Determination of the positive parity band for the $^{14}C + \alpha$ molecular rotation in ^{18}O

Yanlin Ye
School of Physics and State Key Lab of Nuclear Physics and Technology , Peking University

at INPC2019, Glasgow

Collaborators

PHYSICAL REVIEW C **99**, 064315 (2019)

Investigation of the $^{14}C + \alpha$ molecular configuration in ^{18}O by means of transfer and sequential decay reaction

B. Yang,[1] Y. L. Ye,[1,*] J. Feng,[1] C. J. Lin,[2] H. M. Jia,[2] Z. H. Li,[1] J. L. Lou,[1] Q. T. Li,[1] Y. C. Ge,[1] X. F. Yang,[1] H. Hua,[1] J. Li,[3] H. L. Zang,[1] Q. Liu,[1] W. Jiang,[4] C. G. Li,[1] Y. Liu,[1] Z. Q. Chen,[1] H. Y. Wu,[1] C. G. Wang,[1] W. Liu,[1] X. Wang,[1] J. J. Li,[1] D. W. Luo,[1] Y. Jiang,[1] S. W. Bai,[1] J. Y. Xu,[1] N. R. Ma,[2] L. J. Sun,[2] D. X. Wang,[2] Z. H. Yang,[5,6] and J. Chen[3]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

[2]*China Institute of Atomic Energy, Beijing 102413, China*

[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

[4]*Institute of High Energy Physics, CAS, Beijing 100049, China*

[5]*Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki 567-0047, Japan*

[6]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

Chinese Physics C Vol. 43, No. 8 (2019) 084001

Spin determination by in-plane angular correlation analysis in various coordinate systems*

Biao Yang(杨彪) Yan-Lin Ye(叶沿林)[1)] Jian-Ling Lou(楼建玲) Xiao-Fei Yang(杨晓菲)
Jing-Jing Li(李晶晶) Yang Liu(刘洋) Wei Liu(刘威) Han-Zhou Yu(余翰舟)

Outline

I. Introduction

II. Measurement

III. Results and discussion

IV. Summary

Expanding and clustering – the threshold effect

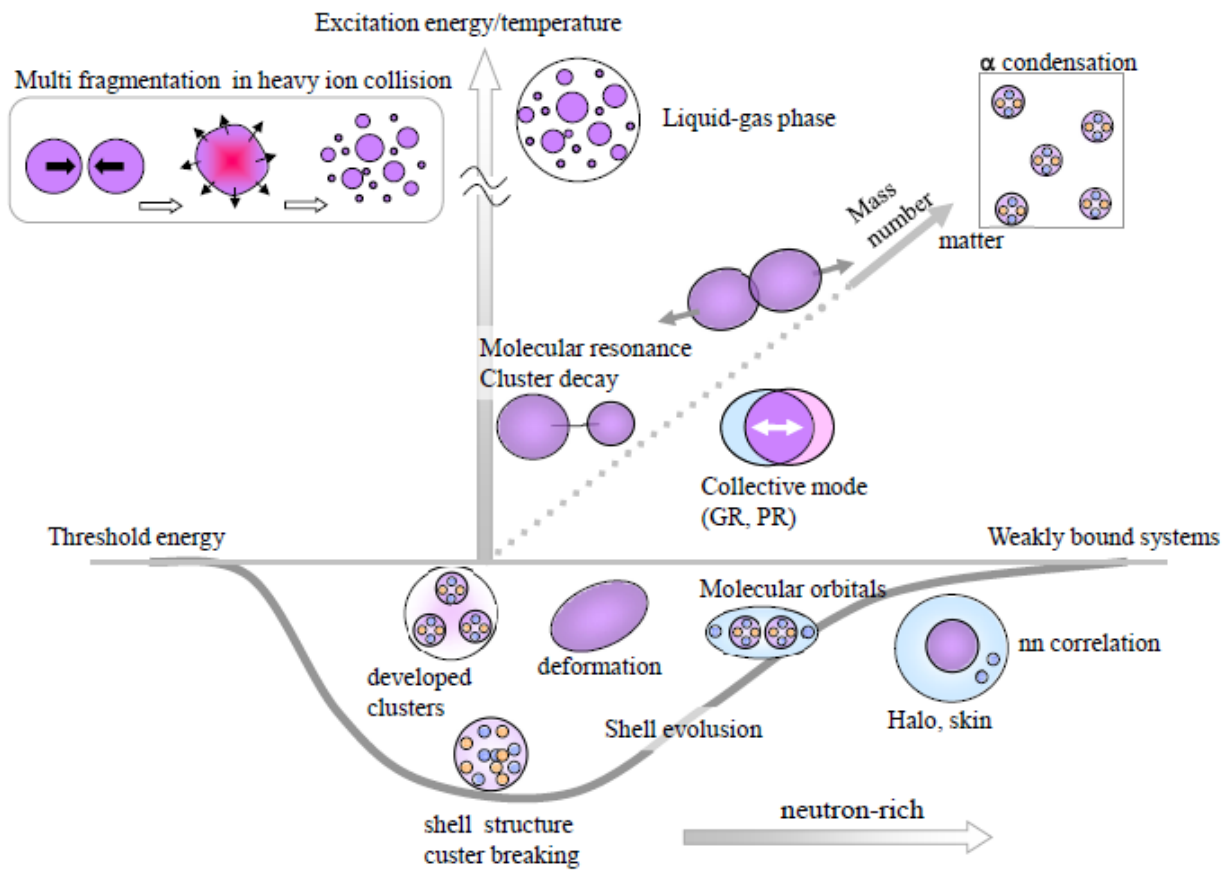
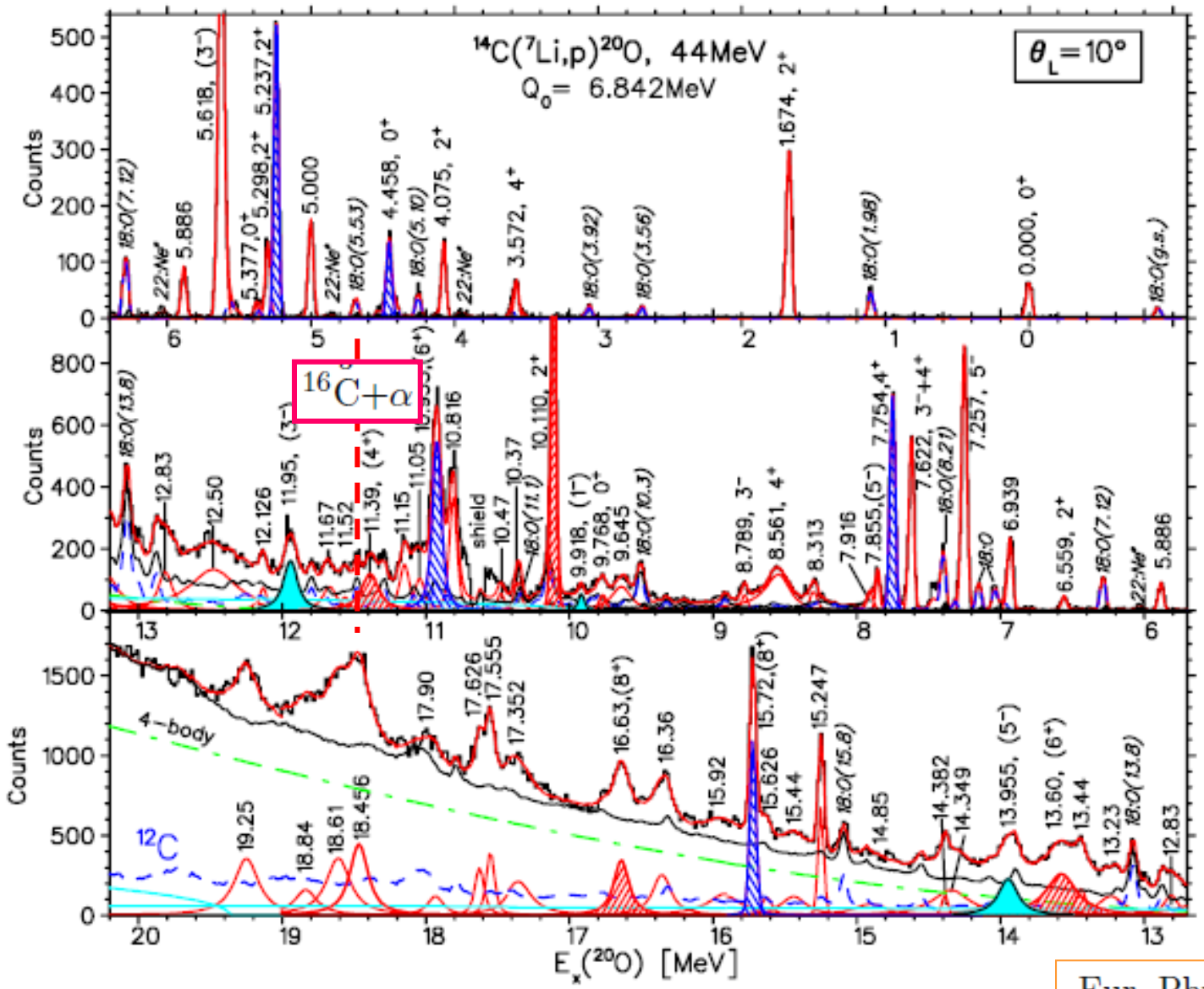


