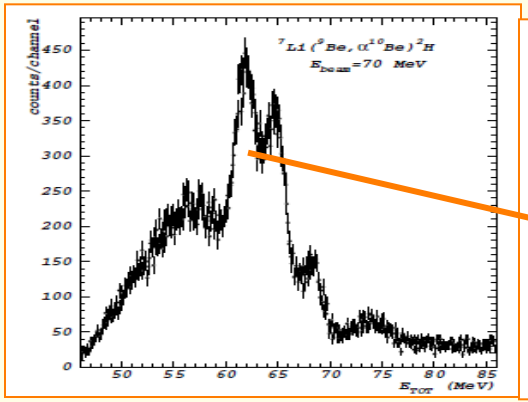
^{10}Be

Experimental probes

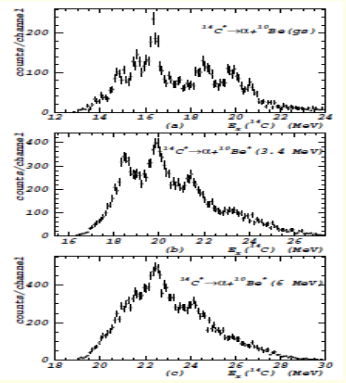
^{14}C

Previous ^{14}C experiments with ^{10}Be*(~6 MeV) selection

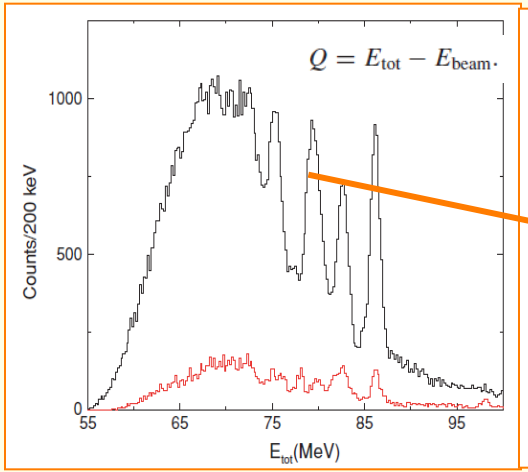
N. Soic, M. Freer et al., PRC68(2003) 014321; ^{7}Li(^{9}Be, ^{4}He^{10}Be)^{2}H, E_{beam}=70 MeV



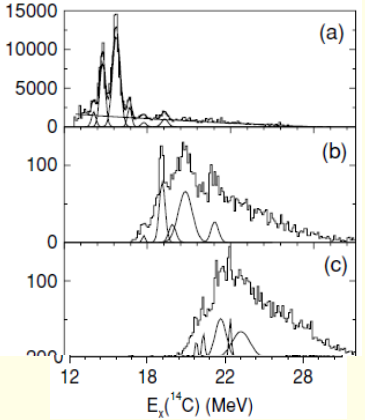
^{10}Be$_{gs}$	^{10}Be(2^{+})	^{10}Be(6 MeV)	Previous
14.7(0.1)			14.667 (4^{+})
15.5(0.1)			15.44 (3^{-})
16.4(0.1)			16.43
18.5(0.1)	18.5(0.1)		18.5
	[19.1(0.1)]		
19.8(0.1)	19.8(0.1)		
20.6(0.1)			
	21.4(0.1)		
		22.4(0.3)	
	[23.2(0.1)]		
		24.0(0.3)	



D.L. Proce, M. Freer et al., PRC75(2007) 014305; ^{14}C(^{14}C, ^{4}He^{10}Be)^{14}C, E_{beam}=98.2 MeV



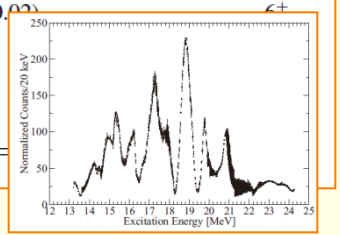
^{10}Be$_{gs}$ + α	^{10}Be(2^{+}, 3.37 MeV) + α	^{10}Be(6 MeV) + α
14.3(1)		
14.8(1)		
15.6(1)		
16.4(1)		
17.3(1)	17.3(1)	
(18.1)		
18.6(1)	**18.4(1)**	
	(19.0(2))	
	19.8(1)	
		20.4(1)
		20.9(1)
	(21.6(2))	*(21.9(1))*
		(22.5(1))
		(23.1(2))



