

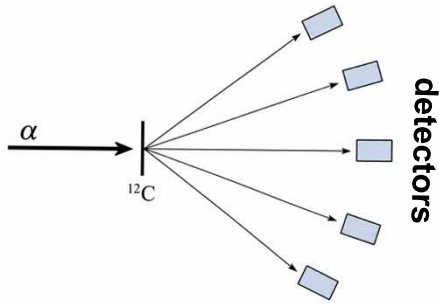
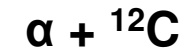
α -cluster structure of neutron rich nuclei between ^{16}O and ^{20}Ne .

Many-body correlations, phase transitions, and clustering: how to identify and quantify them?

CEA Saclay

V.Z. Goldberg September 10 2026

Conventional resonant scattering



Advantage

Perfect energy resolution (3-5 keV) provided by electrostatic accelerators

Disadvantage

Very thin target, many small steps of the beam energy

Selectivity: $(\Gamma_\alpha/\Gamma_{\text{tot}})^2$ Analysis is terrible.

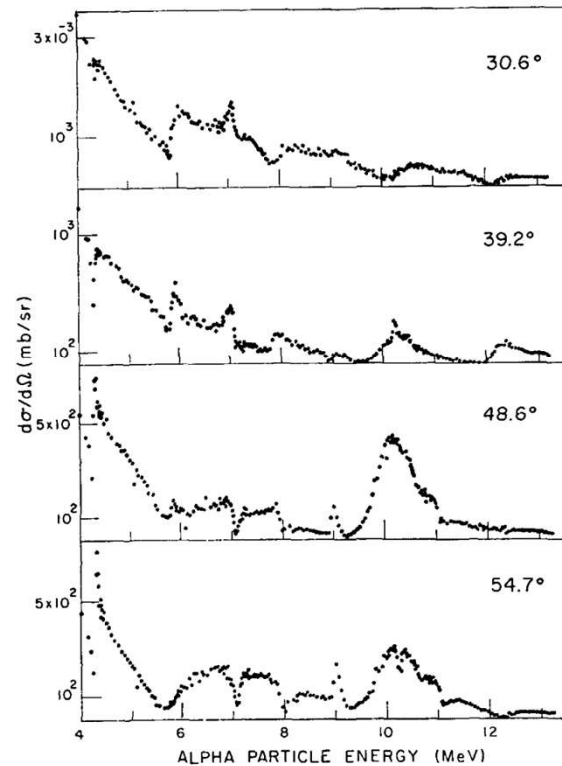


Fig. 4. Excitation functions at the c.m. angles of 30.6°, 39.2°, 48.6° and 54.7°.

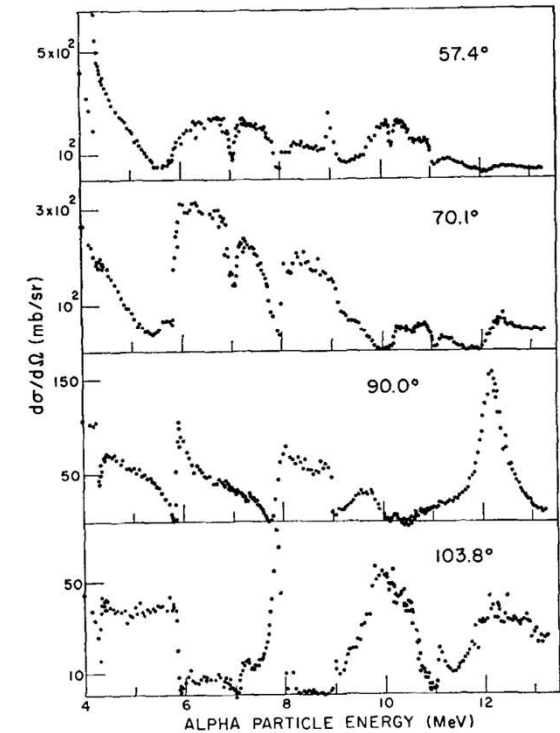


Fig. 5. Excitation functions at the c.m. angles of 57.4°, 70.1°, 90.0° and 103.8°.