Fig. 1. Schematic figure for rich phenomena in nuclear systems.

From PTEP,2012,01A202

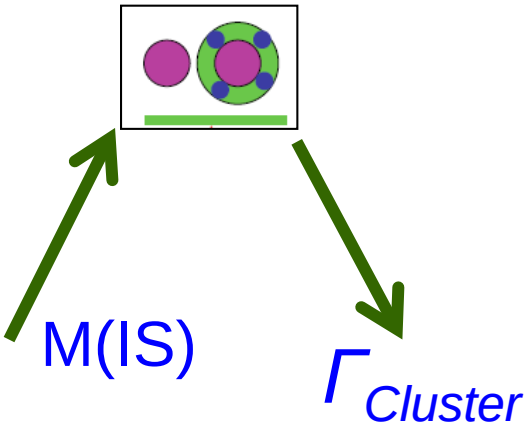
Examples at high excitation



Members of the $K = 0^+_2$, 1^-_2, and 0^+_4 bands of ^{20}O (with tentative assignments) are marked by downward hatched (blue), filled (cyan), and upward hatched (red) areas, respectively.

Eur. Phys. J. A (2011) **47**: 44

Observation criteria



i) E_x - spin systematics:
high moment of inertia

ii) Large cluster decay width:
large $\Gamma_{Cluster}/\Gamma$; $\gamma^2_{Cluster}$; $\theta^2_{Cluster}$

iii) Characteristic transition strength
large M(IS) !!

iv) Structural link in population and decay
selective path

Cluster-decay: E_x selectivity; AC/spin;
BR/SF; decay-path

Reflection asymmetric systems

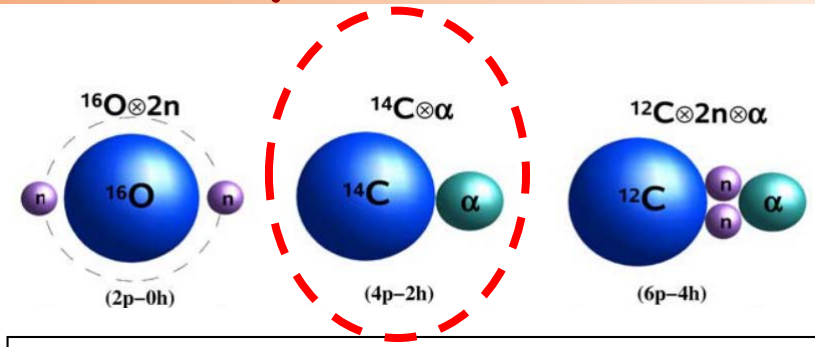
- symmetry breaking under reflection operation
- parity inversion doublet bands: almost parallel, separated by ~ 5 MeV

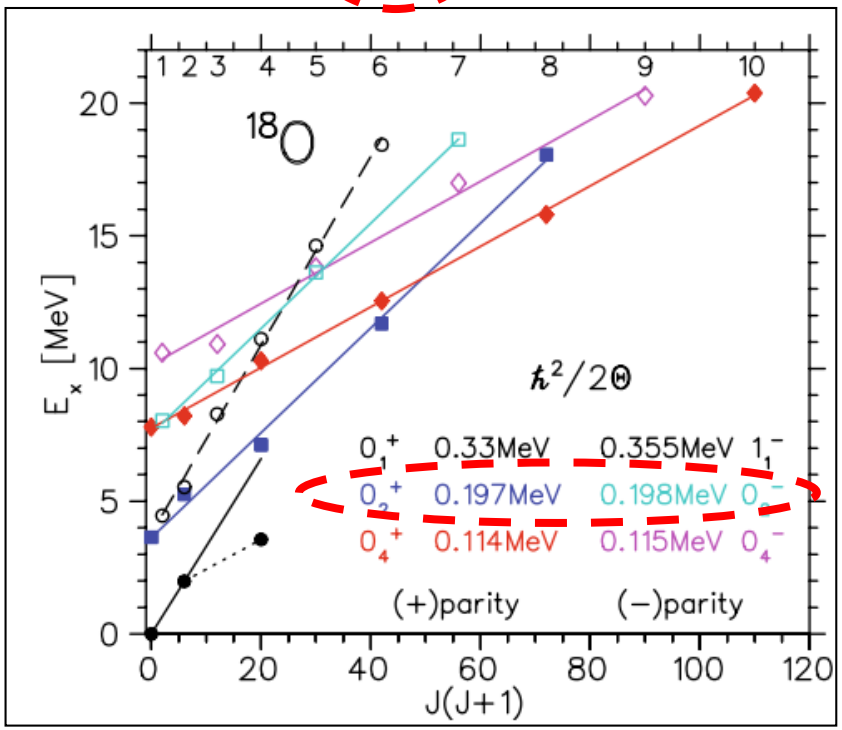
$$\phi_r = |^{14}\mathrm{C} \otimes \alpha\rangle \ (\alpha\text{-cluster right})$$

$$\phi_l = |\alpha \otimes {}^{14}\mathrm{C}\rangle \ (\alpha\text{-cluster left})$$

$$\Phi^{\pm} = N(\phi_r \pm \phi_l).$$

- observed in some even-even stable nuclei.