Recently reported results: no selection on ^{10}Be*(~6 MeV)

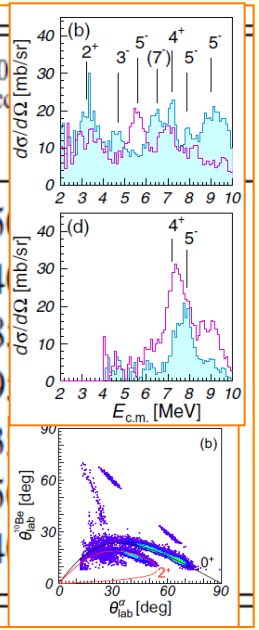
E_x	E_x	J^π
14.3(1)	Present measurements	
14.8(1)	possess features	
15.55(10)[a]	consistent with	
15.9	these states	
16.43(10)		
17.3(1)	17.32(0.02)	3^-
18.1	17.97(0.02)	2^+
	18.22(0.02)	4^+
18.5(1), 18.6(1)	18.82(0.02)	5^-
19.07(1)		
19.3(1)		
19.83(1)	19.67(0.02)	5^-
20.3(1)		
20.6(1)	20.80(0.02)	6^+
21.43(1)		
22.45(3)		
23.15(1)		
24.0(3)		

[a]Assigned $J^\pi = 3^-$ in Ref. [12].



M. Freer et al., PRC90(2014) 054324; α(^{10}Be, α)^{10}Be, E_x=13 to 24 MeV

$E_{c.m.}$ [MeV]	E_x [MeV]	J^π	$\lvert U^0_{c\alpha}$
3.0	15.0	2^+	0.5
4.7	16.7	3^-	0.4
5.6	17.6	5^-	0.8
6.5	18.5	(7^-)	0.9
7.0	19.0	4^+	0.3
7.9	19.9	5^-	0.5
8.7	20.7	5^-	0.4



A. Fritsch et al., PRC93(2016)014321; α(^{10}Be, α)^{10}Be, E_x=15.0 to 20.7 MeV

Possible observation of the triangle-like and π-bond linear-chain states, but not σ-bond states.

Outline

I. Some background

II. The experiment

III. Preliminary results

IV. Summary

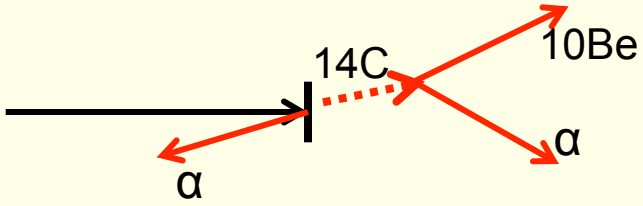
Basic considerations for experimentation

- Projectile and target in favor of cluster formation
- Large Q-value reaction in order to excite high lying states in ^{14}C and to have a good selection of the states in ^{10}Be fragment;
- MM + IM measurements in order to extract the reduced cluster-decay width from branching ratio.

selected reaction (5 AMeV beam; 185 ug/cm^2 target) **:**

$$^{9}\mathrm{Be} + {}^{9}\mathrm{Be} \rightarrow {}^{4}\mathrm{He} + {}^{14}\mathrm{C} \qquad Q=17.25\ \mathrm{MeV}$$

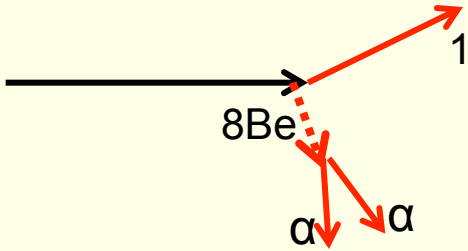
a $\quad {}^{4}\mathrm{He} + {}^{10}\mathrm{Be} \qquad Q=5.239\ \mathrm{MeV}$



main contamination in Q-value:

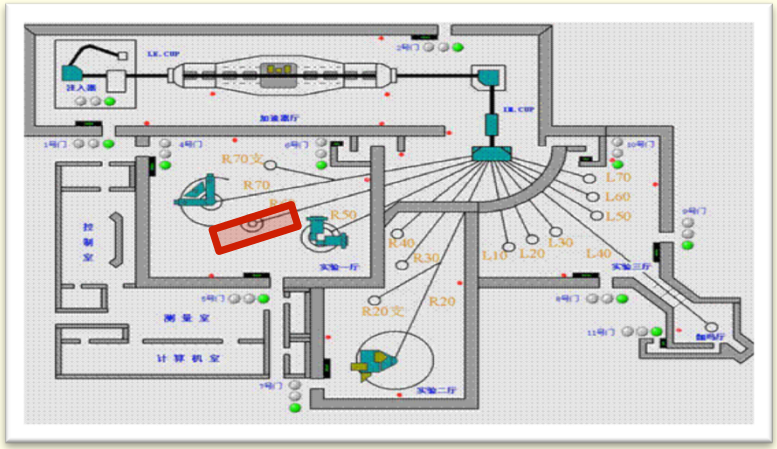
$$^{9}\mathrm{Be} + {}^{9}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + {}^{8}\mathrm{Be} \qquad Q = 5.148\ \mathrm{MeV}$$

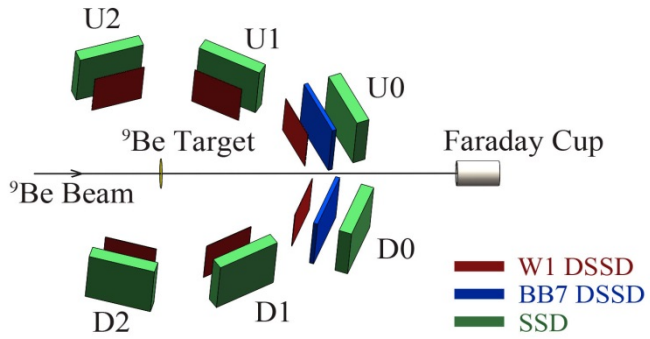
a $\quad {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$



can be removed via kinematics analysis

Experiment setup at CIAE

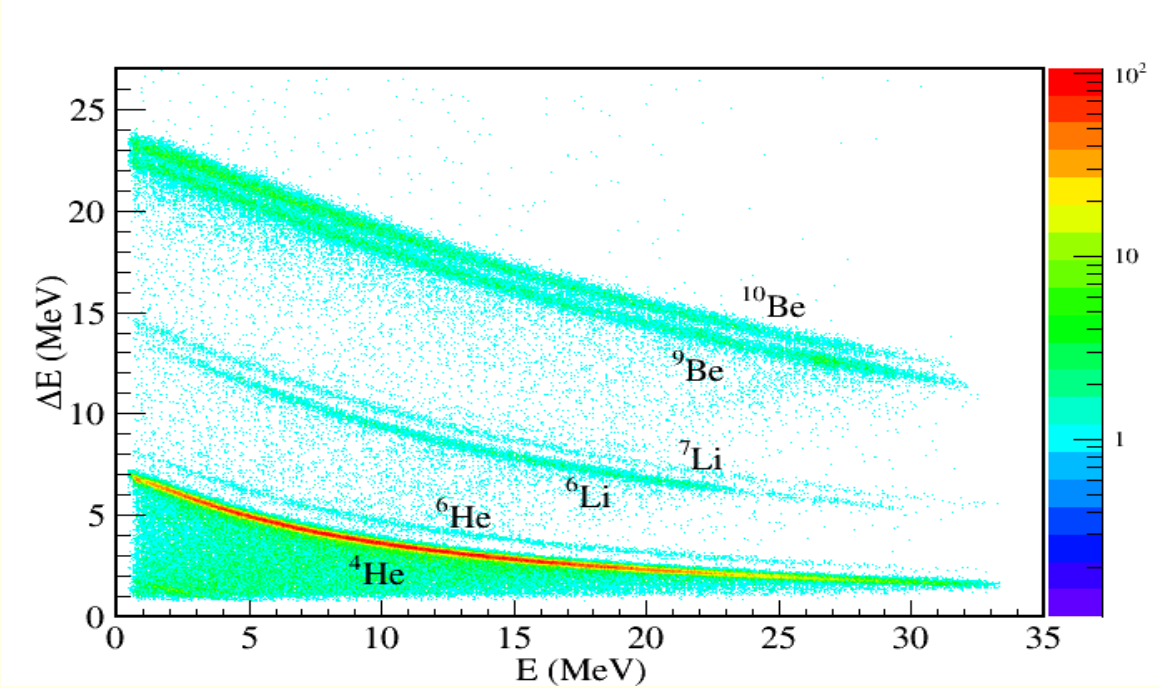




Detector	Segmen-tation	Thickness (μm)	Covering angle (degree)	Purpose
Telescope U0&D0	U0&D0 are symme-trical		13-33	10Be&alpha from 14C Alpha（14C）
DSSD	16 x 16	64		ΔE
DSSD	32x32	500		E
SSD		1500		E(4He)
Telescope U1&D1	U0&D0 are symme-trical		48-72	Alpha（14C）
DSSD	16*16	60		ΔE
SSD		1500		E
Telescope U2&D2	symmetrical		97-121	Alpha(14C)
DSSD	16	20		ΔE
SSD		1500		E