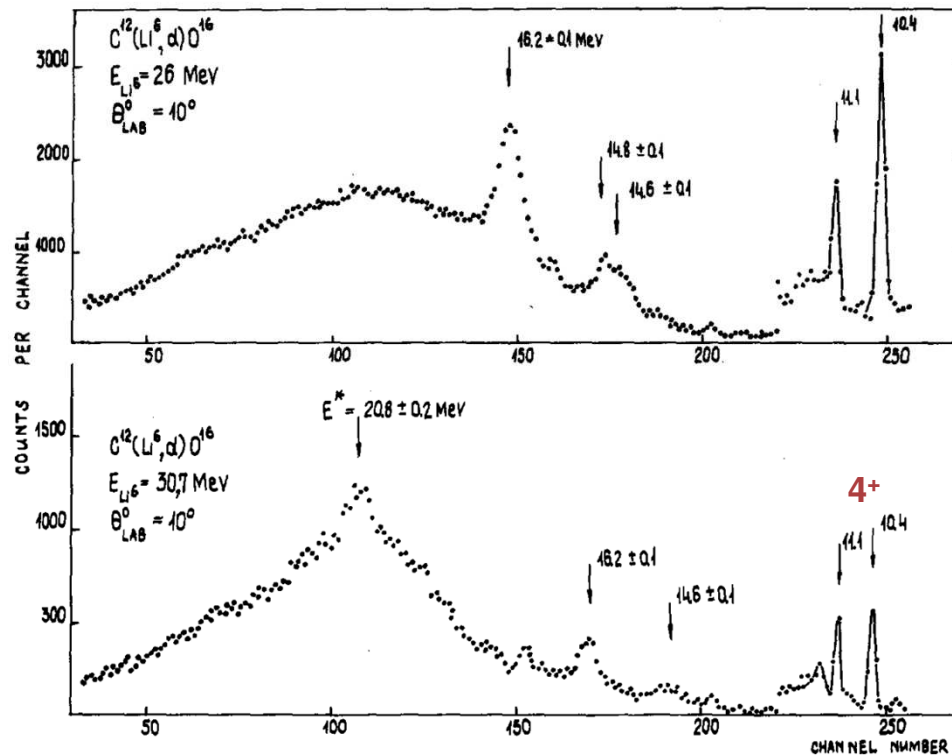
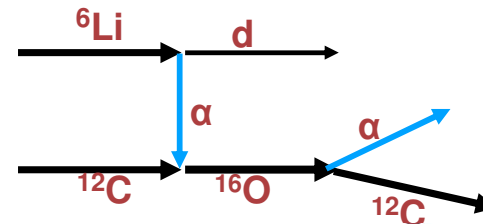
T.P.Marvin and P.P.Singh Nucl.Phys. A180 (1972) 282

Energy levels of ${}^{16}\text{O}$ between 10.0 and 17.1 MeV excitation

$(^6\text{Li},d)$ and $(^7\text{Li},t)$ α cluster transfer reactions d- α correlations in reactions induced by ^6Li