W. von Oertzen, Eur. Phys. J. A 43,17-33(2010)

Question

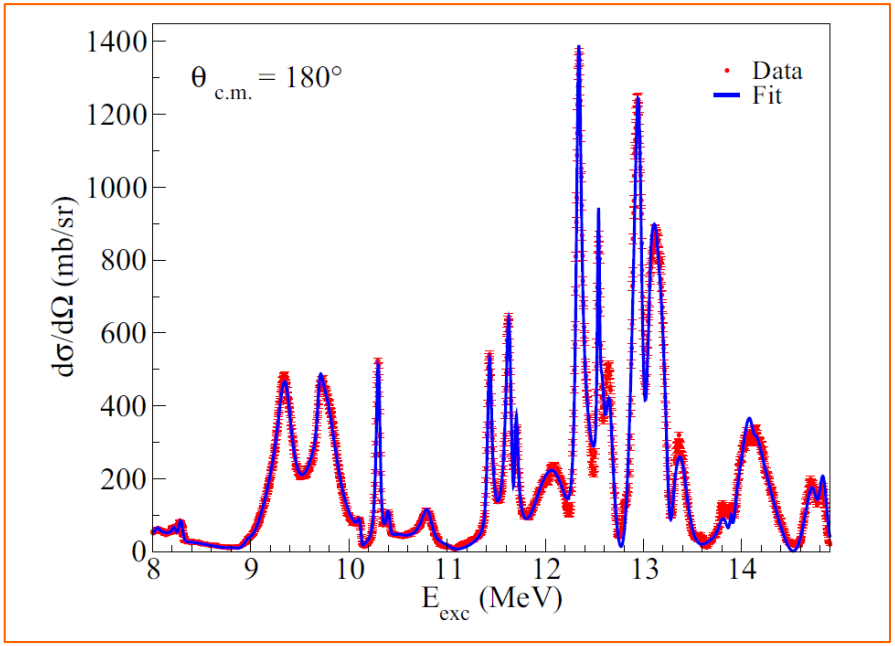
M. L. Avila, PHYSICAL REVIEW C **90**, 024327 (2014)

α-cluster structure of ^{18}O

Resonant scattering; R-matrix analysis;

Finding:

- Previously classified molecular states are mostly with very small SF;
- The larger SFs are very much fragmented.



* Importance to determine the spins, cluster decay BRs (SFs) of the possible molecular states.