Beam	⁹Be	45MeV	~7enA
Target	⁹Be	0.9um	

Typical PID at forward angles



^{9}Be(^{9}Be,^{14}C[^{10}Be+α])α

Outline

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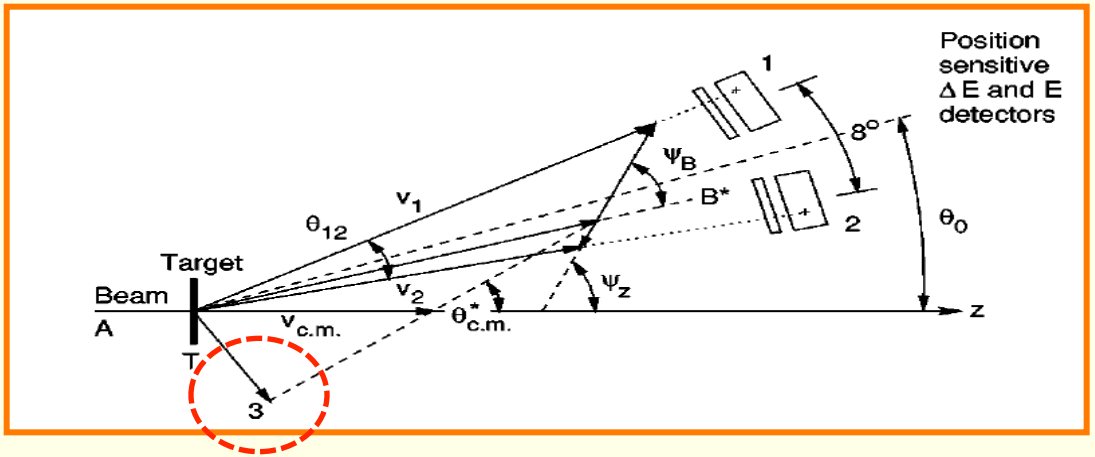
III. Preliminary results

IV. Summary

Missing mass method (inelastic or transfer)



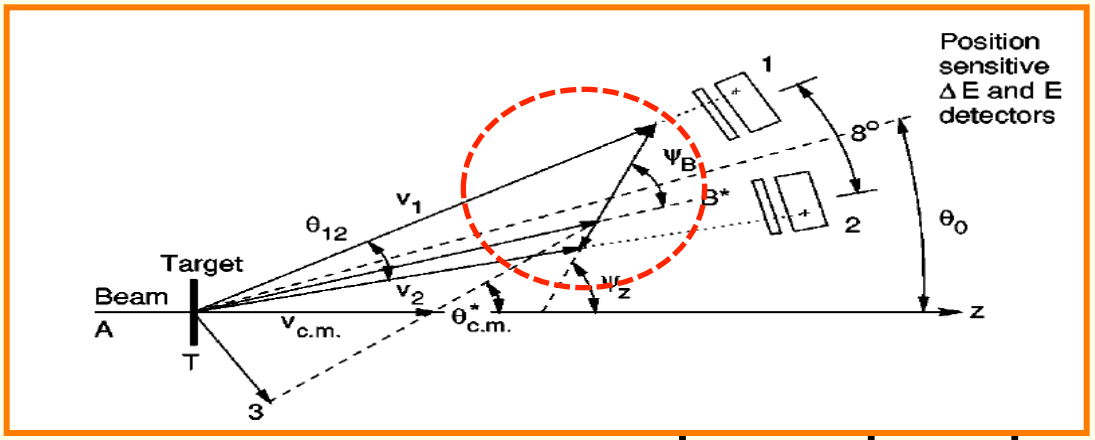
$$A + T \longrightarrow B^* + 3$$
$$\hookrightarrow 1 + 2$$

$$Q = T_3 + T_{B^*} - T_A = m_T + m_A - m_3 - m_{B^*}$$

$$m_{B^*} = m_T + m_A - m_3 - Q$$

$$Q = \left(\frac{m_A}{m_B} - 1\right)T_A + \left(\frac{m_3}{m_B} + 1\right)E_3 - \frac{2\left(m_A m_3 T_A T_3\right)^{1/2}\cos\theta}{m_B}$$