Advantage
Selectivity ~ S factor
Disadvantage

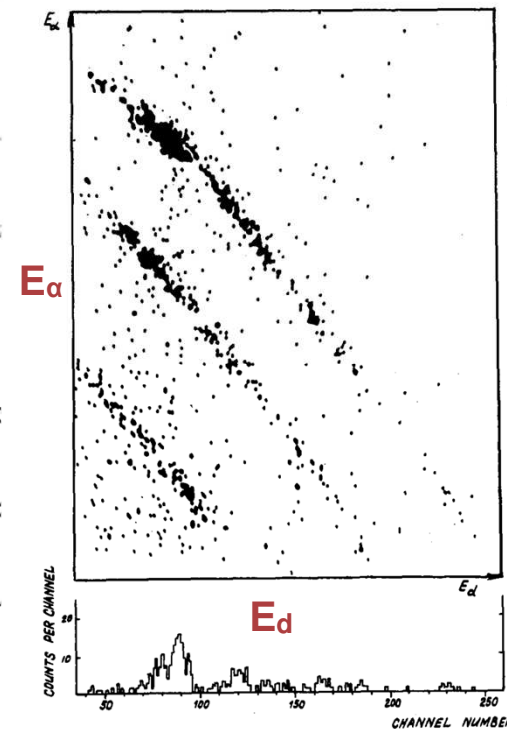
Li break up and many parameter analysis



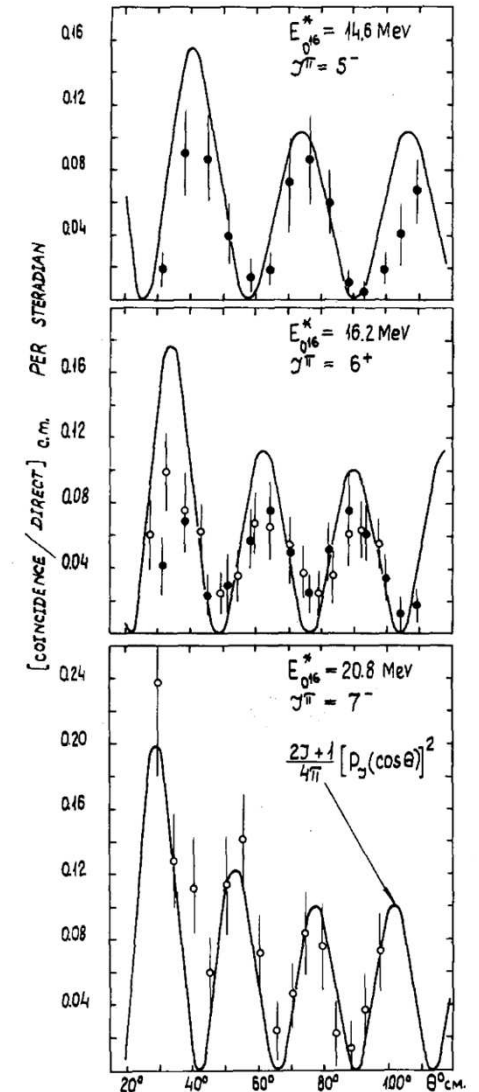
d spectra from $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ reaction

K. P. ARTEMOV, V. Z. GOLDBERG, I. P. PETROV et al., Phys. Lett. 37B(1971)

61



Two-dimensional d- α energy spectrum and projection of the ground state locus



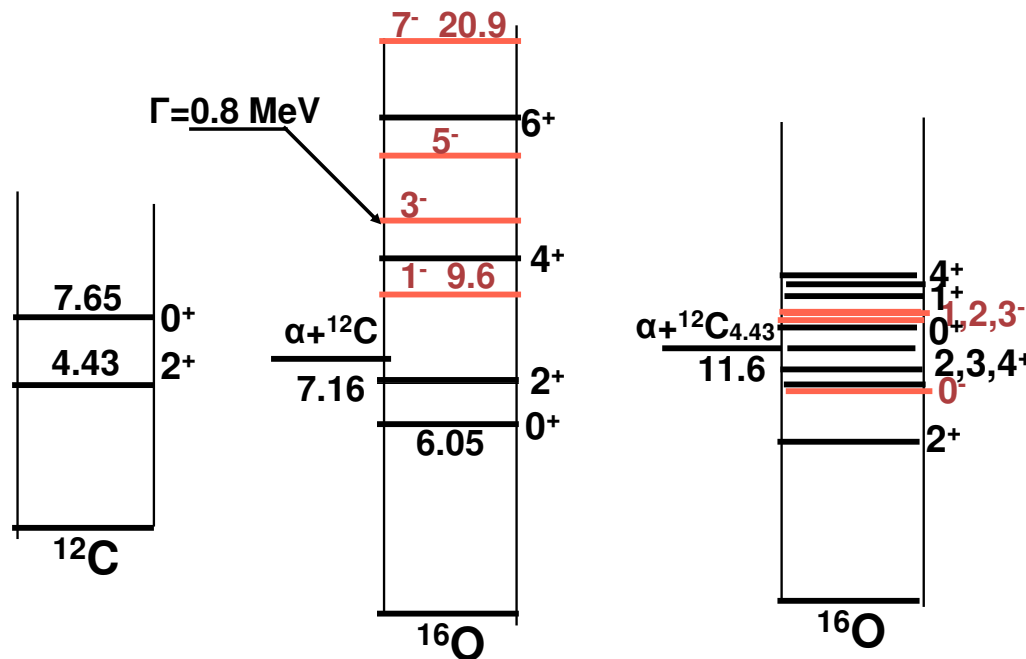
d- α Angular correlations for the ^{16}O levels at 14.6, 16.2 and 20.8 MeV