Outline

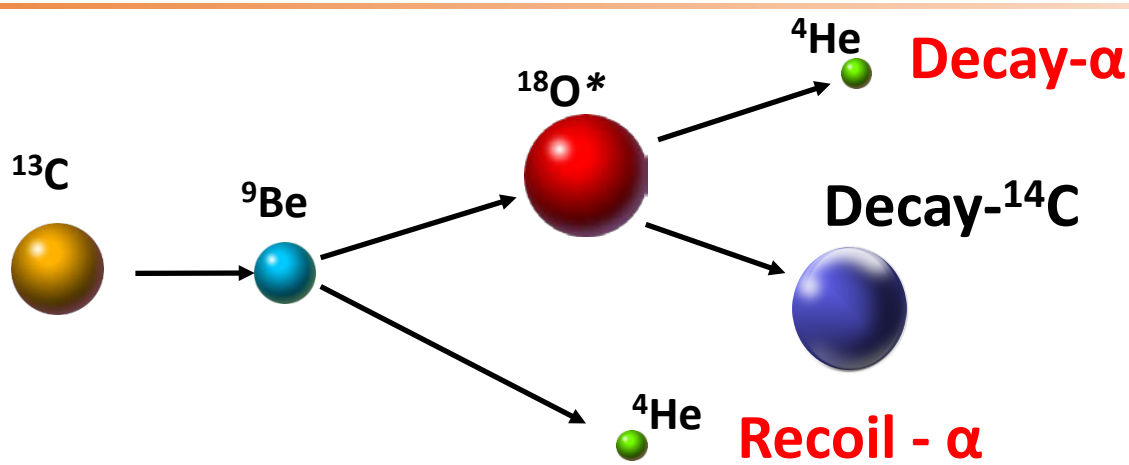
I. Introduction

II. Measurement

III. Results and discussion

IV. Summary

Reaction channel



$^{13}C + {}^{9}Be \rightarrow {}^{18}O + \alpha$ Q: 12.83 MeV

$\hookrightarrow {}^{14}C + \alpha$ Q: 6.60 MeV

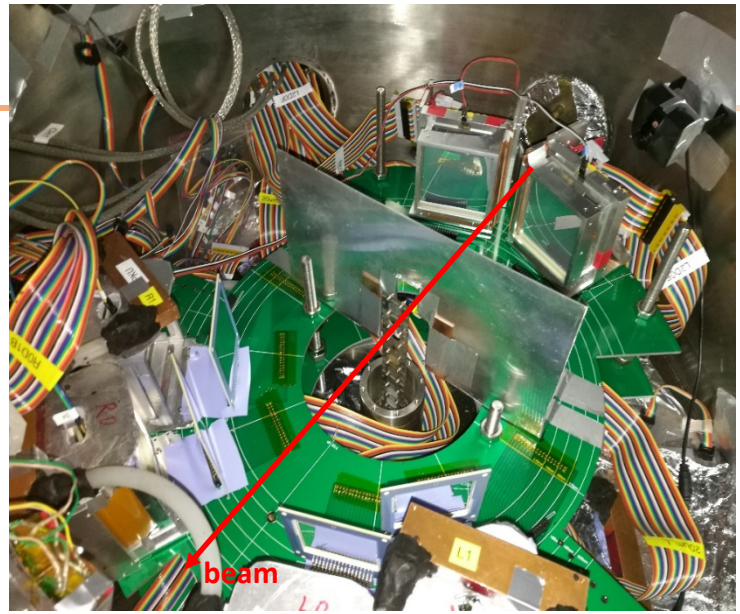
- beam: ^{13}C; 65MeV

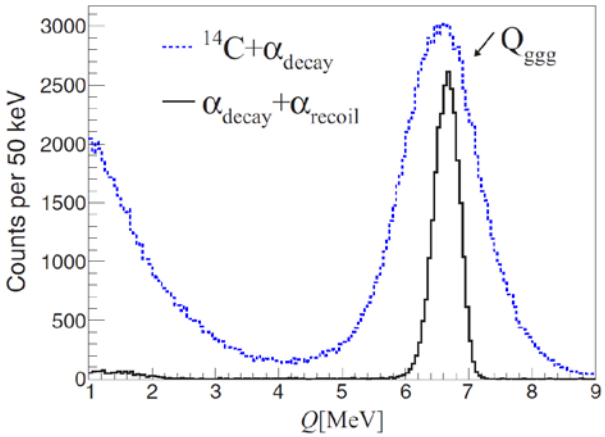
  target: ^{9}Be; 1.4μm

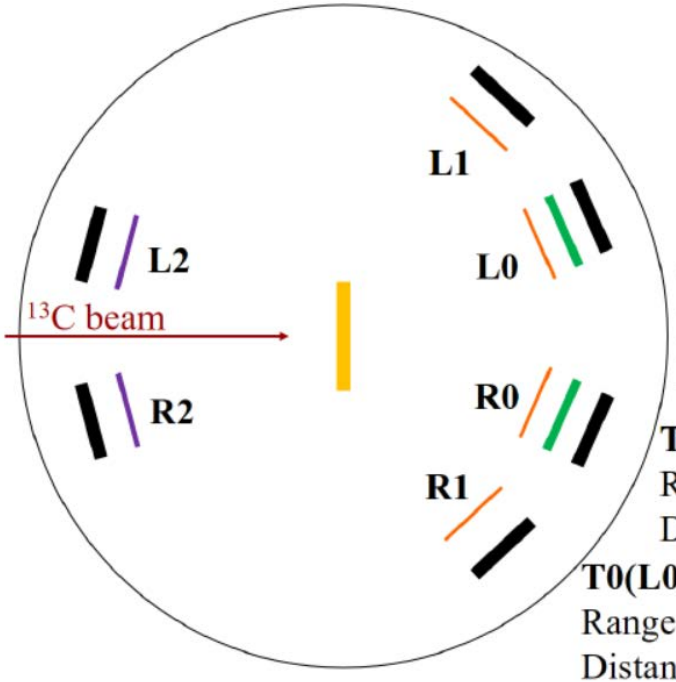
Detector setup

Combinations:

- L0+R0: $^{14}C + \alpha_{dec.}$
- L0+R0/R2: $\alpha_{dec.} + \alpha_{rec.}$







W1(40um)
BB7(60um)
BB7(300um)
SSD(1500um)

T2(L2/R2):
Range : 155~175deg
Distance: 175mm/195mm

T1(L1/R1):
Range : 37~57deg
Distance: 140mm/200mm

T0(L0/R0):
Range : 15~35deg
Distance: 160mm/205mm/225mm

Outline

I. Introduction

II. Measurement

III. Results and discussion

IV. Summary

High resolution energy-spectra

E_x(IM):

7-19MeV; 28 states;

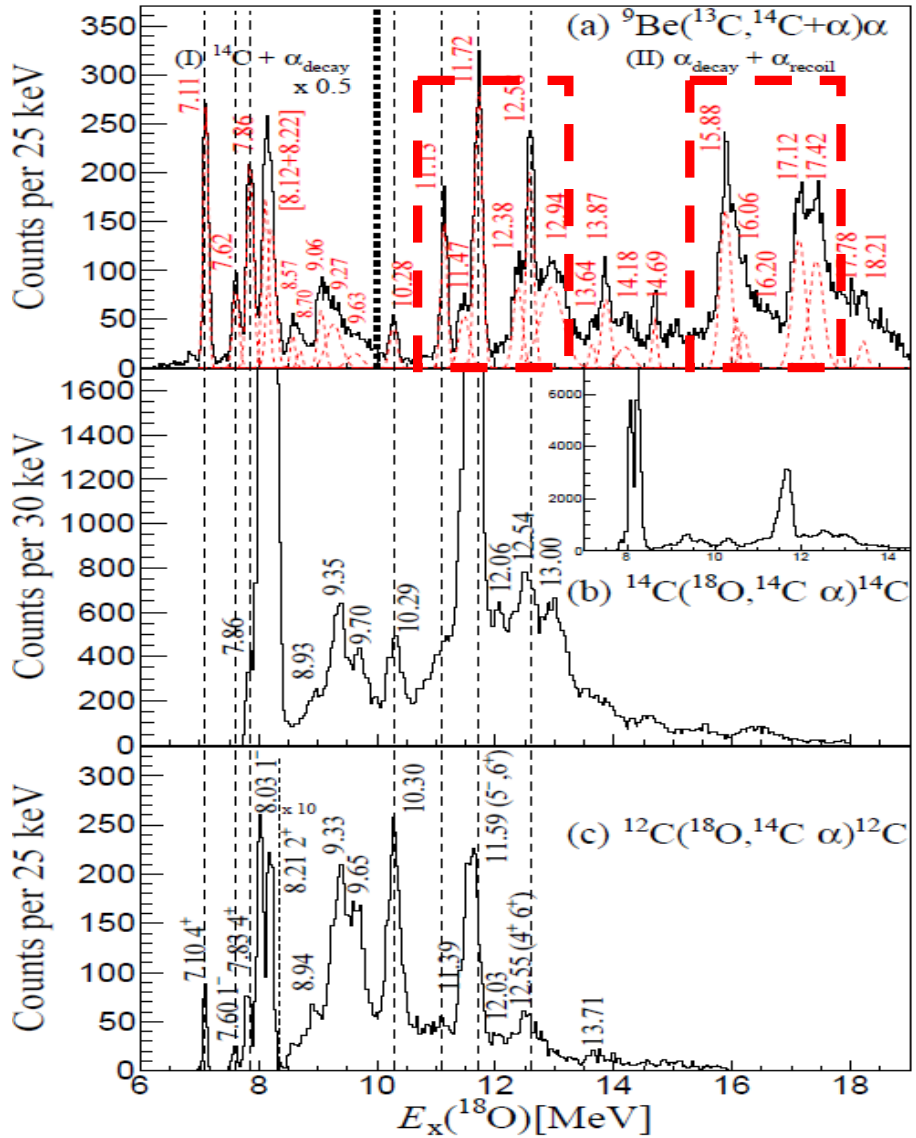
New states E_x > 14 MeV

High resolution:

11.15/1.47/111.72MeV,

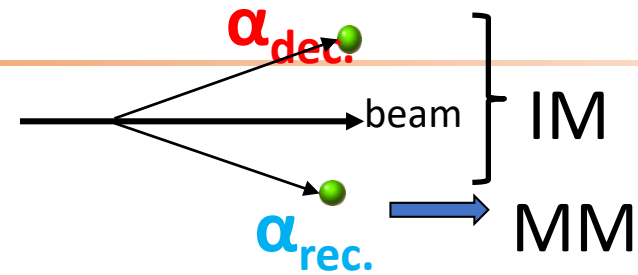
12.38/12.58/12.94 MeV

Well resolved.



