Preliminary Experimental Results of the Molecular States in ^{16}C

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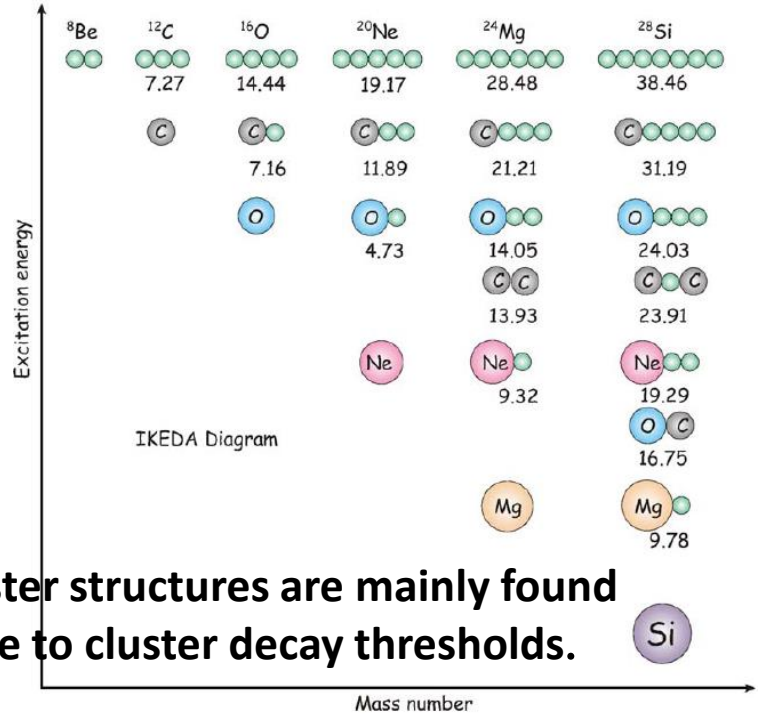
Outline

- 1. Introduction
- 2. Previous experiments on ^{16}C clustering
- 3. ^{16}C Experimental Setup of PKU
- 4. Preliminary Data Analysis Results
- 5. Summary

Introduction: Clustering

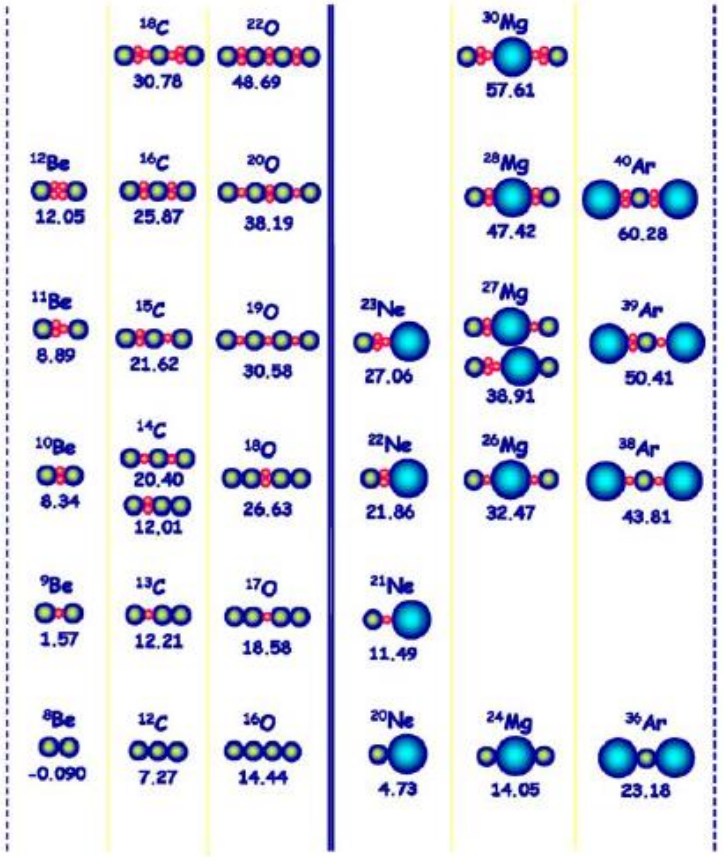
Cluster in stable Self-Conjugate 4*N* Nuclei



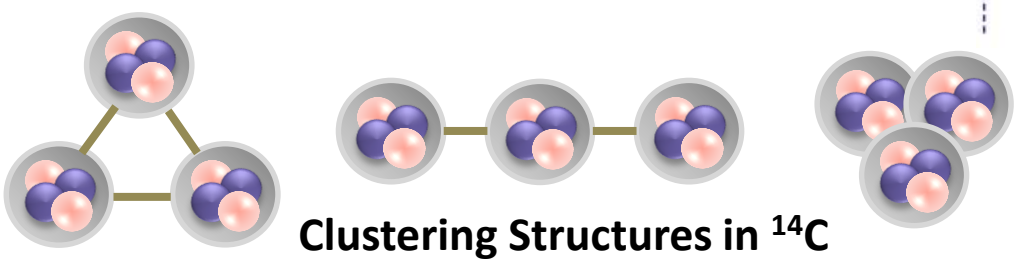
Cluster structures are mainly found close to cluster decay thresholds.

K. Ikeda, PTPs (1968) E68 464-475.

Cluster toward neutron dripline



W. von Oertzen, Phys. Rep. 432(2006)43-113

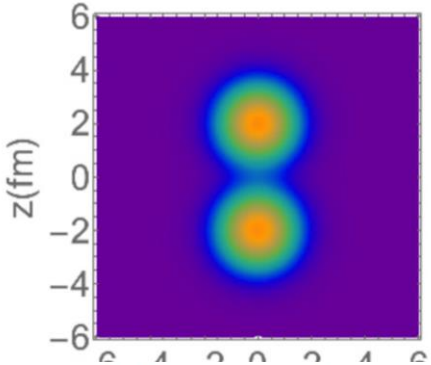


Clustering Structures in ^{14}C

- ✓ **Neutron-rich domain**
- ✓ **High Excitation energy**

Introduction: Experimental studies

^{8}Be

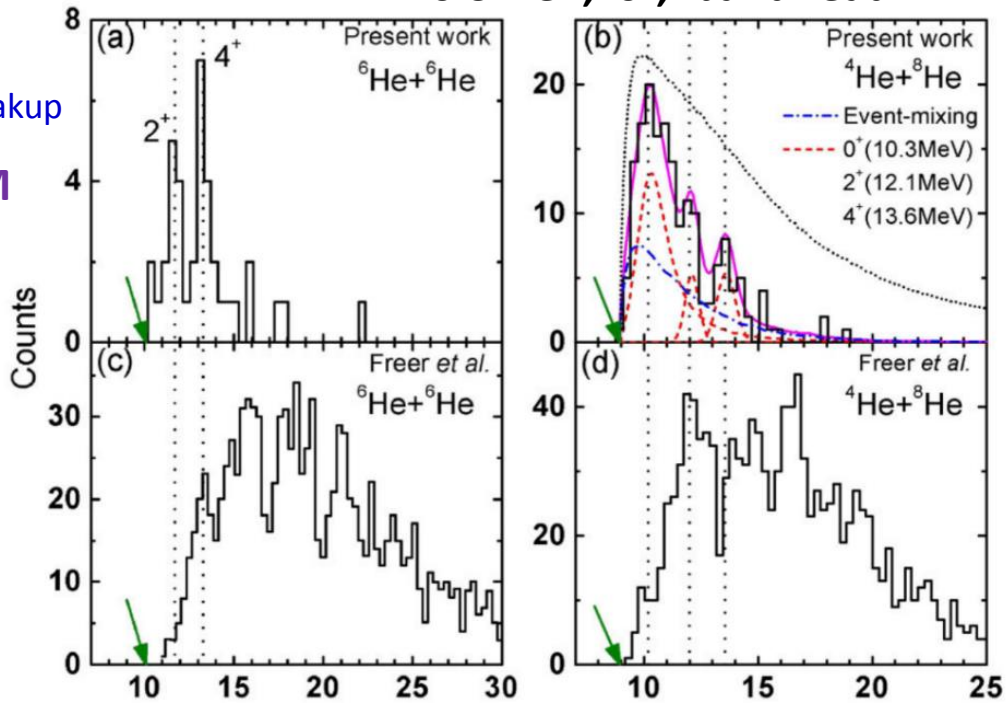


^{12}Be

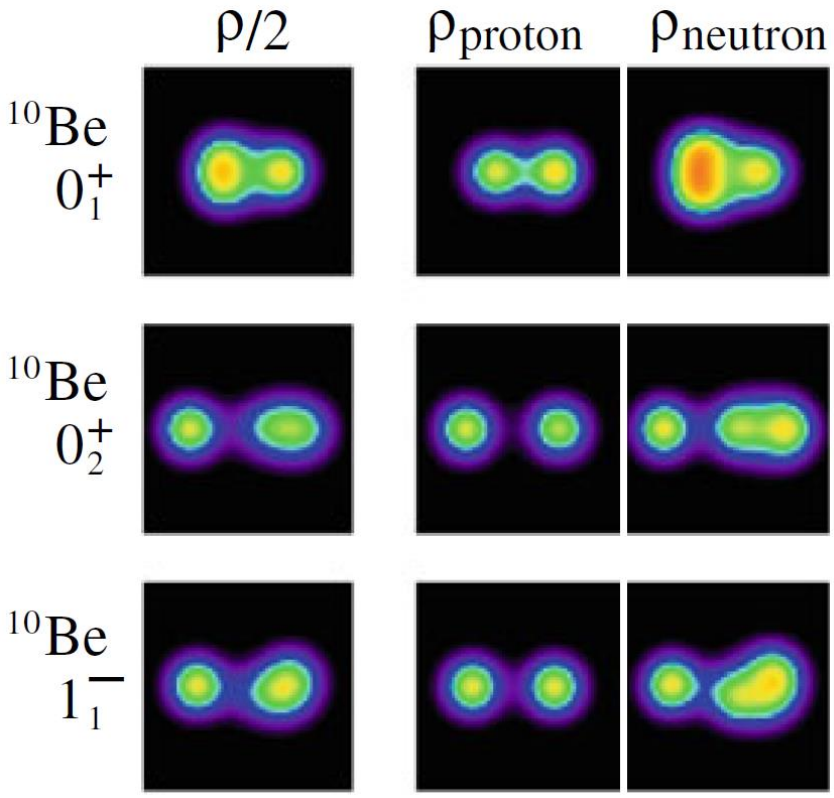
Inelastic breakup

GTCM

10.3MeV, 0^+, bandhead



Z. H. Yang et. al., PRL 112(2014)162501



1) E_x - spin systematics:

high moment of inertia

Clustering Criterion

2) Large cluster decay width:

large $\Gamma_{Cluster}/\Gamma$; $\gamma^2_{Cluster}$; $\theta^2_{Cluster}$

3) Characteristic transition strength

large M(IS) !!