Invariant mass method



$$A + T \longrightarrow B^* + 3$$
$$\hookrightarrow 1 + 2$$

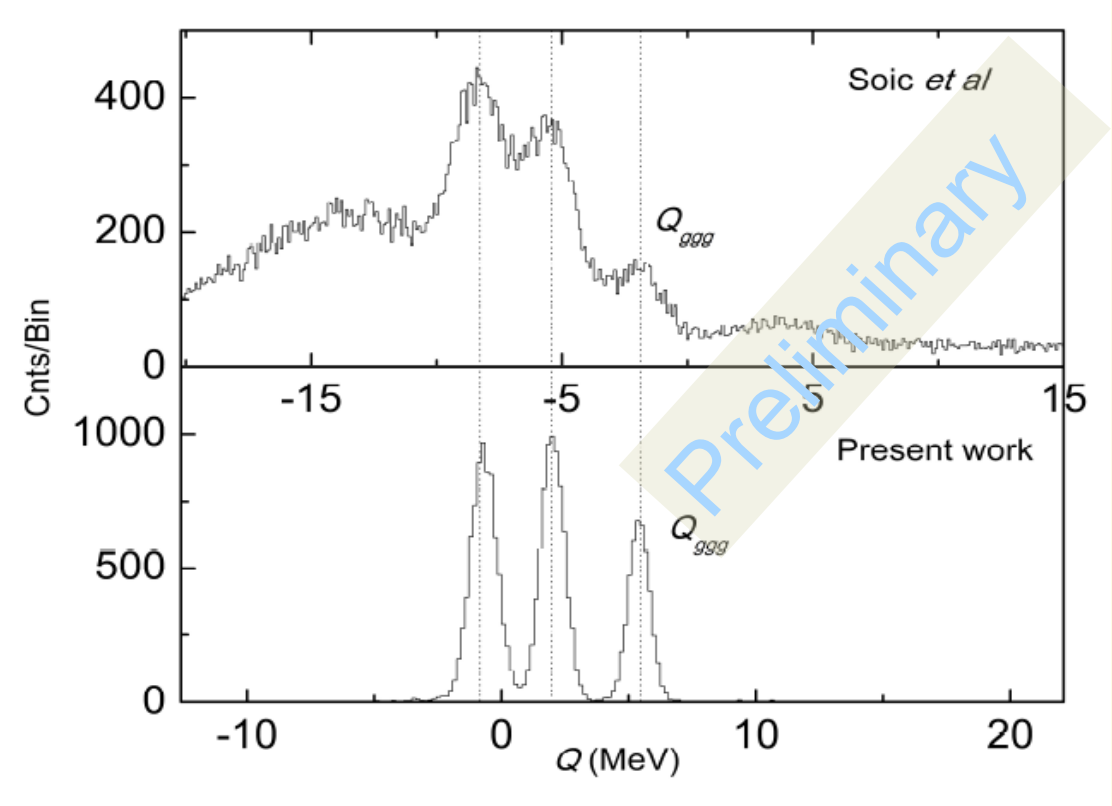
$$E_{B^*} = E_1 + E_2, \qquad p_{B^*} = p_1 + p_2$$

$$m_{B^*}c^2 = [E_{B^*}^2 - c^2 p_{B^*}^2]^{1/2} = [(E_1 + E_2)^2 - c^2 \mid \vec{p}_1 + \vec{p}_2 \mid^2]^{1/2}$$