- Plot b : N. Curtis et al., Phys. Rev.C 66, 024315(2002)
- Plot c : W.D.M. RAE et al., Nucl. Phys. A 420(1984)320-350

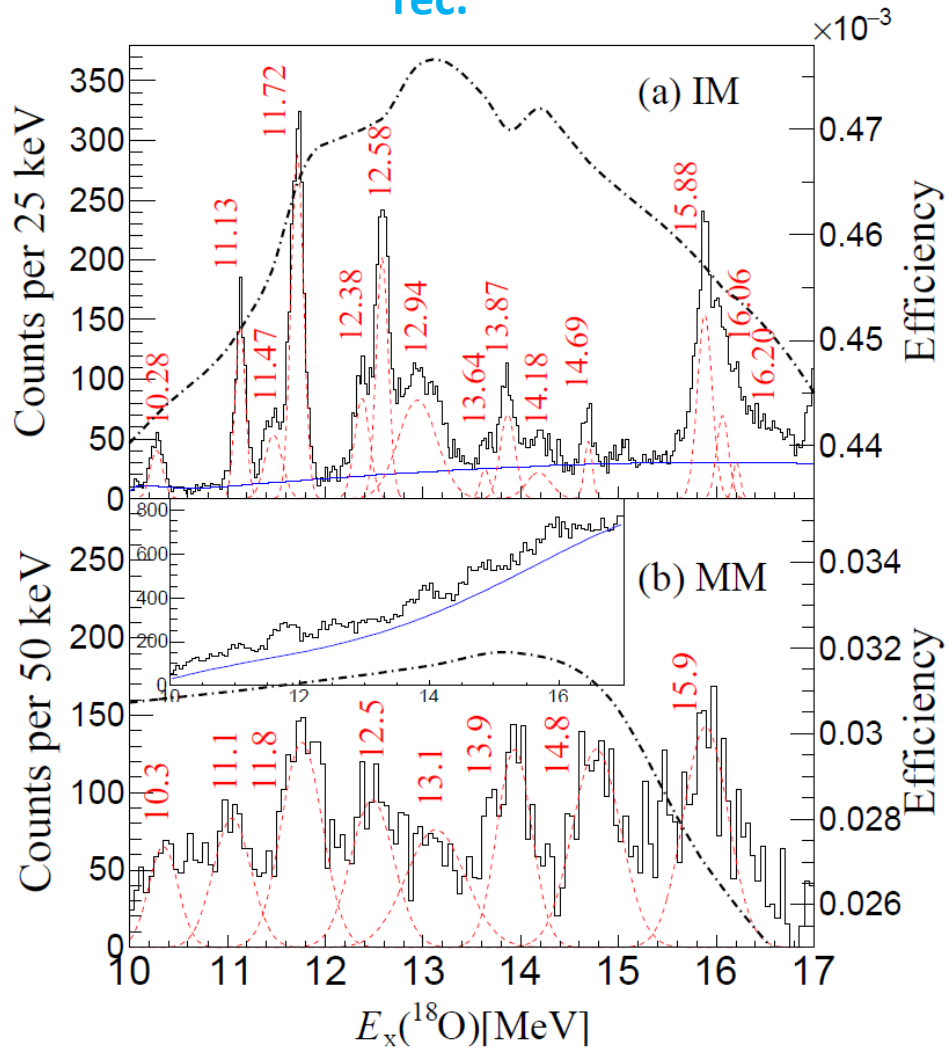
Branching Ratio



$$BR = \frac{N_{\mathrm{IM}}/\epsilon_{\mathrm{IM}}}{100\times N_{\mathrm{MM}}/\epsilon_{\mathrm{MM}}}$$

Obtained for 14 states

IM/MeV	MM/MeV	Branching Ratio
10.28	10.3	0.37±0.13
11.13	11.1	0.65±0.22
11.47	11.8	> 0.23±0.08
11.72		> 0.89±0.29
12.38	12.5	> 0.41±0.14
12.58		> 0.79±0.26
12.94	13.1	> 0.94±0.31
13.64	13.9	> 0.07±0.02
13.87		> 0.32±0.11
14.18		> 0.16±0.05
14.69	14.8	0.08±0.03
15.88	15.9	> 0.57±0.19
16.06		> 0.09±0.03
16.20		> 0.09±0.03



Angular correlation and spin [CPC43(2019)084001]

$$a(A, B^* \to c + C)b,$$

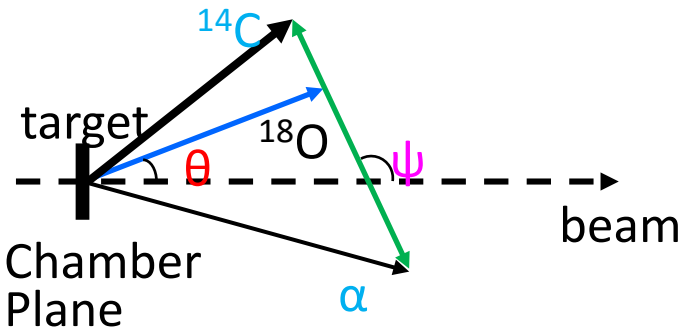
Spin 0 for c & C

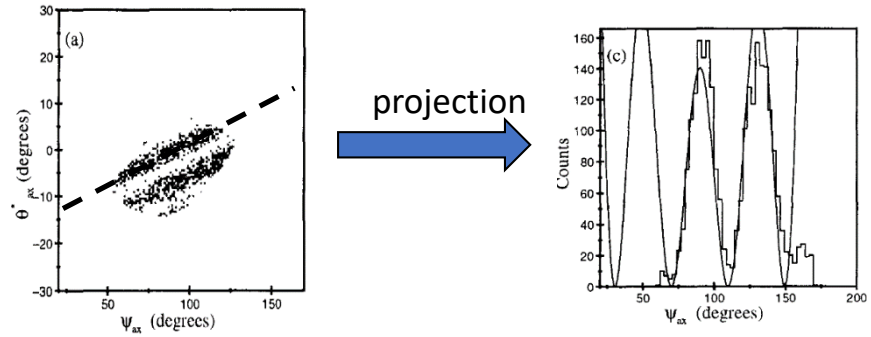
$$W(\theta^* = 0°, \psi' = \psi - \alpha\theta^*)$$

$$\alpha = \frac{l_i - J}{J},$$

$$l_i = r_0(A_p^{1/3} + A_t^{1/3})\sqrt{2\mu E_{\text{c.m.}}}$$

$$|P_J(\cos(\psi))|^2.$$





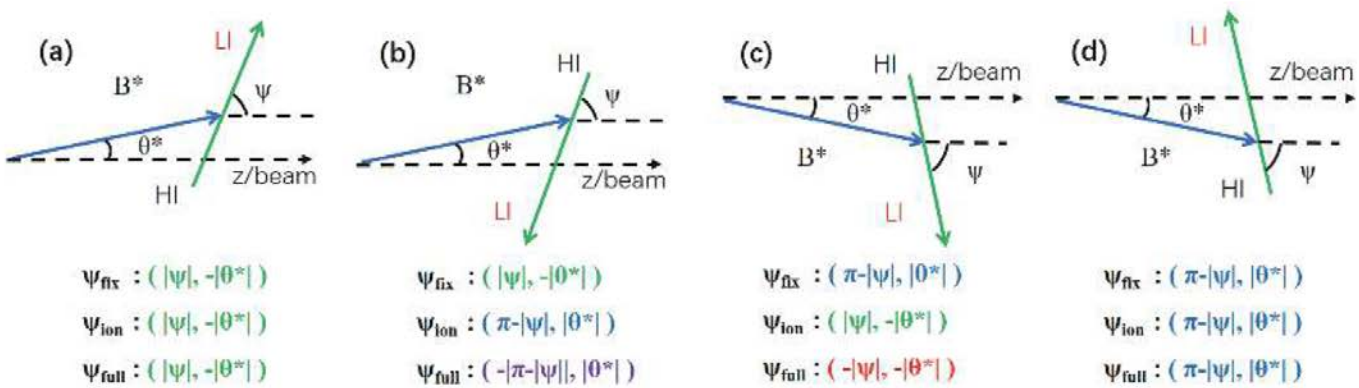
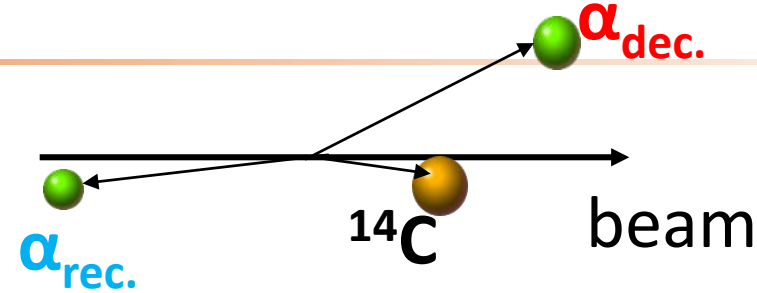