Introduction: Experimental studies

^{14}C

Transfer reaction

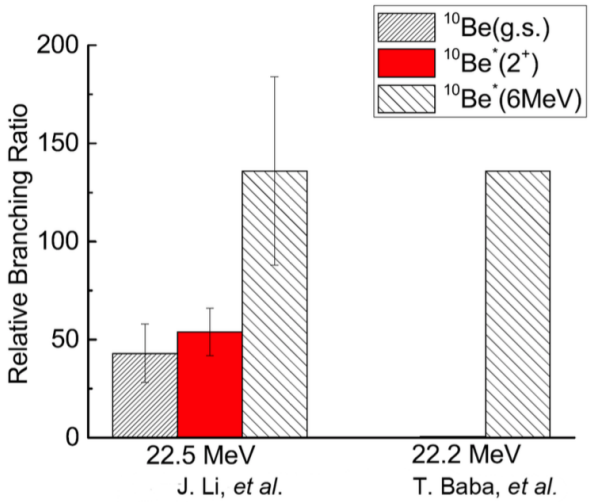
AMD

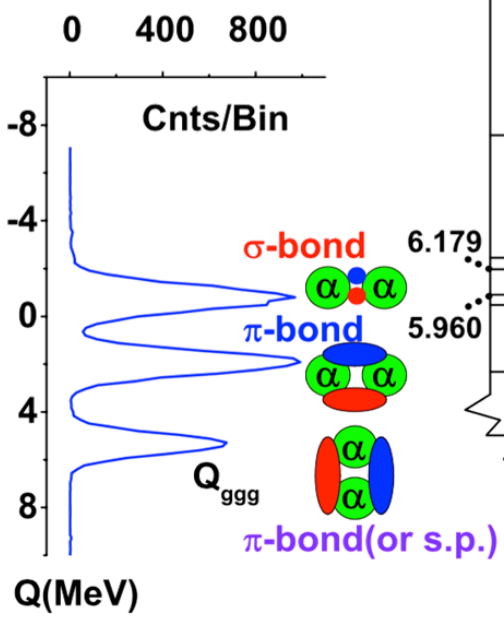
Clustering Criterion

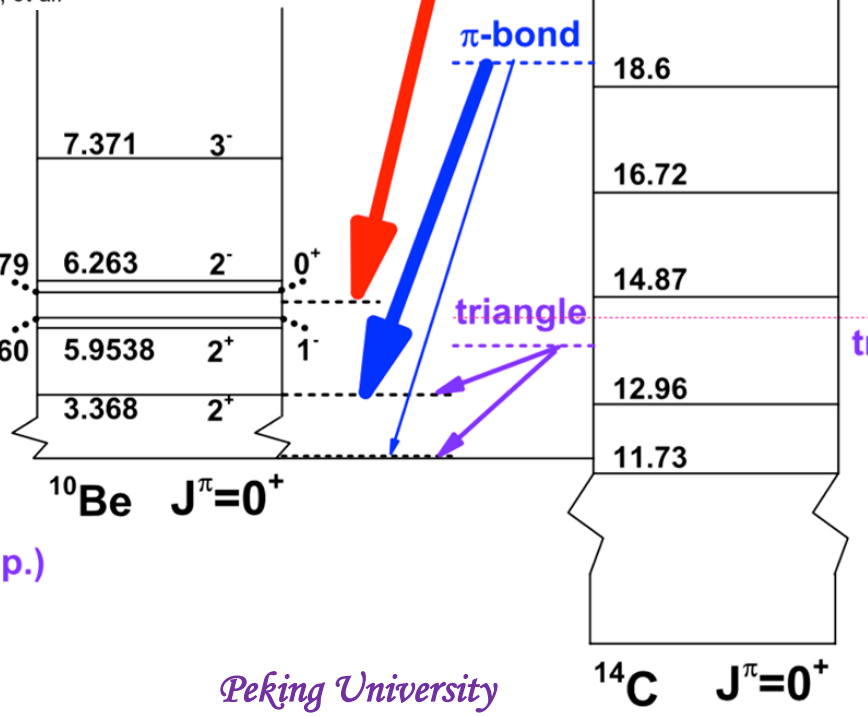
T. Baba et. al., PRC 94(2016)044303

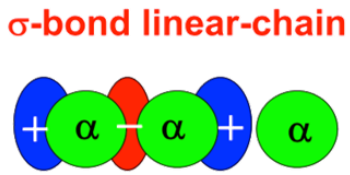
J. Li et. al., PRC 95(2017)021303(R)

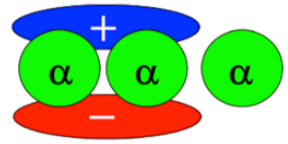
4) Selective decay mode

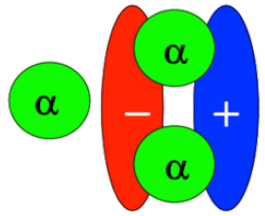








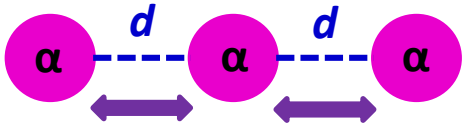




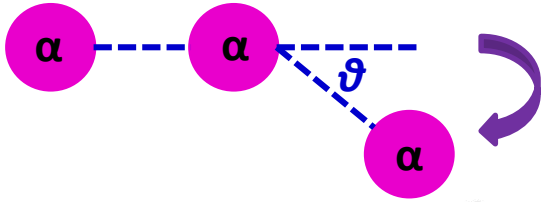
Introduction: ^{16}C

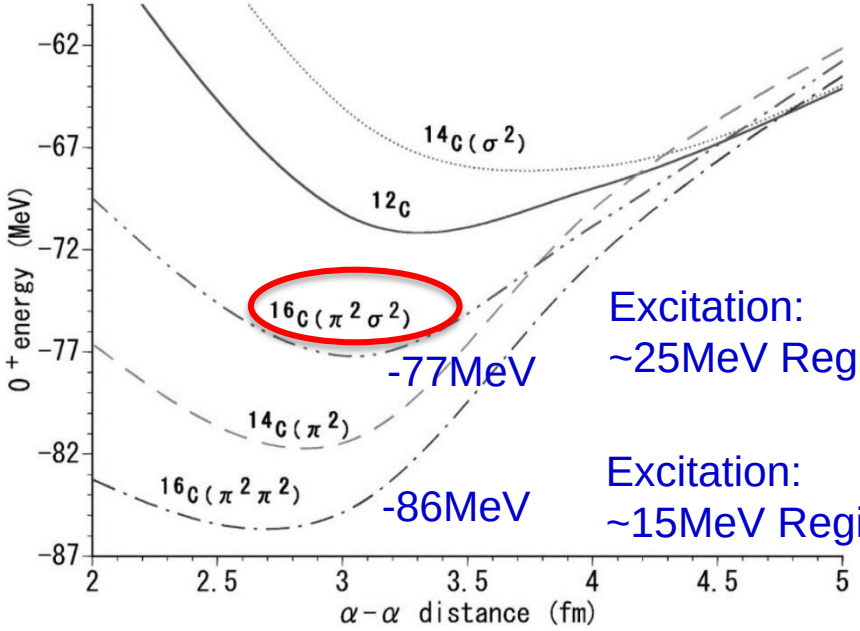
^{16}C Molecular-orbital structure in neutron-rich C isotopes. N. Itagaki et. al., PRC64(2001)014301