$$E_S = (m_1 + m_1 - m_B)c^2$$

$$E_x = m_{B^*}c^2 - m_B c^2 = E_S + E_{rel}$$

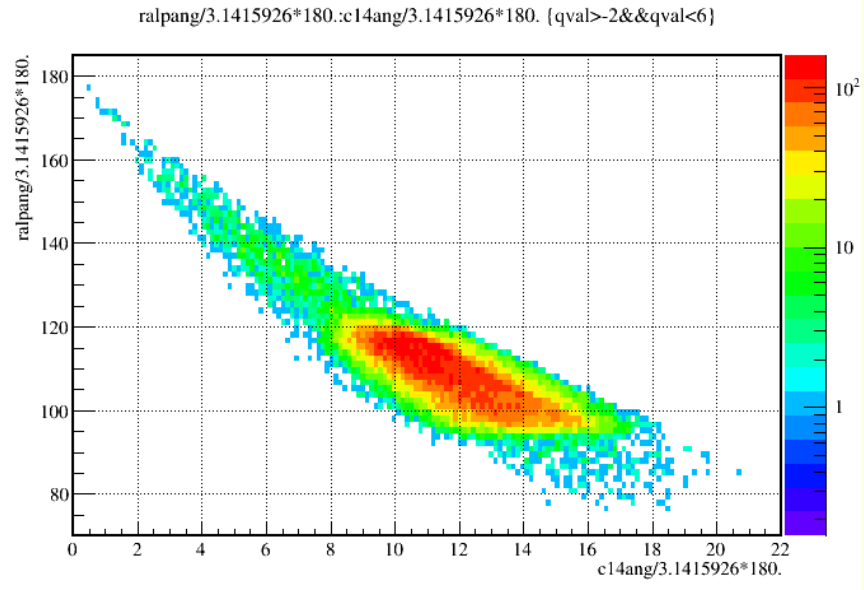
Comparison of *Q*-values



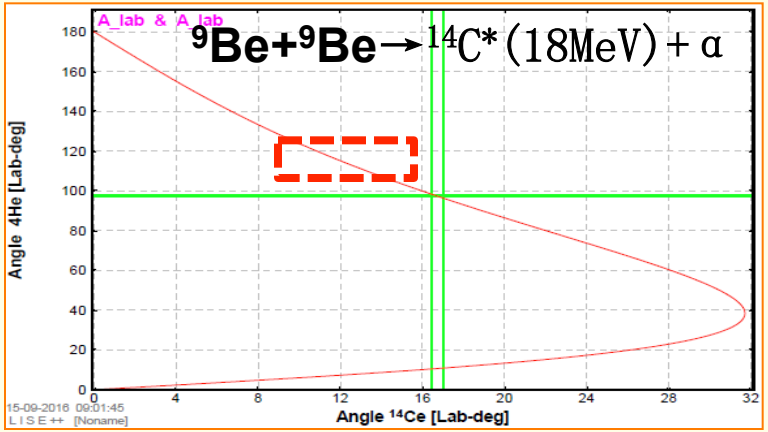
Soic et al.:
^{7}Li(^{9}Be, α ^{10}Be)d,
E_{beam}=70 MeV,
PID for forward ^{10}Be + α,
deduced recoil α.

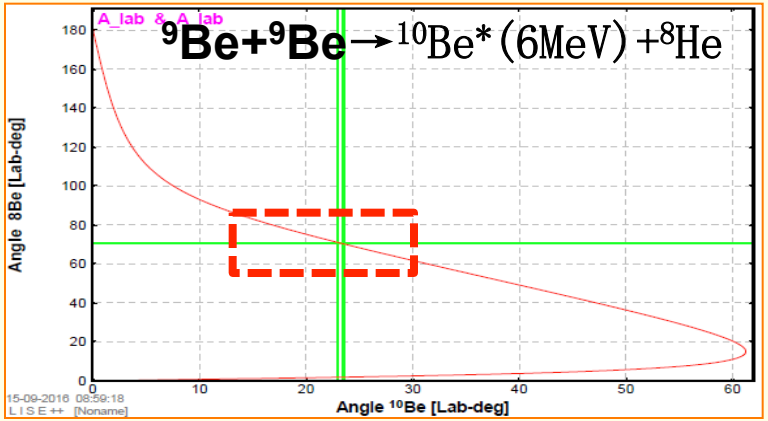
Present work:
^{9}Be(^{9}Be, α ^{10}Be)α,
E_{beam}=45 MeV,
PID for forward ^{10}Be + α,
deduced recoil α.