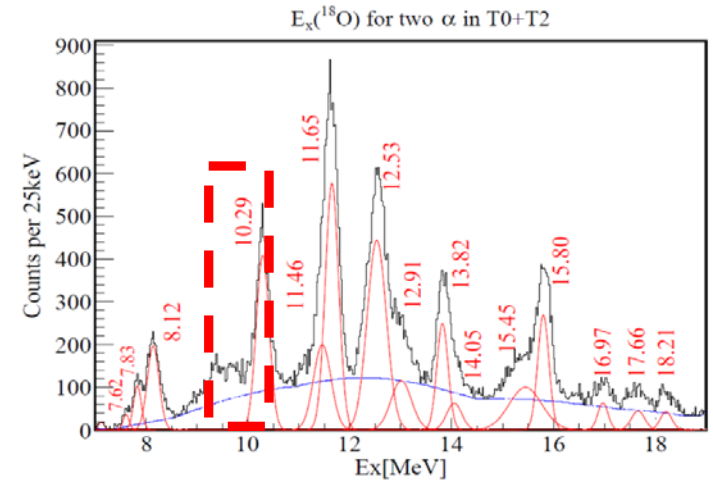
Fig. 3. (color online) Schematic diagram of the four symmetric reaction-decay processes in the chamber plane. (a) and (b) are parity-symmetric processes, while (c) and (d) are their axial-symmetric processes, respectively. All processes are identified by the angles θ^* and ψ defined in various coordinate systems, as described in the text.

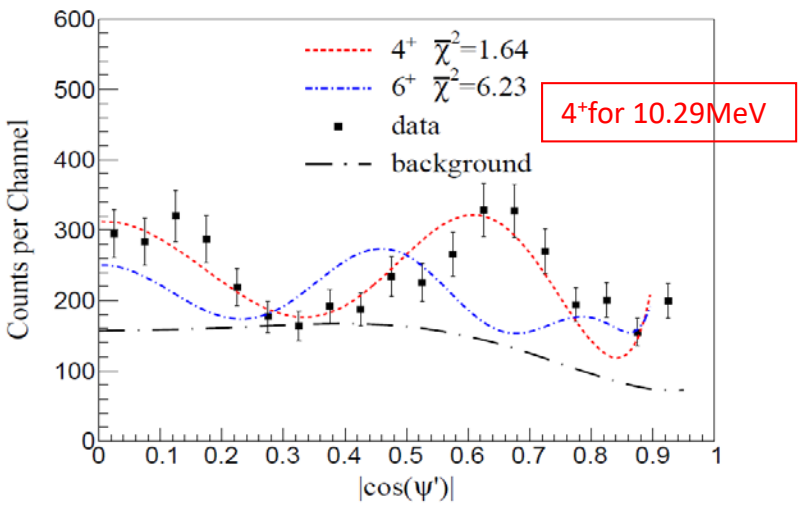
For the 10.3 MeV state

$\alpha_{dec.}$ (T0)+ $\alpha_{rec.}$ (T2) events

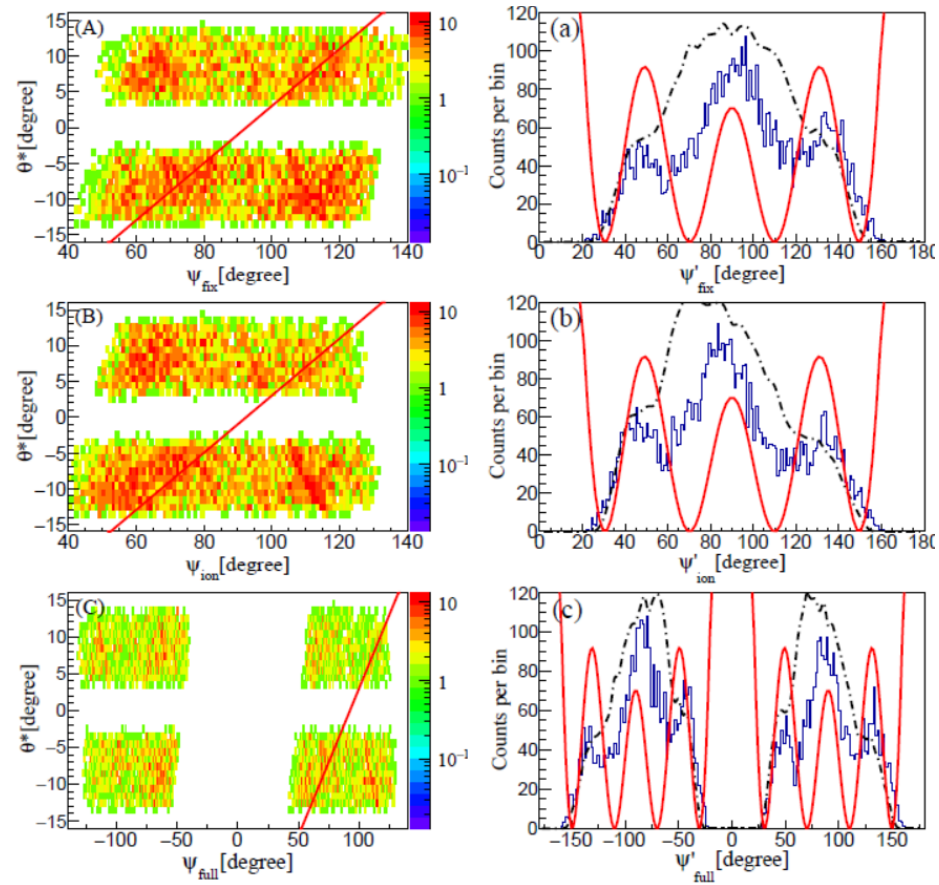
θ_{cm}: 4°~15°







$4^+$for 10.29MeV



Positive-parity band confirmed

Prediction (2010):

0^+(3.63MeV), bound;