Breathing motion



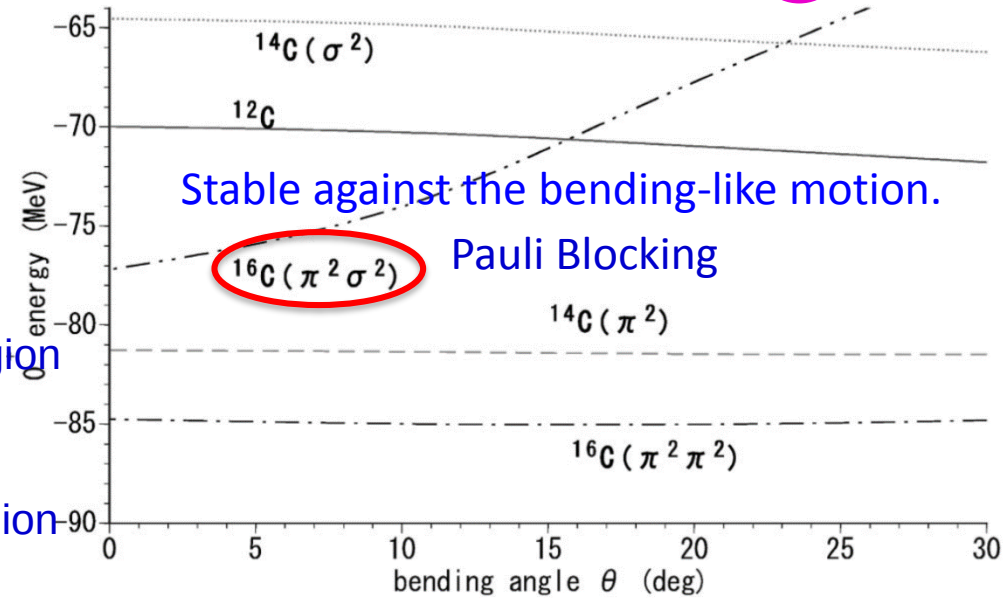
Bending motion





Excitation:
~25MeV Region

Excitation:
~15MeV Region



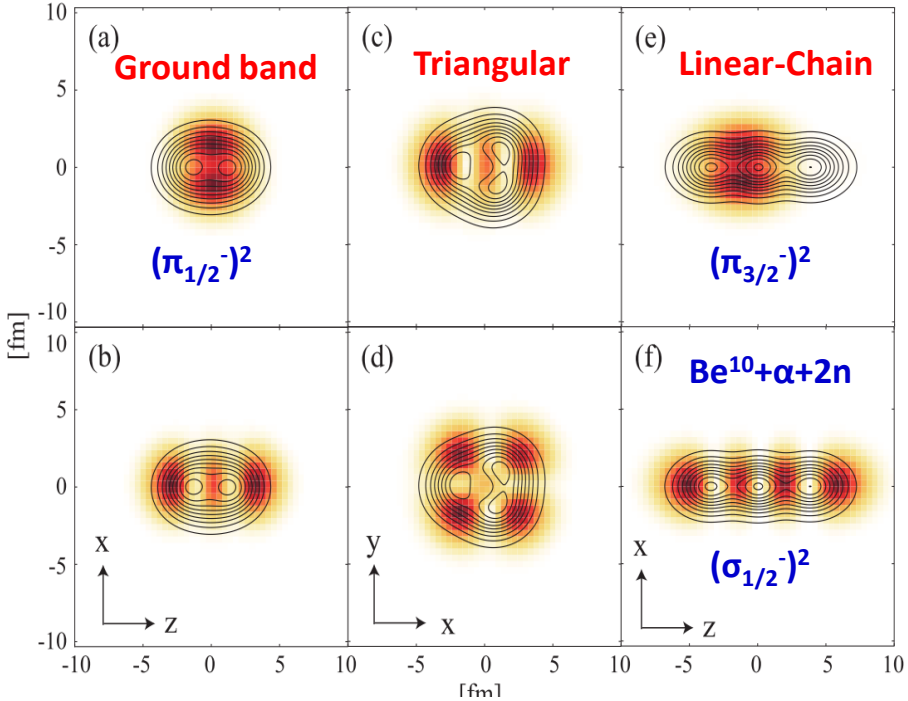
Stable against the bending-like motion.

Pauli Blocking

The excited states of ^{16}C with $\pi^2\sigma^2$ configuration for the 4 four valence neutrons is one of the most promising candidates for the linear-chain structure. (~25MeV)

Introduction: ^{16}C

^{16}C AMD calculation: extract the single-particle wave functions of the valence neutrons.

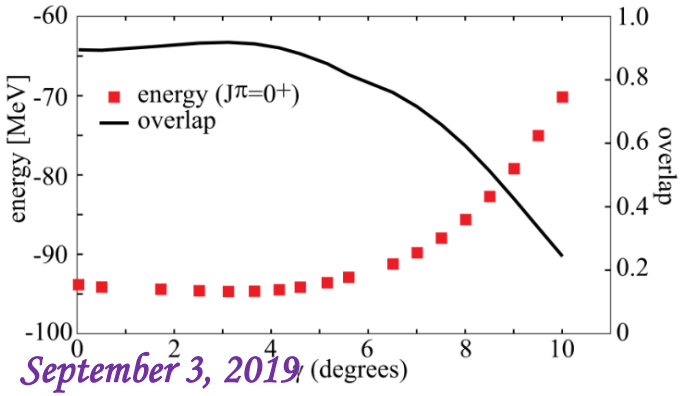


Tightly Bound

Weakly Bound

Band	J^π	E_x	r_p	r_n
Ground	0_1^+	0.0	2.61	2.84
	2_1^+	1.3 (1.77)	2.60	2.83
	4_1^+	3.9 (4.14)	2.56	2.77
			$n+^{15}C$	4.54
Triangular	0_2^+	8.0	2.75	3.09
$K^\pi = 0^+$	2_4^+	9.4	2.74	3.08
	4_4^+	12.7	2.76	3.06
Triangular	2_5^+	10.1	2.74	3.08
$K^\pi = 2^+$	3_3^+	11.7	2.74	3.07
	4_6^+	13.7	2.74	3.08
			$^4He+^{12}Be$	13.81
Linear chain	0_5^+	15.5	3.54	3.71
	2_9^+	15.9	3.14	3.27
	2_{10}^+	16.3	3.38	3.54
			$^6He+^{10}Be$	16.51
	4_{11}^+	17.6	3.22	3.38
	4_{12}^+	17.8	3.21	3.39
			$^8He+^8Be$	22.86

T. Baba et. al., PRC 90, 064319 (2014)

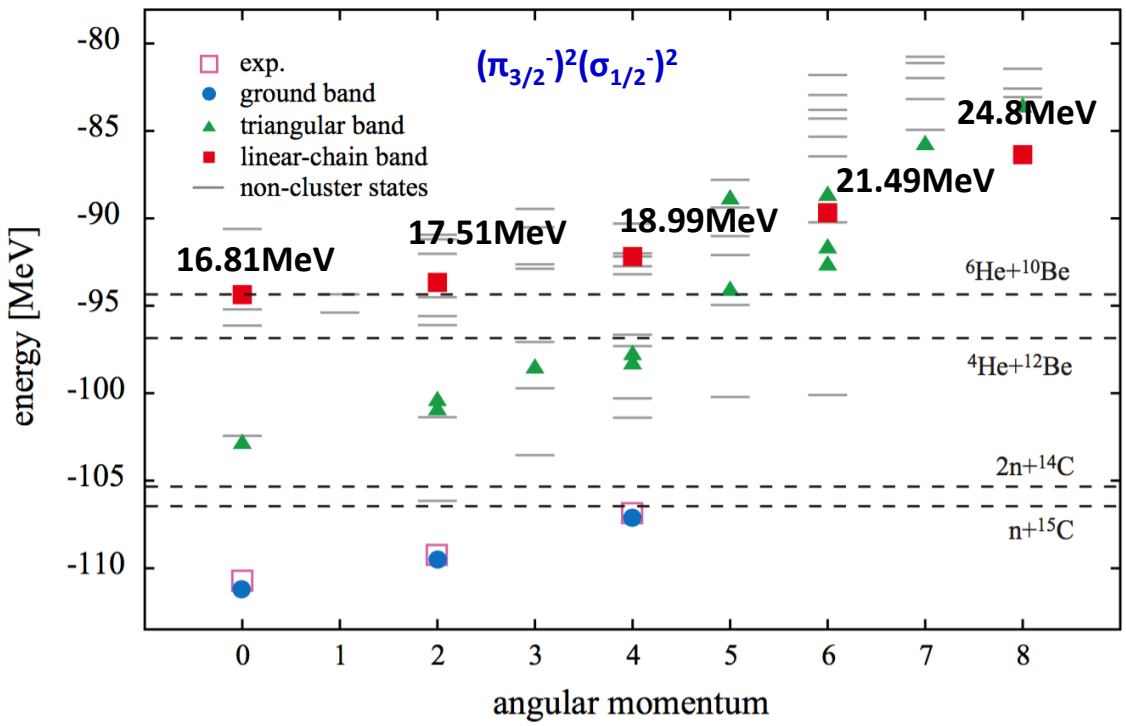


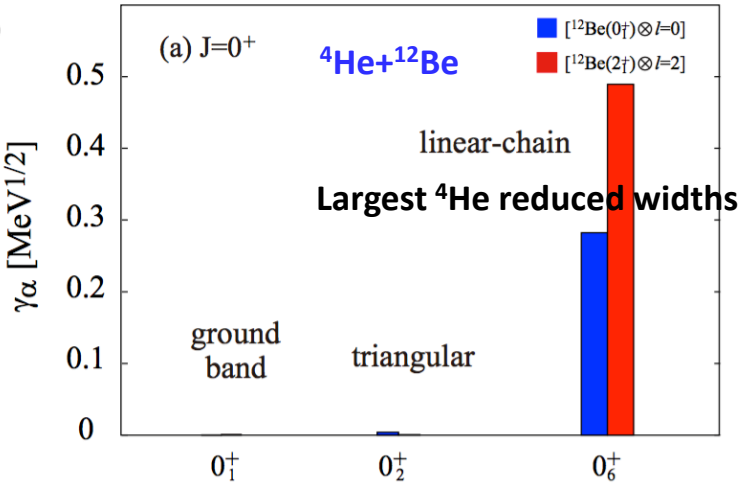
The linear-chain configuration generates a rotational band built on the 0_5^+ state at 15.5MeV that is close to the ^{4}He+^{12}Be and ^{6}He+^{10}Be threshold energies and stable against the bending motion.