Kinematics check

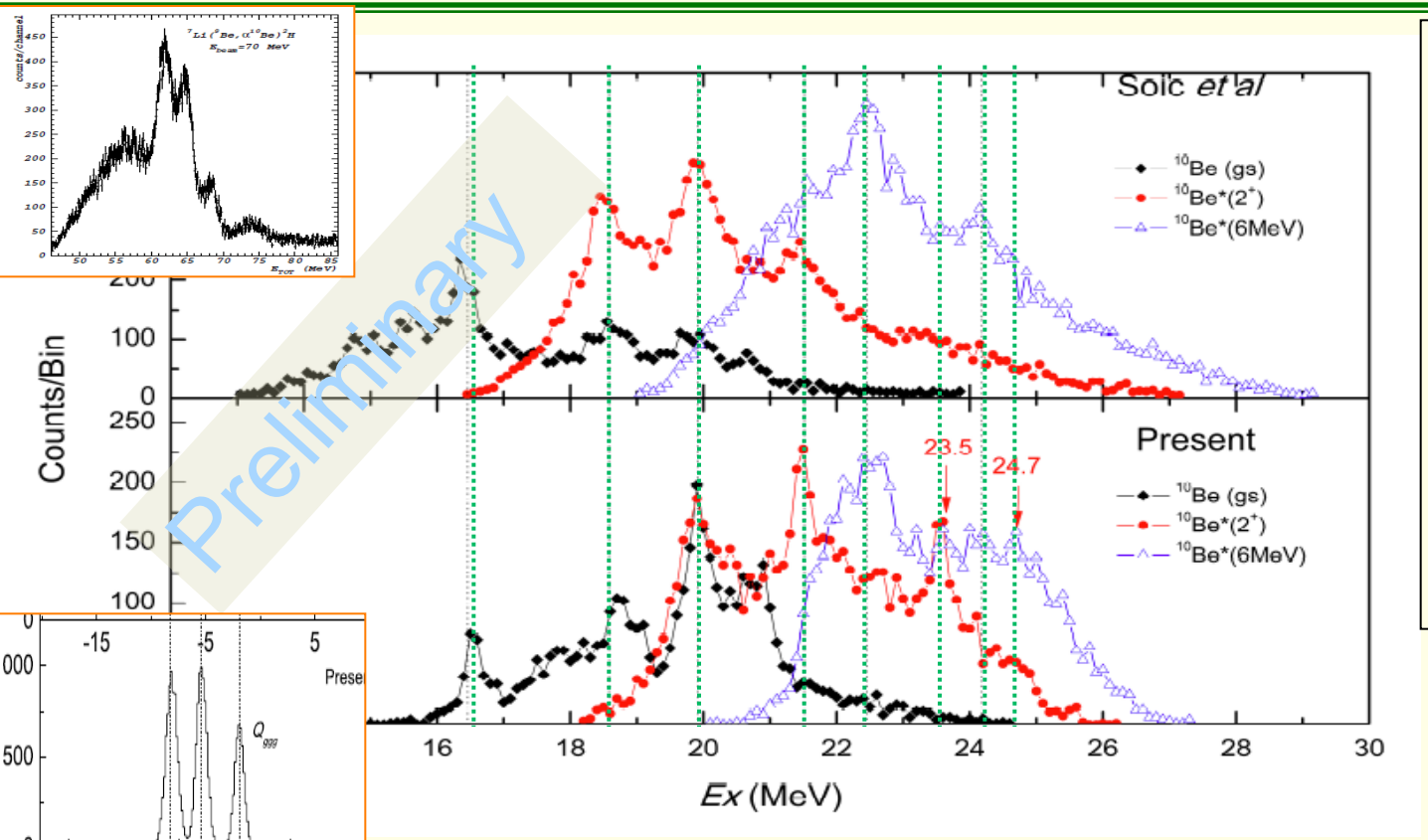


deduced recoil α angle vs measured ^{14}C angle





Comparison of IM spectra for various ^{10}Be states



Tentative:

π-bond chain?

18.5 MeV

21.4

23.5 (new)

σ-bond chain?