2^+(5.24MeV), bound

4^+(7.11MeV), previously determined

6^+(11.69MeV), now separated and large SF determined

Present work				
E_x(MeV)	J^π	Γ_{tot}(keV)	BR	θ^2_α
10.28(4)[2]	4^+	39(19)	0.37(0.13)	0.07
11.13(5)[2]		2(1)	0.65(0.22)	<0.01 (if 2^+)[4]
11.47(5)[2]		61(14)	>0.23(0.08)	0.02 (if 4^+)[5]
				0.07 (if 5^-)[4]
11.72(5)[2]		32(5)	>0.89(0.29)	0.56 (if 6^+)[4,8]
12.38(5)[2]		23(12)	>0.41(0.14)	0.02 (if 5^-)[4,5]
12.58(5)[2]		25(8)	>0.79(0.26)	0.02 (if 4^+)[7,8]
				0.15 (if 6^+)[4,7]
12.94(5)[2]		337(16)	>0.94(0.31)	0.10 (if 2^+)[6,7]
				0.50 (if 5^-)[4]
				0.14 (if 3^-)[4]
13.64(6)[2]		35(26)	>0.07(0.02)	<0.01 (if 2^+)[4]
13.87(6)[2]		71(17)	>0.32(0.11)	0.02 (if 5^-)[4]
				0.01 (if 4^+)[4]
				<0.01 (if 3^-)[4]
14.18(6)[2]		169(27)	>0.16(0.05)	0.02 (if 5^-)[4]
14.69(6)[2]		21(18)	0.08(0.03)	<0.01 (if 5^-)[4]

[1] Phys. Rev. C, 1985, 31: 2274-2284
[2] Phys. Rev. C, 2002, 66: 024315
[3] Phys. Rev. C, 2014, 90: 024327

Negative-parity band not-confirmed

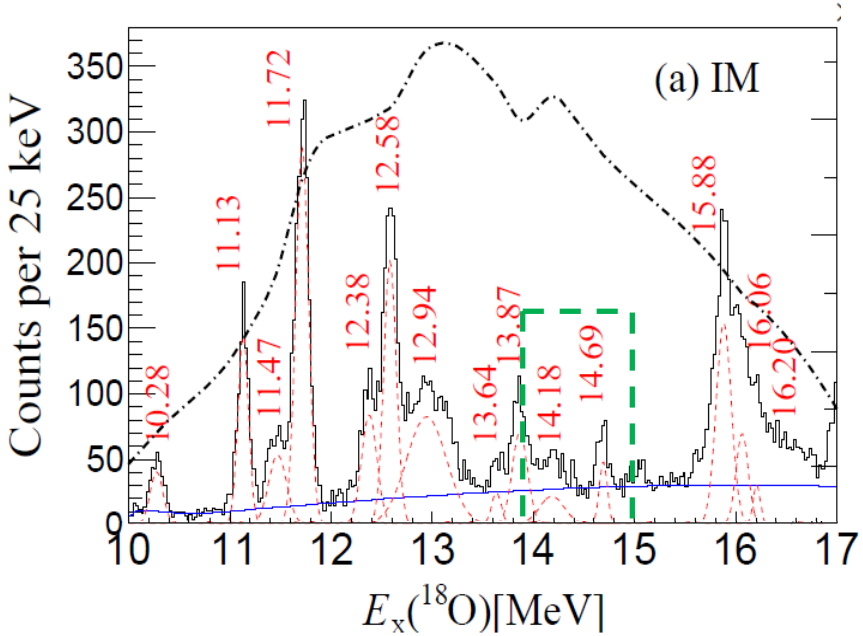
Prediction (2010):

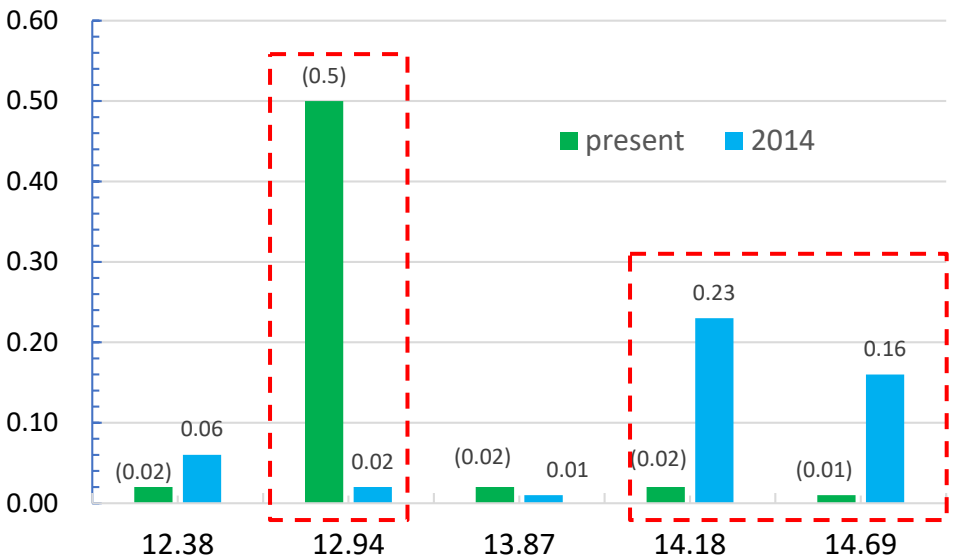
1- (9.6MeV),

3- (9.8MeV),

5- (13.1MeV)

SF fragmented?