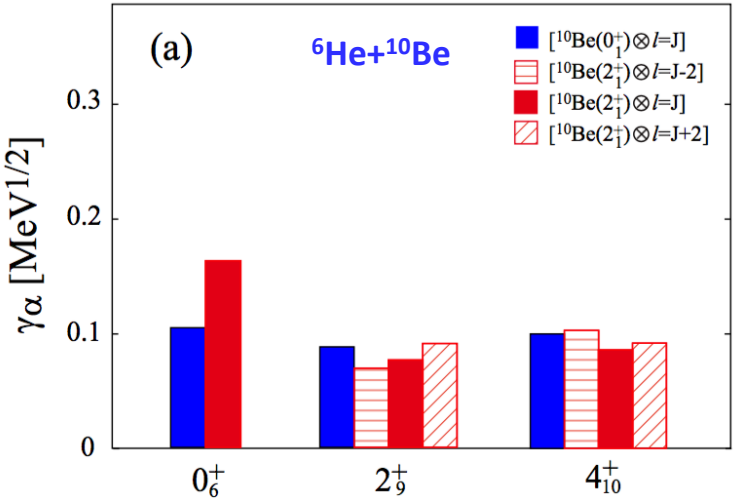
Introduction: ^{16}C

^{16}C Characteristic ^{4}He and ^{6}He decay patterns in the linear-chain states in ^{16}C

Positive Parity States T. Baba et. al., PRC 97, 054315 (2018)







- ✓ **The linear-chain band has the largest ^{4}He reduced widths.**
- ✓ **The dominant component of Linear-chain band is ^{12}Be(2_1^+).**
- ✓ **The ^{6}He reduced widths are about 2 times smaller than ^{4}He.**

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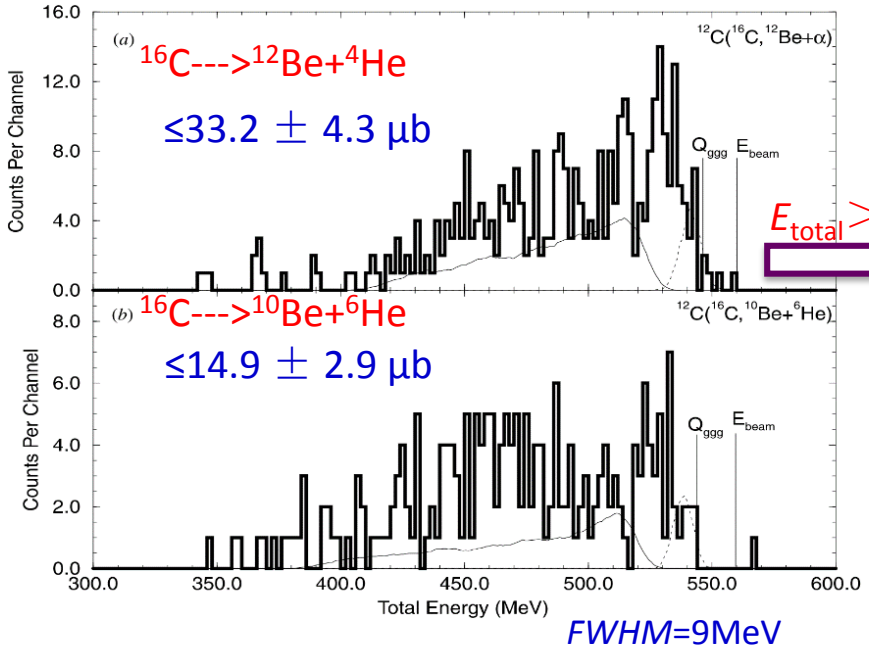
Previous experiments on ^{16}C clustering

^{16}C is inelastically excited by ^{12}C target foils and then breaks up into two fragments.

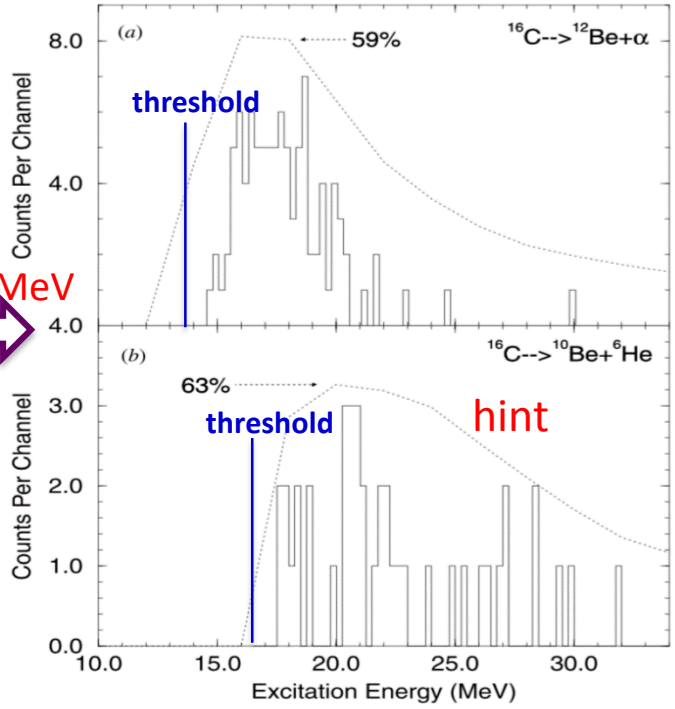
35MeV/A, ^{16}C, 2*10^{4}pps
zero degree telescope

P J Leask et.al., J. Phys. G 27 (2001) B9–B14

two-body breakup channels:



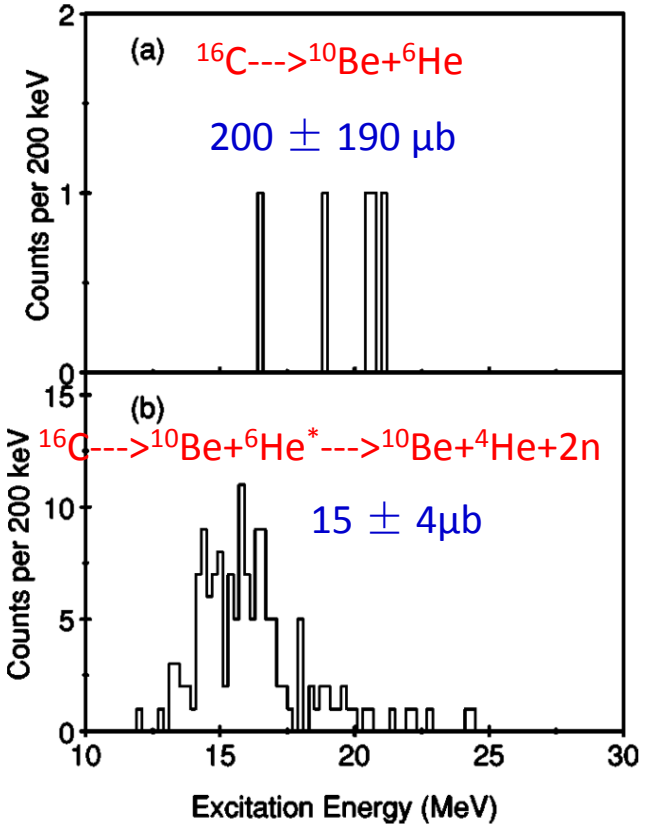
E_{total} > 520MeV



The high ^{16}C beam energy (35MeV/A) opens so many additional reaction channels that the *Q*-value is not good enough to exclude the influence of breakup fragments in different final states.

Previous experiments on ^{16}C clustering

^{16}C is inelastically excited by ^{12}C target foils and then breaks up into two fragments.



46MeV/A, ^{16}C, 300pps
zero degree telescope

The reaction products in unbound states may contribute to the decay channel so no significant structure was seen in the excitation energy spectra.

The beam intensity is so low (300pps) that the statistics is insufficient to get peaks information or spin-parity values.

N. I. Ashwood et.al., PRC 70, 064607 (2004).

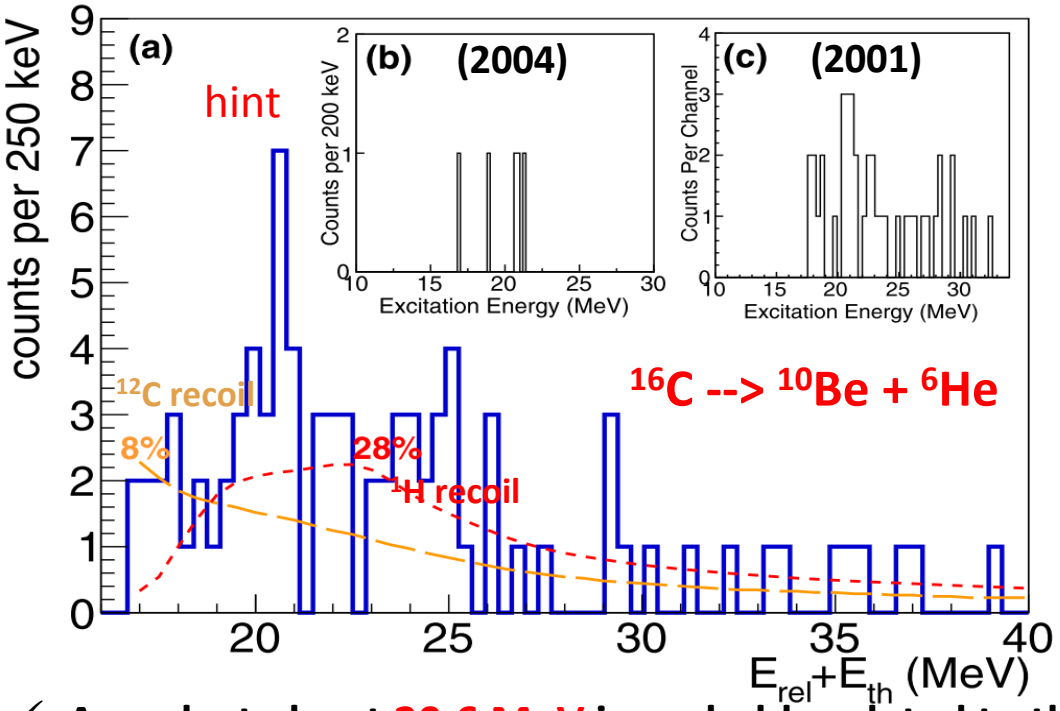
Previous experiments on ^{16}C clustering

^{16}C is inelastically excited by $(CH_2)_n$ target and $(CD_2)_n$ target then breaks up into two fragments.