“Experimental” approach to the problem of the alpha clusterization

Consider a potential in Schrödinger equation that satisfies the boundary conditions $\psi_\alpha(R)=0$ and $\psi_\alpha(R - \Delta R)=0$ where R is the radius of the nucleus and ΔR is the thickness of the surface layer, I.e., a potential that confines the particle to a spherical surface layer of thickness ΔR . For the limiting case $\Delta R \ll R$, the energy eigenvalues can be obtained analytically

$$E = \frac{n^2 \pi^2 \hbar^2}{2\mu(\Delta R)^2} + \frac{\hbar^2 l(l+1)}{2\mu R^2}$$

V. Z. Gol'dberg, V. P. Rudakov, and V. A. Timofeev
Yad. Fu. 19, 503-515(March 1974)

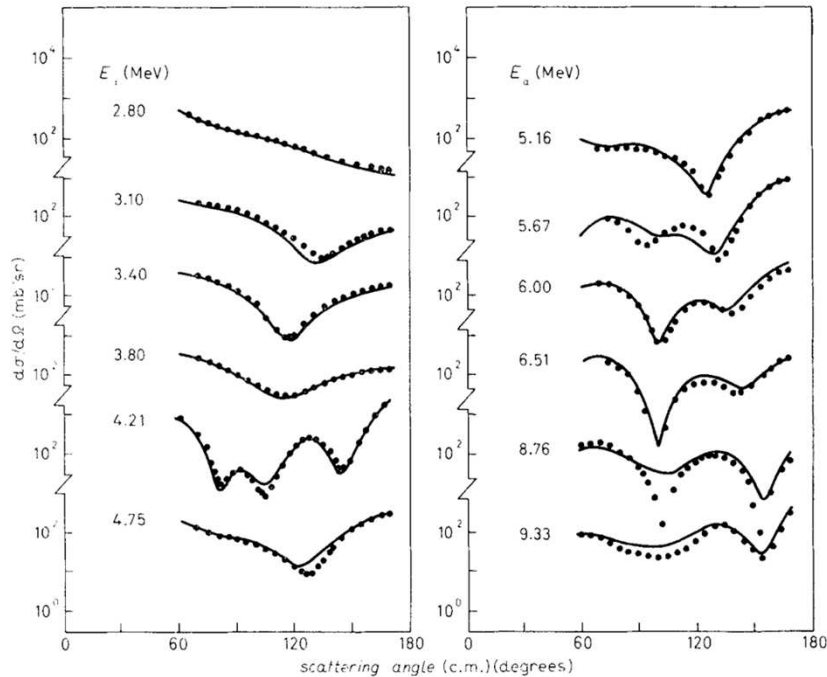


Reduced widths for α decay to the first excited state in ^{12}C

1⁺ 13.66 MeV $\Theta^2=1.02$
 3⁻ 13.14 MeV $L=1$ $\Theta^2=0.58$
 3⁻ 13.26 MeV $L=1$ $\Theta^2=0.20$
 4⁺ 13.87 MeV $L=2$ $\Theta^2=0.19$
 4⁺ 14.51 MeV $L=2$ $\Theta^2=0.47$
 0⁺ 13.61 MeV $L=2$ $\Theta^2=0.07$