Present data based on precise coincident measurement. PRC99(2019)064315

Ref. PRC90(2014)024327

Outline

I. Introduction

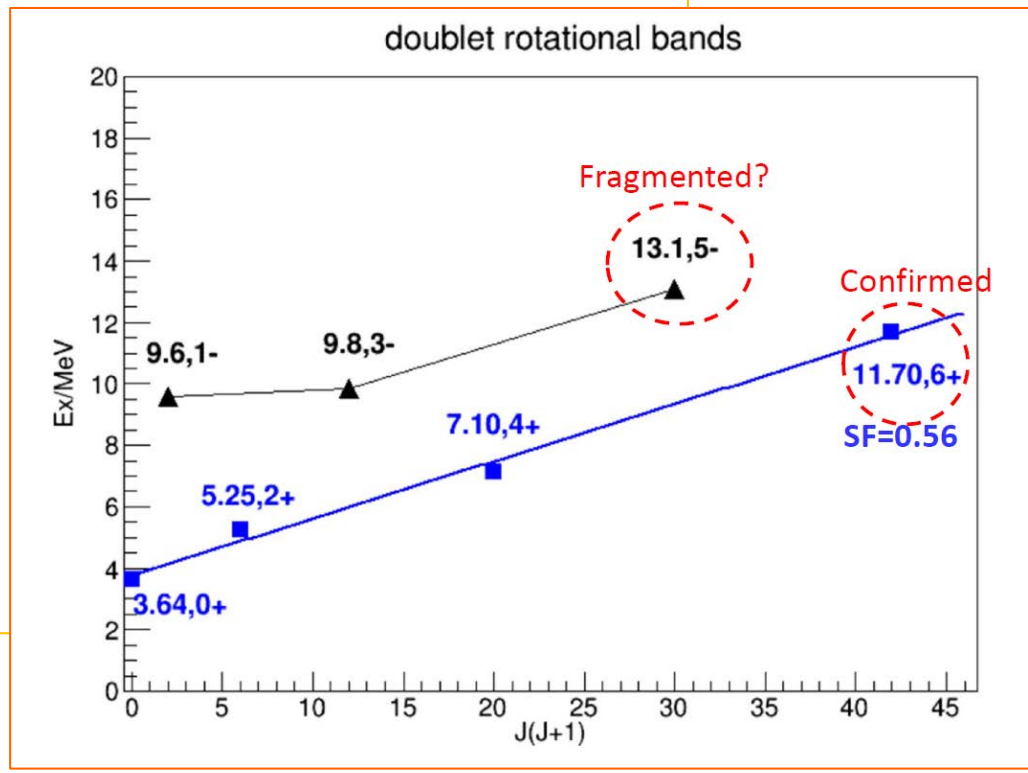
II. Measurement

III. Results and discussion

IV. Summary

Summary

- 28 α-decay states in ^{18}O were observed with high precision, including a few new states.
- α-decay BR are extracted for 14 resonances, and their SF are deduced by usinf existing tentative spins.
- Spin-parity of 4^+ is determined for the 10.3 MeV atate, by using the AC method.
- the positive parity band is conformed for the 14C + α configuration in ^{18}O, whereas the related negative-parity band is still questionable.



Thank you for your attention!

TABLE I. Summary of the excited states with $\alpha+{}^{14}$C configuration, observed in the present ^{9}Be(^{13}C, ^{18}O$^{*} \rightarrow {}^{14}$C$+\alpha)\alpha$ reaction. For comparison, results from previous resonant scattering and cluster-decay measurements are also presented. Spins in brackets mean tentative assignments. For comparative purposes, the dimensionless reduced α width θ_{α}^{2} (cluster SF) is deduced under the same definition as in Ref. [24], namely $\theta_{\alpha}^{2} = \gamma^{2}/(\hbar^{2}/\mu R^{2})$ and $R = 5.2$ fm. In this table, only statistical errors are presented for all TWs and BRs extracted in the present work.

Present work					Resonant scattering [24]					^{14}C(^{18}O, ^{14}Cα)^{14}C [28]		^{12}C(^{18}O, ^{14}Cα)^{12}C [29]		^{12}C(^{18}O, ^{14}Cα)^{12}C [26]	
E_x (MeV)	J^{π}	Γ_{tot} (keV)	BR	θ_{α}^{2}	E_x (MeV)	J^{π}	Γ_{tot} (keV)	Γ_{α} (keV)	θ_{α}^{2}	E_x (MeV)	J^{π}	E_x (MeV)	J^{π}	E_x (MeV)	J^{π}
7.11(3)[a]														7.10	4^{+}
7.62(3)[a]														7.60	1^{-}
7.86(3)[a]										7.86				7.83	5^{-}
[8.12(3)][a]										8.04				8.03	1^{-}
[8.22(3)][a]										8.22				8.21	2^{+}
8.57(4)[a]															
8.70(4)[a]															
9.06(4)[a]					8.96(1)	(4^{+})	70(30)	5(1)	0.20	8.93				8.94	
9.27(4)[a]					9.35(2)	3^{-}	180(30)	110(30)	0.48	9.35	$(2^{+}, 3^{-})$			9.33	
9.63(4)[a]					9.70(1)	3^{-}	140(10)	15(2)	0.04	9.70	$(1^{-}, 2^{+}, 3^{-})$			9.65	
10.28(4)[b]	4^{+}	39(19)	>0.37(0.03)	0.07	10.290(4)	4^{+}	29(4)	19(2)	0.09	10.29	$(3^{-}, 4^{+}, 5^{-})$	10.29		10.30	4^{+}
11.13(5)[b]		2(1)	>0.65(0.03)	<0.01 (if 2^{+})[d]	10.98(4)	2^{+}	280(130)	20(10)	0.01						
11.47(5)[b]		61(14)	>0.23(0.01)	0.02 (if 4^{+})[d]	11.43(1)	4^{+}	40(10)	30(10)	0.05					11.39	
				0.07 (if 5^{-})											
11.72(5)[b]		32(5)	>0.89(0.03)	0.56 (if 6^{+})[d,h]	11.699(5)	6^{+}	23(2)	12(1)	0.23	11.62	5^{-}	11.63		11.59	$(5^{-}, 6^{+})$
12.38(5)[b]		23(12)	>0.41(0.02)	0.02 (if 5^{-})[d,e]	12.339(4)	5^{-}	39(4)	26(2)	0.06						
12.58(5)[b]		25(8)	>0.79(0.03)	0.02 (if 4^{+})[g,h]	12.542(4)	4^{+}	6(3)	5(2)	<0.01	12.54		12.61	$(2,4,6)^{+}$	12.55	$(4^{+}, 6^{+})$
				0.15 (if 6^{+})[d,g,h]	12.576(9)	6^{+}	70(20)	50(10)	0.38						
12.94(5)[b]		337(16)	>0.94(0.04)	0.10 (if 2^{+})[d,f,g]	12.90(3)	2^{+}	310(30)	285(30)	0.09	13.00	$(2,4)^{+}$	13.11	$(2,4)^{+}$		
				0.50 (if 5^{-})[d]	12.94(1)	5^{-}	40(10)	15(2)	0.02						
				0.14 (if 3^{-})[d]	12.98(4)	3^{-}	1040(200)	770(120)	0.32						
13.64(6)[b]		35(26)	>0.07(0.01)	<0.01 (if 2^{+})[d]	13.69(1)	2^{+}	530(120)	40(20)	0.01						
13.87(6)[b]		71(17)	>0.32(0.02)	0.02 (if 5^{-})[d]	13.82(1)	5^{-}	25(6)	3(1)	<0.01			13.94		13.71	
				0.01 (if 4^{+})[d]	13.89(1)	4^{+}	24(10)	14(6)	0.01						
				<0.01 (if 3^{-})[d]	13.96(2)	3^{-}	150(50)	80(10)	0.03						
14.18(6)[b]		169(27)	>0.16(0.01)	0.02 (if 5^{-})[d]	14.1(1)	5^{-}	560(70)	260(20)	0.23						
14.69(6)[b]		21(18)	>0.08(0.01)	<0.01 (if 5^{-})[d]	14.7(1)	5^{-}	280(100)	230(80)	0.16	14.58					
15.88(6)[b]		44(10)	>0.57(0.02)												
16.06(6)[b]															
16.20(6)[b]												16.20			
17.12(6)[b]															
17.42(7)[b]												17.40			
17.81(9)[c]															
18.25(9)[c]															

[a]From events with ^{14}C $+ \alpha_{decay}$ detected in the same telescope (L0/R0).
[b]From events with $\alpha_{decay} + \alpha_{recoil}$ detected in two telescopes (L0+R0).
[c]From events with ^{14}C $+ \alpha_{decay}$ detected in two telescopes (L0+R0).
[d]Possible spin assignment from Ref. [24].
[e]Possible spin assignment from Ref. [25].
[f]Possible spin assignment from Ref. [28].
[g]Possible spin assignment from Ref. [29].
[h]Possible spin assignment from Ref. [26].