49.5MeV/A, ^{16}C, 10^5pps
Cover angle: 2.2deg-6.4deg

^{1}H(^{16}C ,^{6}He+^{10}Be), ^{2}H(^{16}C ,^{6}He+^{10}Be), ^{12}C(^{16}C ,^{6}He+^{10}Be)

D. Dell'Aquila et. al., PRC93(2016)024611



Band	J^π	E_x	γ_α(6.0 fm)	S_α	S_n
Ground	0_1^+	0.00	0.00	0.03	0.22
	2_1^+	1.69	0.00	0.00	0.35
	4_1^+	4.04	0.00	0.00	0.01
Triangular	0_2^+	8.35	0.01	0.05	0.12
	2_4^+	10.22	0.00	0.00	0.01
	2_5^+	10.79	0.00	0.01	0.02
Linear chain	0_6^+	16.81	0.28	0.11	0.00
	2_9^+	17.51	0.23	0.07	0.00
	4_{10}^+	18.99	0.26	0.09	0.00
	6_5^+	21.49	0.23	0.07	0.00

Band	J^π	E_x	γ_α(5.5 fm)	γ_α(7.0 fm)	S_α
yrast band	2_1^-	6.11			
	3_1^-	7.25	0.00	0.00	0.02
	4_1^-	9.34			
	5_1^-	10.71	0.00	0.00	0.00
Linear chain band 1	1_7^-	18.28	0.04	0.00	0.01
	1_8^-	18.64	0.02	0.01	0.00
	3_9^-	19.45	0.10	0.01	0.03
	3_{13}^-	21.57	0.05	0.02	0.01
Linear chain band 2	1_{11}^-	22.05	0.04	0.12	0.03
	3_{14}^-	23.00	0.04	0.12	0.03
	5_{15}^-	24.76	0.03	0.11	0.02
	7_6^+	27.35	0.06	0.11	0.01

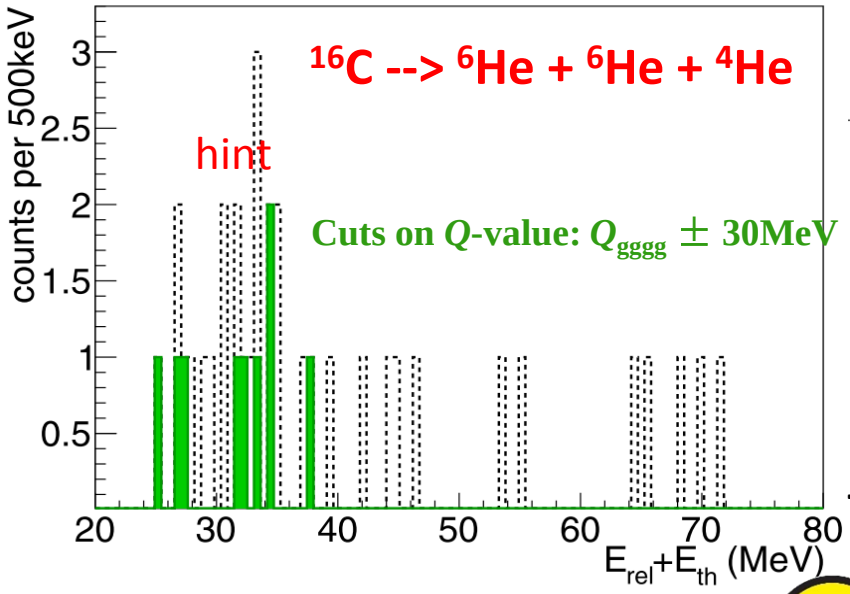
- ✓ **A peak at about 20.6 MeV is probably related to the existence of an high-lying excited state.**
- ✓ **Only linear-chain states have large ^{6}He reduced widths.**

Previous experiments on ^{16}C clustering

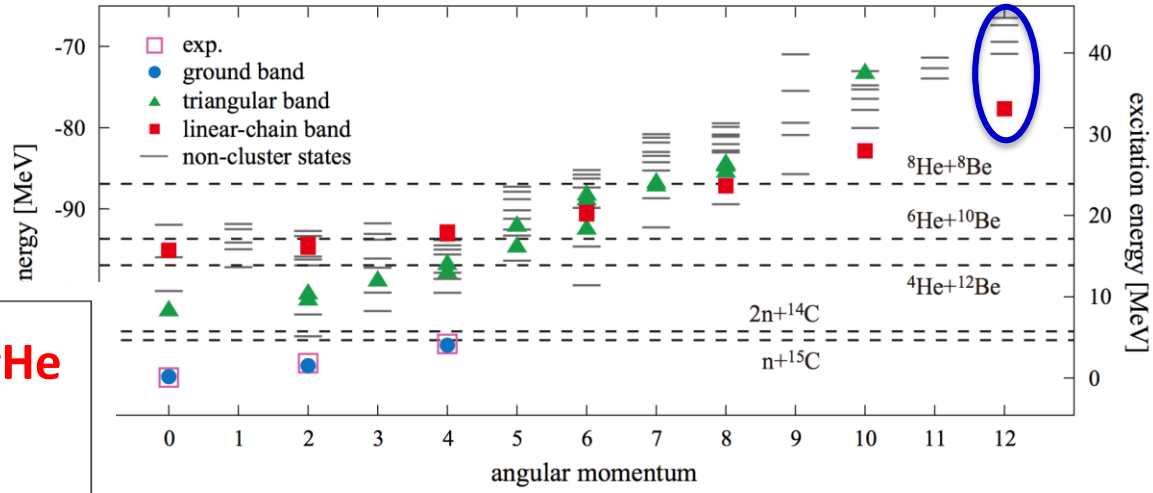
^{16}C is inelastically excited by $(CH_2)_n$ target and $(CD_2)_n$ target then breaks up into two fragments.

D. Dell'Aquila et. al., PRC93(2016)024611

It shows an enhanced of the triple coincidence yield at about 34 MeV.



T. Baba et. al., PRC 90, 064319 (2014)



This state indicates the possible presence of the 12^+ member of the linear chain band. (AMD)

New measurement with better statistics is needed to confirm the present experimental findings.

No Zero-Degree detection → **No cluster states near threshold**

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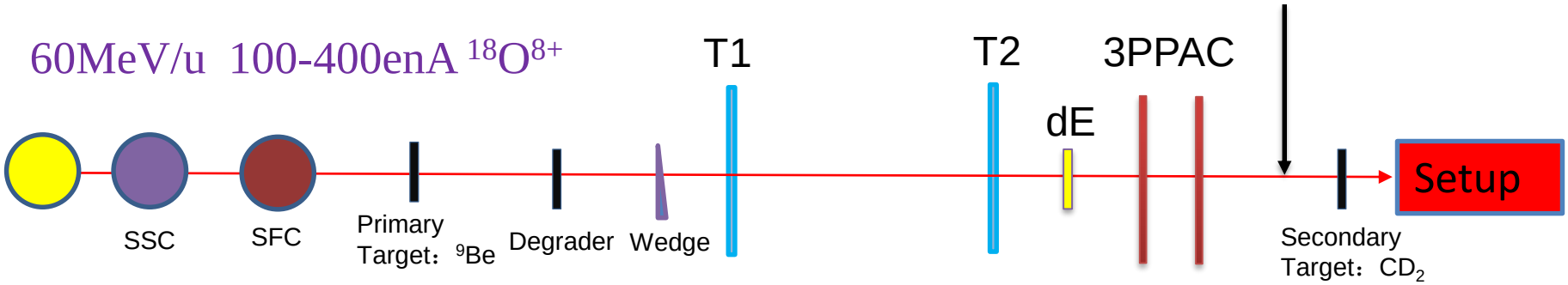
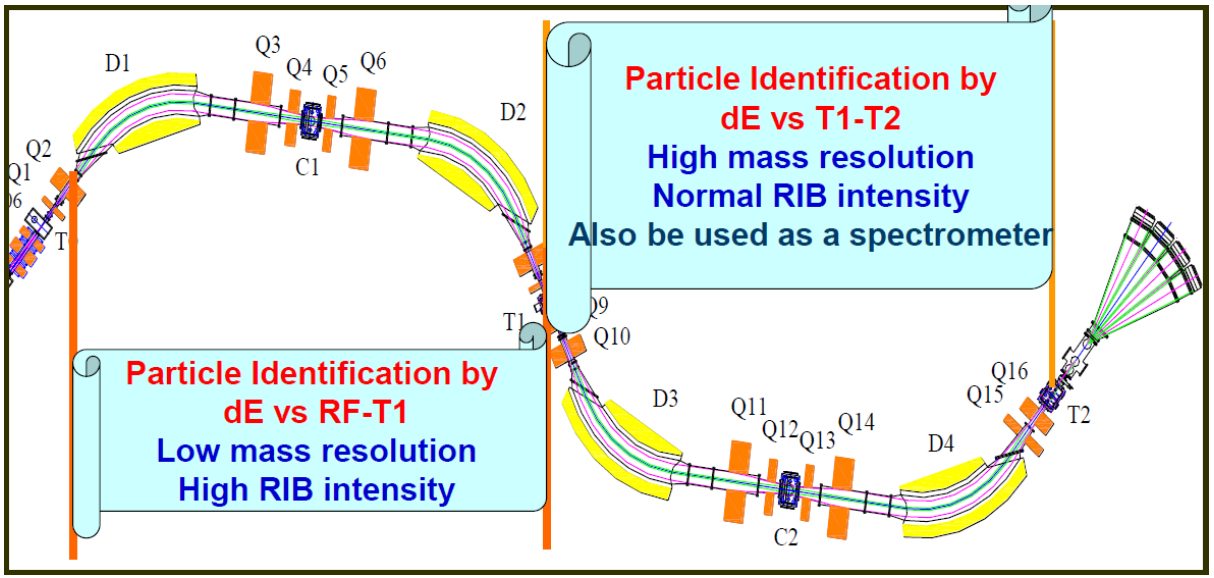
^{16}C Experimental Setup at PKU

Main goals:

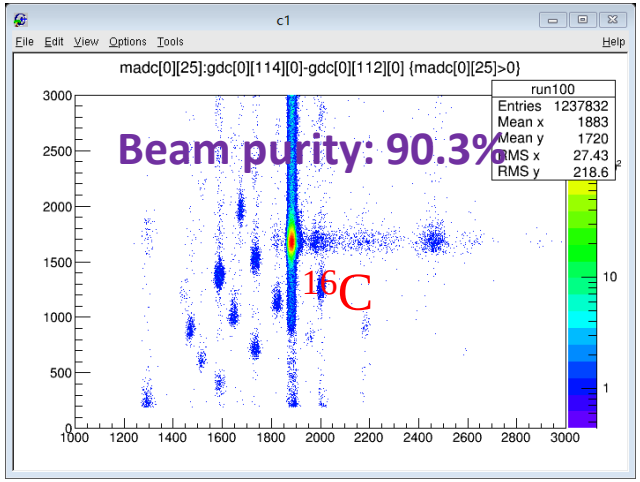
To Investigate the 3alpha linear-chain structure in the high-lying excited state of ^{16}C(Ex=14 ~ 25MeV) via ^{2}H(^{16}C,^{4}He + ^{12}Be) ^{2}H and ^{2}H (^{16}C,^{6}He + ^{10}Be) ^{2}H inelastically break up reaction at 24MeV/A with both the invariant mass and missing mass methods.