R.J. deBoer, A.Boeltzig, K.T.Macom et al., Phys.Rev. C103, 065801 (2021)
Investigation of secondary γ -ray angular distributions using $^{15}\text{N}(p,\alpha,\gamma)^{12}\text{C}^*$

$\alpha + {}^{12}\text{C}$ elastic scattering



J. John, J.P. Aldridge, R.H. Davis *Phys. Rev.* 181, 1455 (1969)

Surface potential

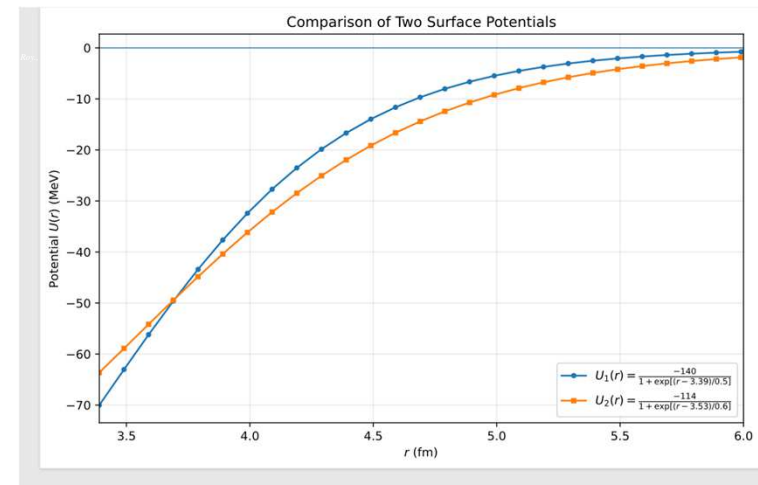
$$U(r) = \begin{cases} U_0(1 + \exp[(r - R_0)/a])^{-1}, & r > R_0 \\ \infty, & r < R_0 \end{cases}$$

V.Z. Goldberg, K.A. Gridnev, V.M. Semenov *Bull. Acad. Sci. USSR, Phys. Ser.* 38, No. 12, 52 (1974) α -Cluster Levels in ${}^{16}\text{O}$ and ${}^{20}\text{Ne}$, and the Surface Potential Well Mode

A.I. Baz, V. Z. Goldberg, N. Z. Darwisch, et al. A Potential for Alpha-Particle–Nucleus Scattering *Lettere al Nuovo Cimento* 18, No. 7 (12 February 1977).

${}^{16}\text{O}$ levels

J^π	E_{ex} (MeV)	E_{th} (MeV)	Γ_{ex} (MeV)	Γ_{th} (MeV)	R_c (fm)
0^+	6.05	6.05			3.100
1^-	9.60	9.61	510 ± 60	460	3.310
2^+	6.92	6.92			3.040
3^-	11.60	11.56	800 ± 100	930	3.200
4^+	10.35	10.35	27 ± 4	21	2.942
5^-	14.60	14.61	480 ± 100	600	2.955
6^+	16.30	16.20	360 ± 40	315	2.784
7^-	20.88	20.80	655 ± 70	660	2.690
0_2^+	11.26	10.70	2500	2900	2.440