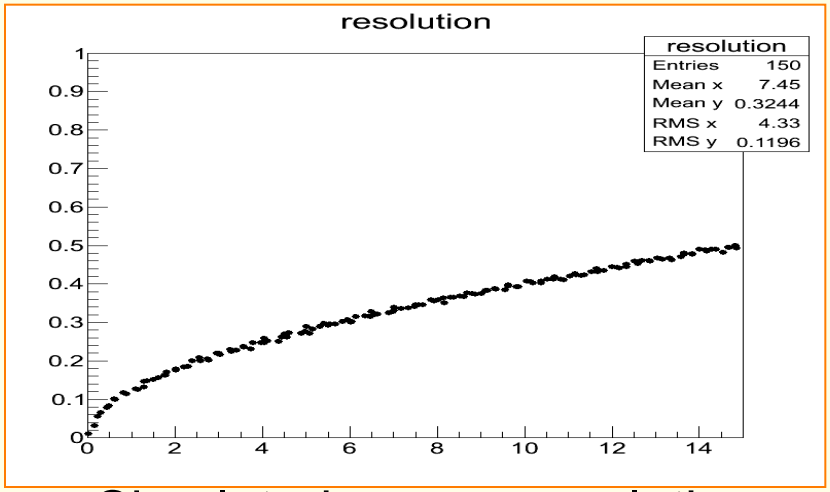
22.4

24.1

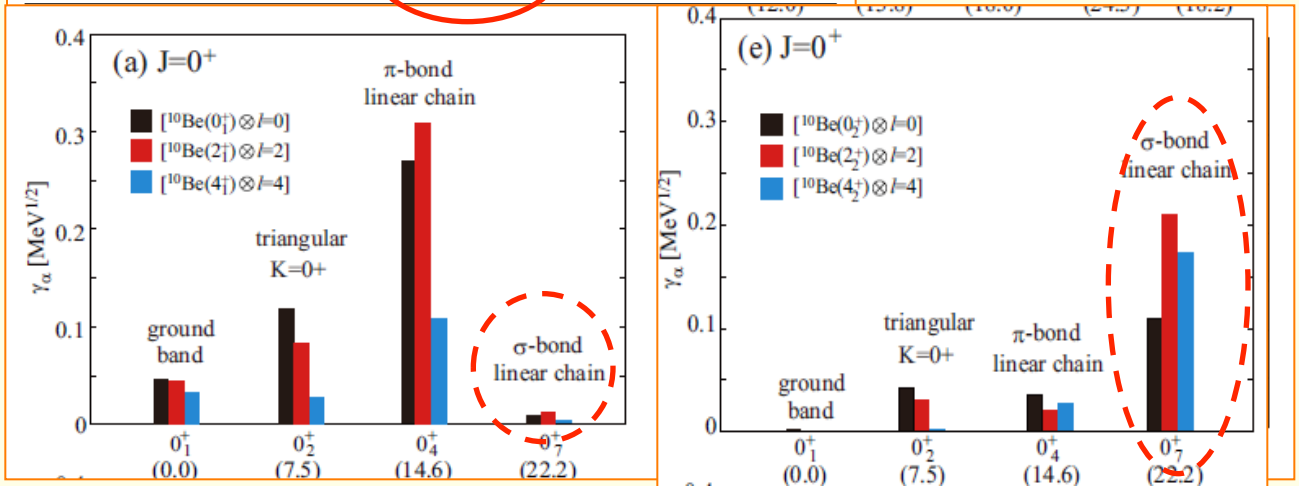
24.7 (new)

Consistent with predictions

band	J^π	E_x	r_p	r_n
ground	0_1^+	0.00	2.53	2.58
	2_1^+	8.41	2.58	2.69
		(7.01)	(2.34)	
triangular	0_2^+	7.49	2.67	2.92
$K^\pi = 0^+$	2_2^+	9.26	2.64	2.83
	4_1^+	12.00	2.65	2.89
triangular	2_3^+	10.99	2.68	2.92
$K^\pi = 2^+$	3_1^+	12.03	2.68	2.92
	4_2^+	13.83	2.68	2.92
π-bond	0_4^+	14.64	3.27	3.20
linear chain	2_5^+	15.73	3.37	3.28
	4_5^+	17.98	3.33	3.24
	6_2^+	21.80	3.39	3.30
σ-bond	0_7^+	22.16	3.91	4.12
linear chain	2_{10}^+	22.93	4.02	4.21
	4_{11}^+	24.30	3.97	4.15



Simulated energy resolution



T. Baba and M. Kimura arXiv: 1605/05567v1

Outline

I. Some background

II. The experiment

III. Preliminary results

IV. Summary

- A reaction with very large Q-value was carried out, allowing to excite ^{14}C to very high lying states and to clearly separate the various states in ^{10}Be fragment.
- Three highly excited states in ^{14}C are observed which decay primarily into $^{10}Be*$(~6 MeV), corresponding likely to the σ-bond linear-chain states according to the latest AMD model predictions.
- Further analysis of the cluster-decay branching ratio, related to the cluster reduced width, are underway in order to make quantitative comparison with theoretical calculations.


Thank you for your attention!