RIBLL1-Lanzhou

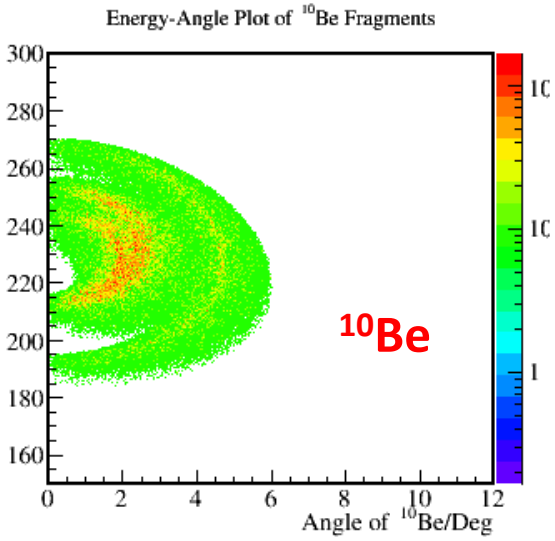


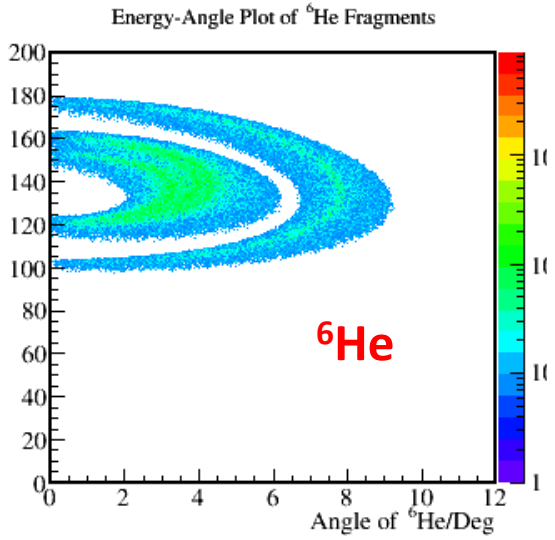
24MeV/u ^{16}C 10^{4}pps

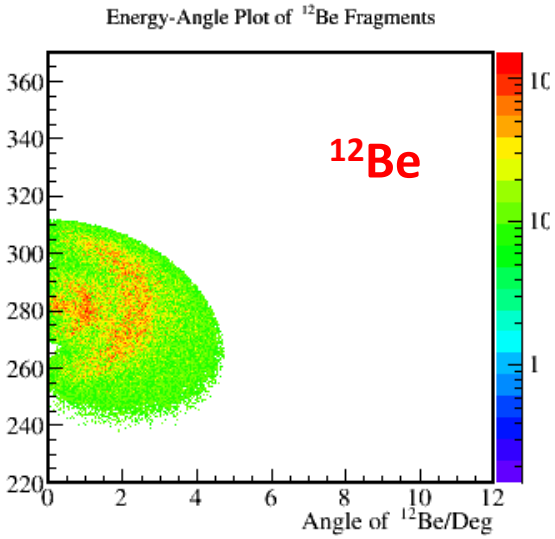


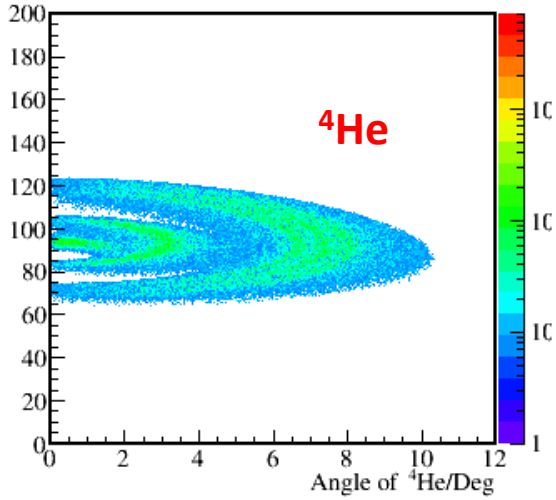
^{16}C Experimental Setup at PKU

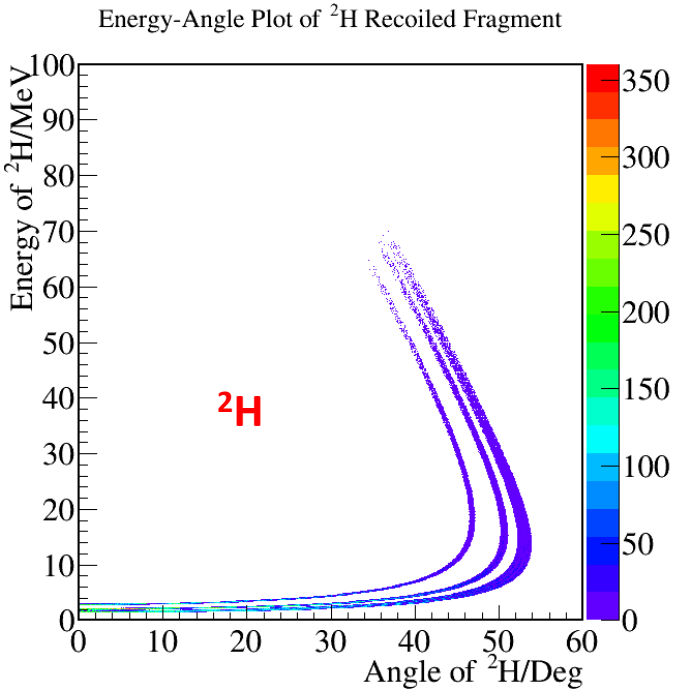
Simulations of the angles of breakup fragments: Geant4











- ✓ **The breakup fragments are at forward angles. (IM)**
  - **Zero-degree detection**
- ✓ **The recoiled light particles are at large angles. (MM)**
- ✓ **The particle energies are high.**
  - **DSSD + SSD + CsI telescopes**

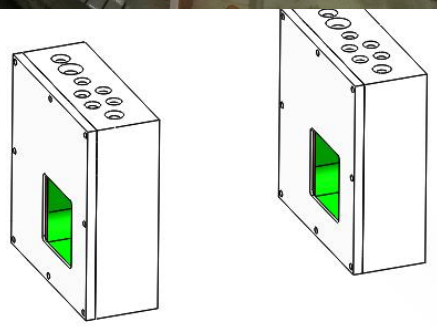
^{16}C Experimental Setup at PKU

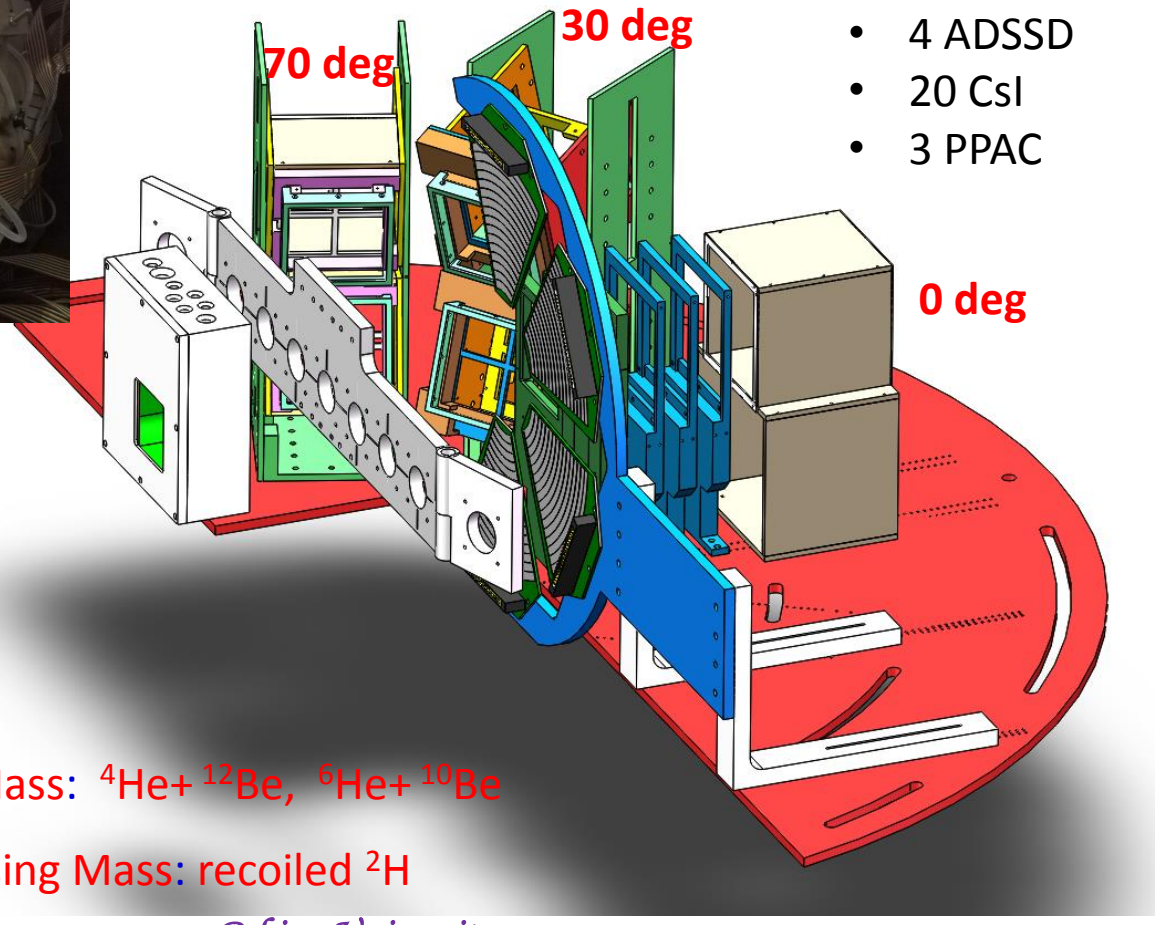
Detectors setup: ^{2}H(^{16}C,^{4}He + ^{12}Be) ^{2}H and ^{2}H (^{16}C,^{6}He + ^{10}Be) ^{2}H **RIBLL1-Lanzhou**

The cooling systems are applied to obtain excellent energy resolution.