Woods-Saxon potential

B. Buck, C. B. Dover and J. P. Vary

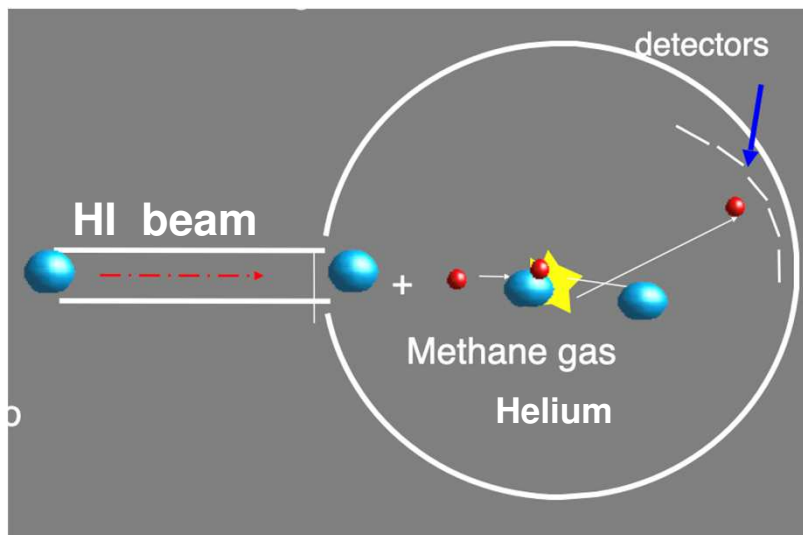
Simple Potential Model for Cluster States in Light Nuclei *Phys. Rev.* 11 (1975) 1804

Thick Target Inverse Kinematics

Very high efficiency, low background,
continuous excitation functions

Disadvantage

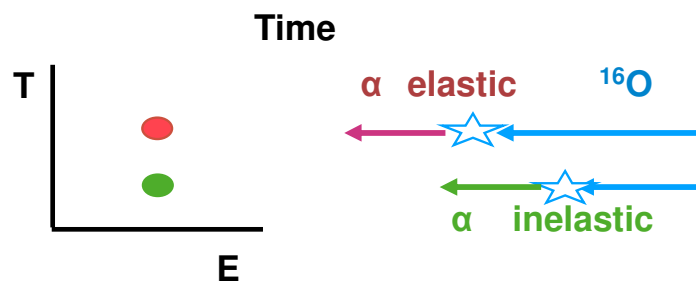
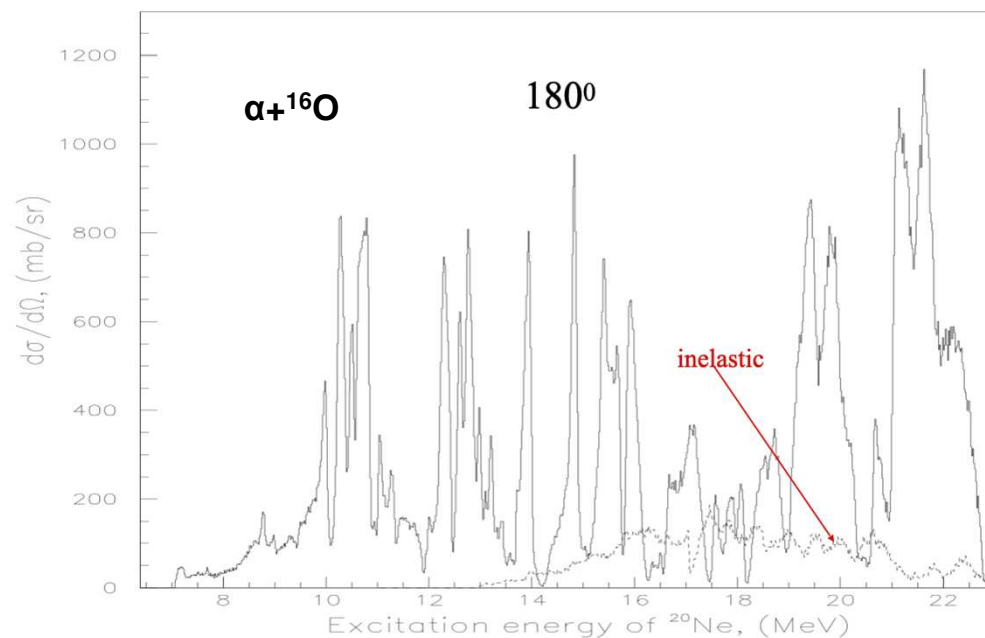
Modest energy resolution, restricted angular region