Detector Array

- 7 DSSD
- 7 SSD
- 4 ADSSD
- 20 CsI
- 3 PPAC





- 3PPACs for beam tracking
- T0 detectors for Invariant Mass: ^{4}He+ ^{12}Be, ^{6}He+ ^{10}Be
- T1/T2/TA detectors for Missing Mass: recoiled ^{2}H

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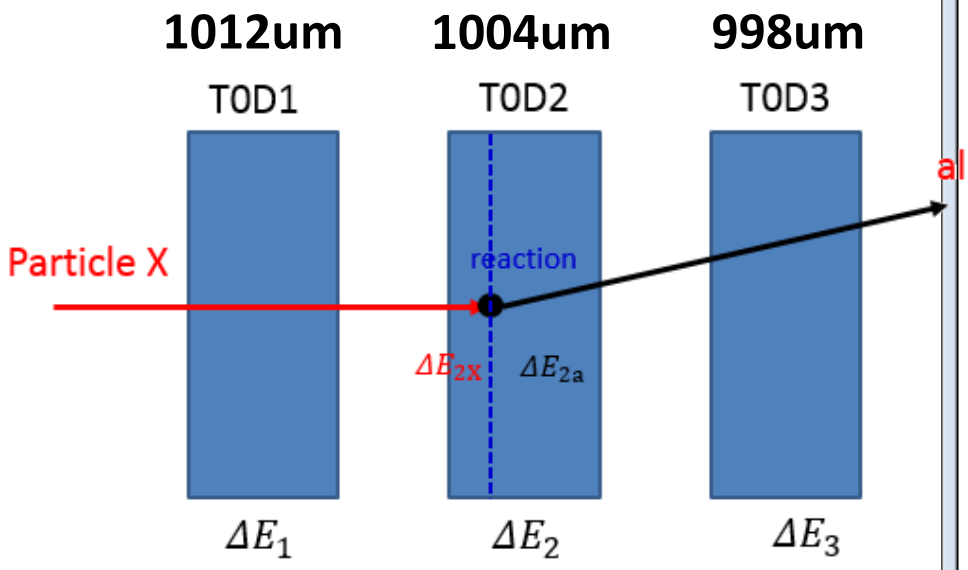
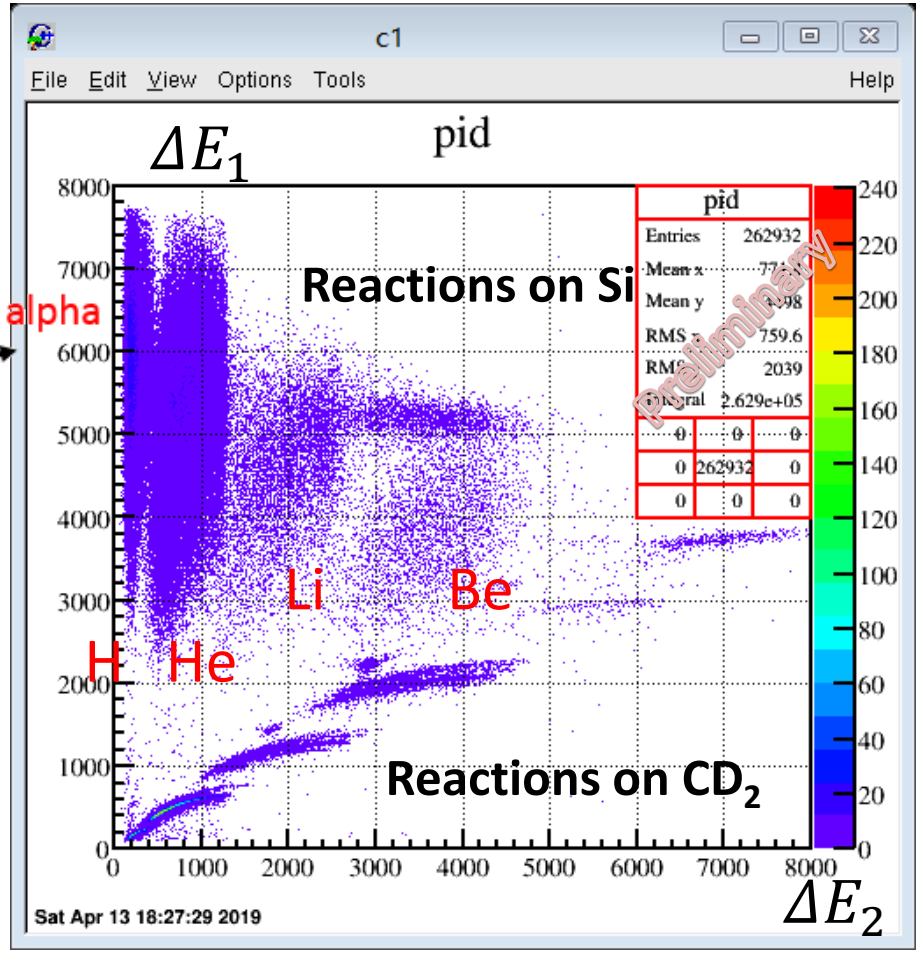
Preliminary Data Analysis Results

Reaction events on Silicon detectors:

T0: 3DSSD + 3SSD + CsI

Target: CD_2 (120 um)



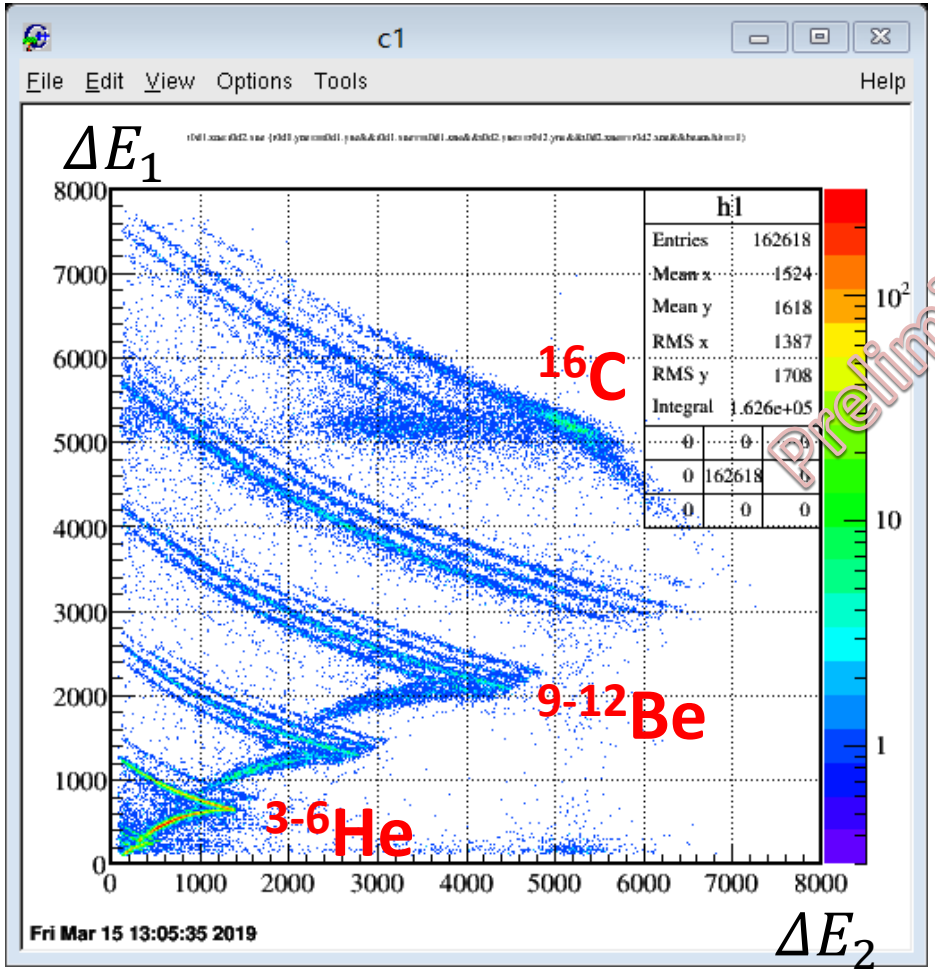


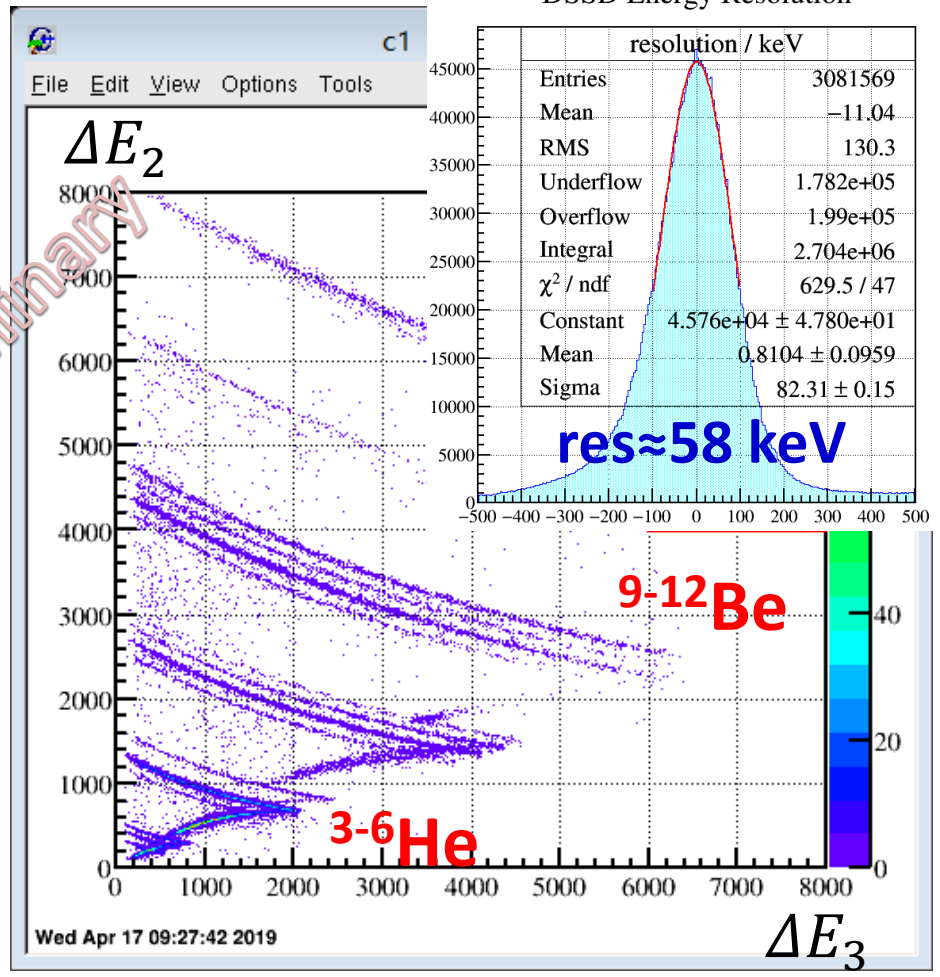
To exclude reaction events on Si:

- ✓ **DSSD tracking of particles**
- ✓ **d*E*-*E* PID curves of particles**

Preliminary Data Analysis Results

Particle Identification:

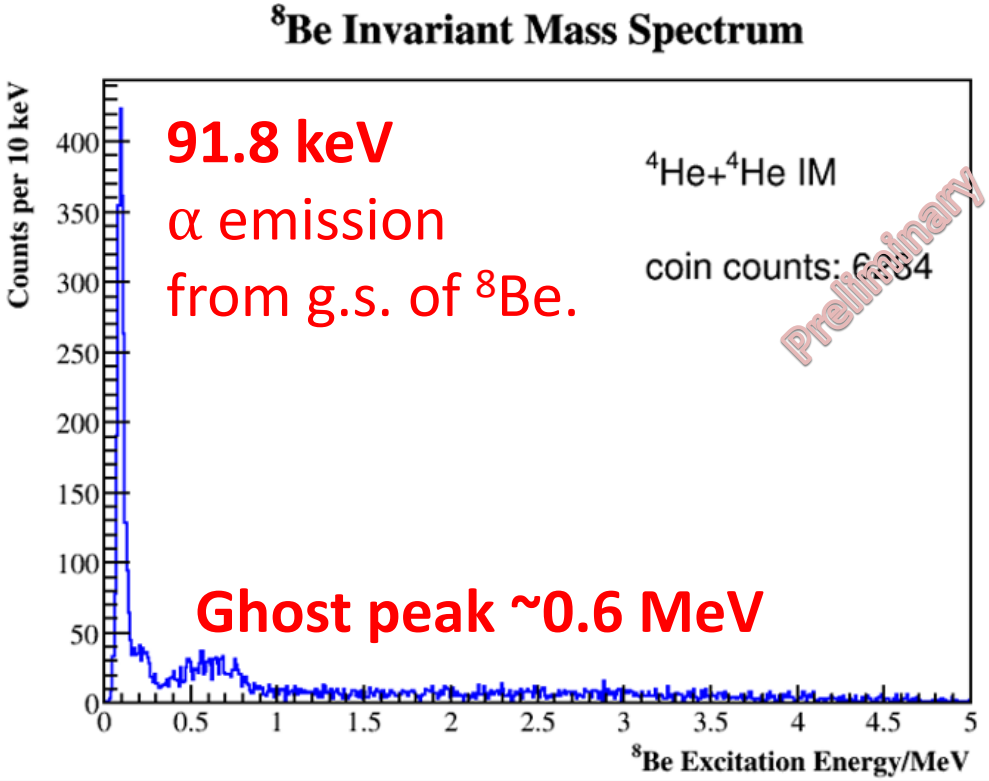


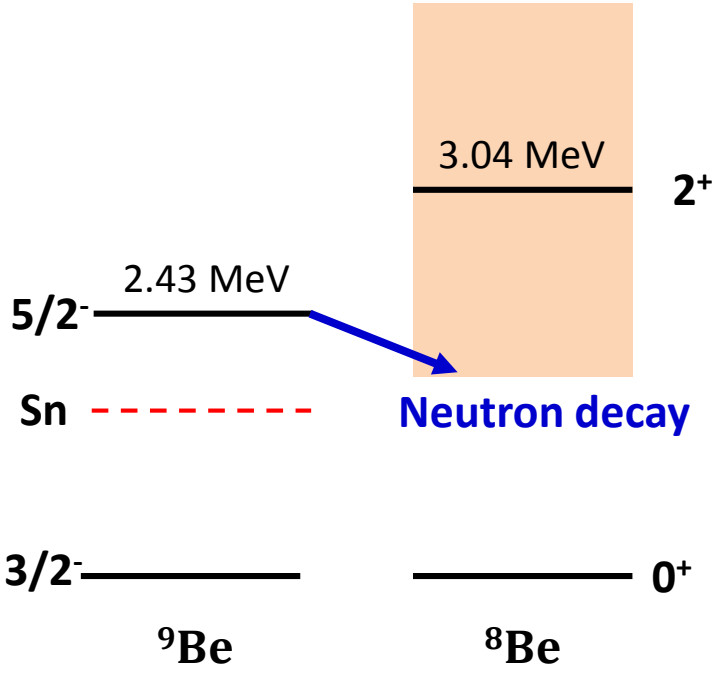


- ✓ Excellent DSSD Front & Back Energy Normalization
- ✓ Precisely Selection of DSSD Timing Information

Preliminary Data Analysis Results

Verification of the experimental technique: (^{4}He+^{4}He)





$^8\mathrm{Be} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He} + 91.8\ \mathrm{keV}$

the decay of the ^{8}Be ground state

The ghost peak at 0.6 MeV is in line with the decay of the 2.43 MeV state in ^{9}Be to the low-energy tail of the 2^+ state in ^{8}Be.

Preliminary Data Analysis Results

Target contaminations analysis: CD_2 (C, D, H)

E. Costanzo et. al., NIMA 295 (1990) 373-376

Inelastic break up reaction: $P + T \rightarrow 1 + 2 + T$

The momentum of the recoiled target:

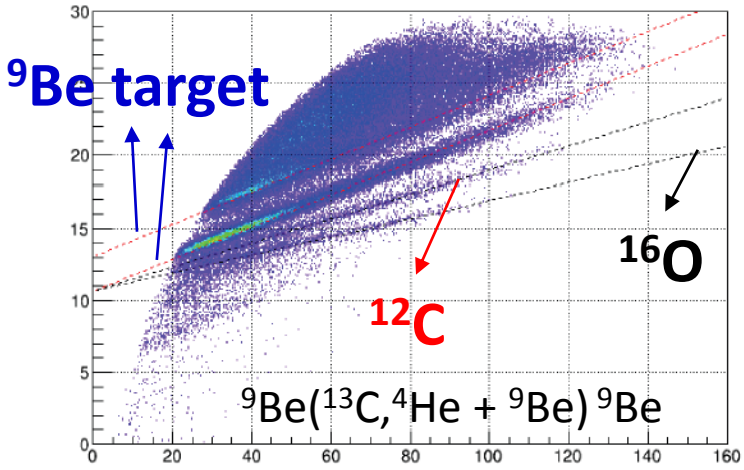
$$p_t^2 = (\boldsymbol{p}_P - \boldsymbol{p}_1 - \boldsymbol{p}_2)^2$$

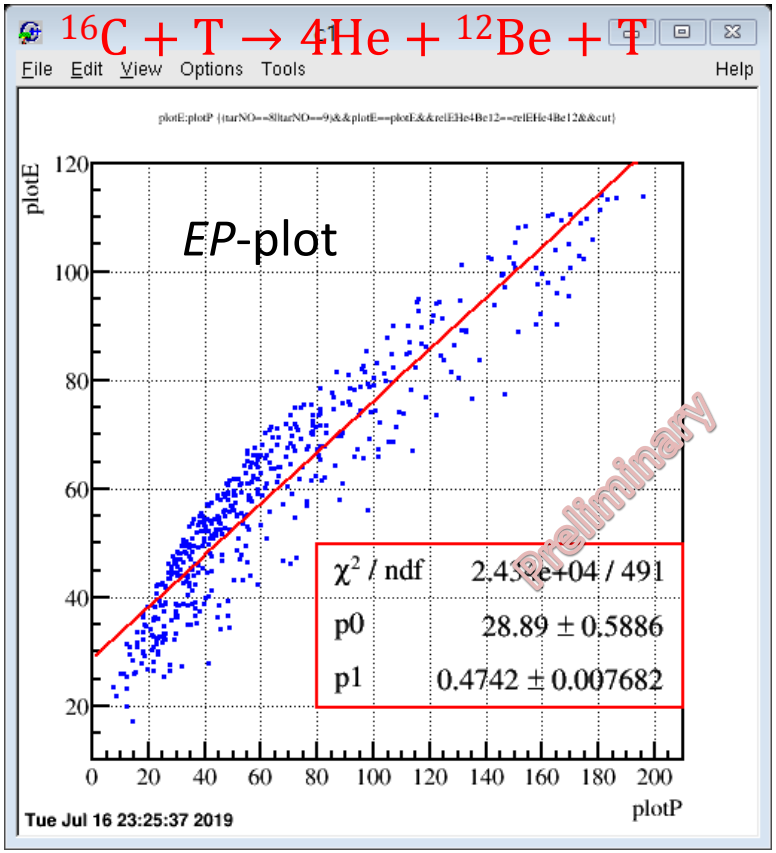
The energy of the recoiled target:

$$E_t = E_P - E_1 - E_2 + Q$$

EP-plot procedure:

$$E_t = p_t^2 / 2A_t$$





The fitted slope is about ½, indicating the recoiled particles are ^{2}H.

Acknowledgement

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Thanks for your attention!