K.P.Artemov et al., *Sov. J. Nucl. Phys.*, 52 (1990)
408

V.Z.Goldberg *Int. Conf. Clustering Phenomena in
Atoms and Nucl.*

1991 Springer Ser. Nucl and Particle Phys. 366

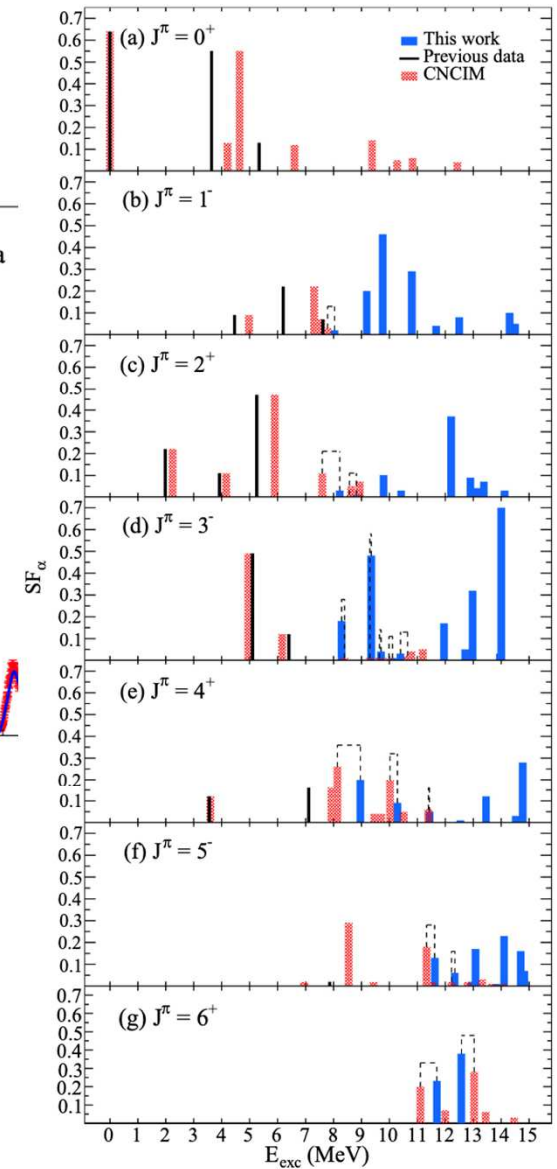
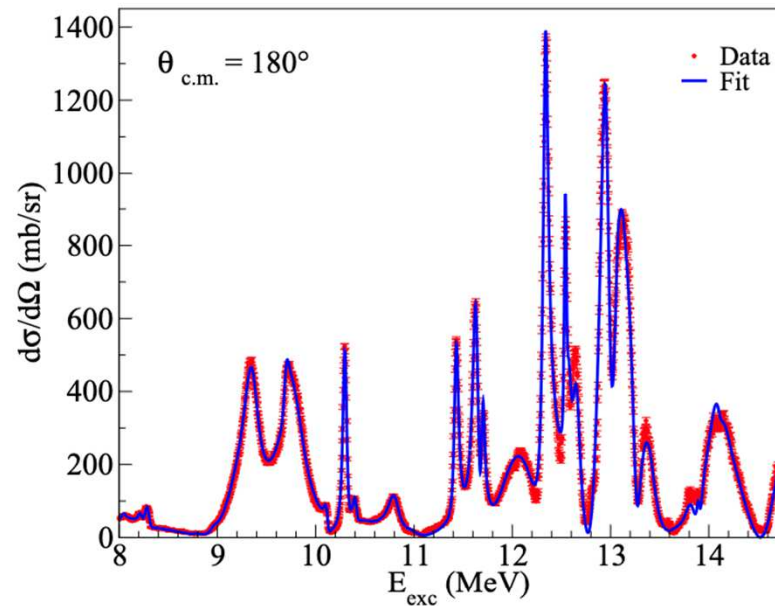


conclusion

α -cluster structure of ^{18}O *quite different from the pattern of known quasirotational bands of alternating parity that are characteristic of $N=Z$, even-even nuclei like ^{16}O and ^{20}Ne .*

α -cluster structure of ^{18}O

There are the conventional $\alpha+^{14}\text{C}$ and the TTIK measurements



Distribution of α strength by spin parity in ^{18}O

G. L. Morgan, D. R. Tilley, G. E. Mitchell, et al., *Phys. Lett. B* 32, 353 (1970)

M. L. Avila, G. V. Rogachev, V. Z. Goldberg et al., *Phys. Rev. C* 90, 024327 (2014)

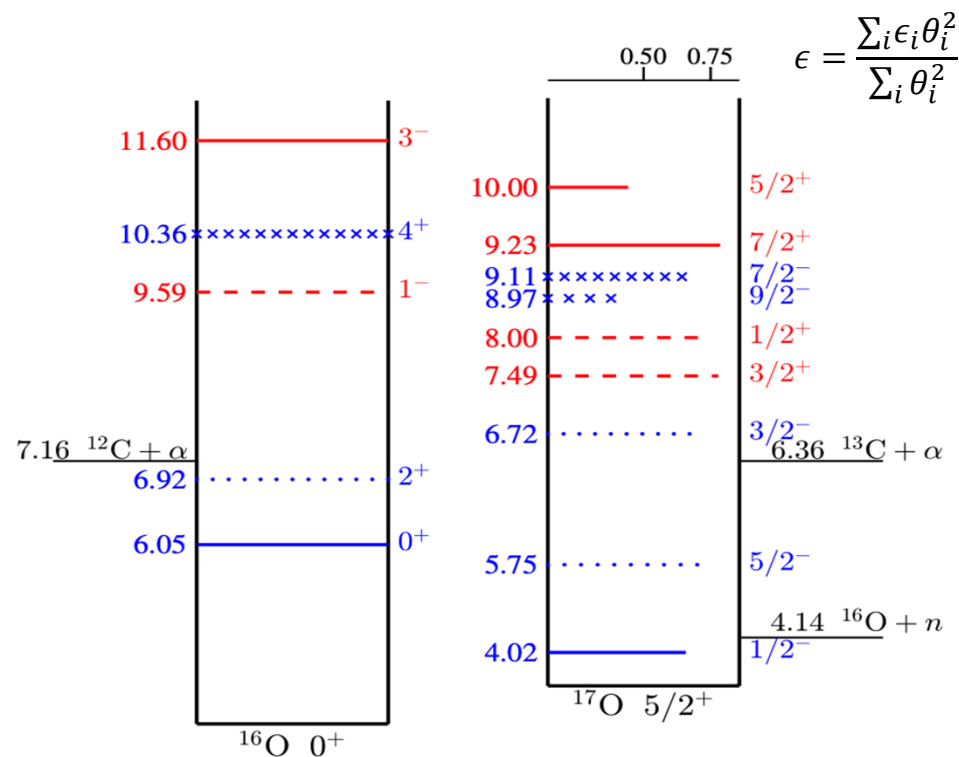
E.D. Johnson, G.V. Rogachev, V.Z. Goldberg, *Eur.Phys.J. A* 42, 135 (2009)

W. von Oertzen et al., *Eur. Phys. J. A* 43, 17 (2010)

S. Pirrie, C. Wheldon, Tz. Kokalova et al., *Phys.Rev. C* 102, 064315 (2020)

¹⁷O spectroscopy using ¹³C(α,α) resonant elastic scattering

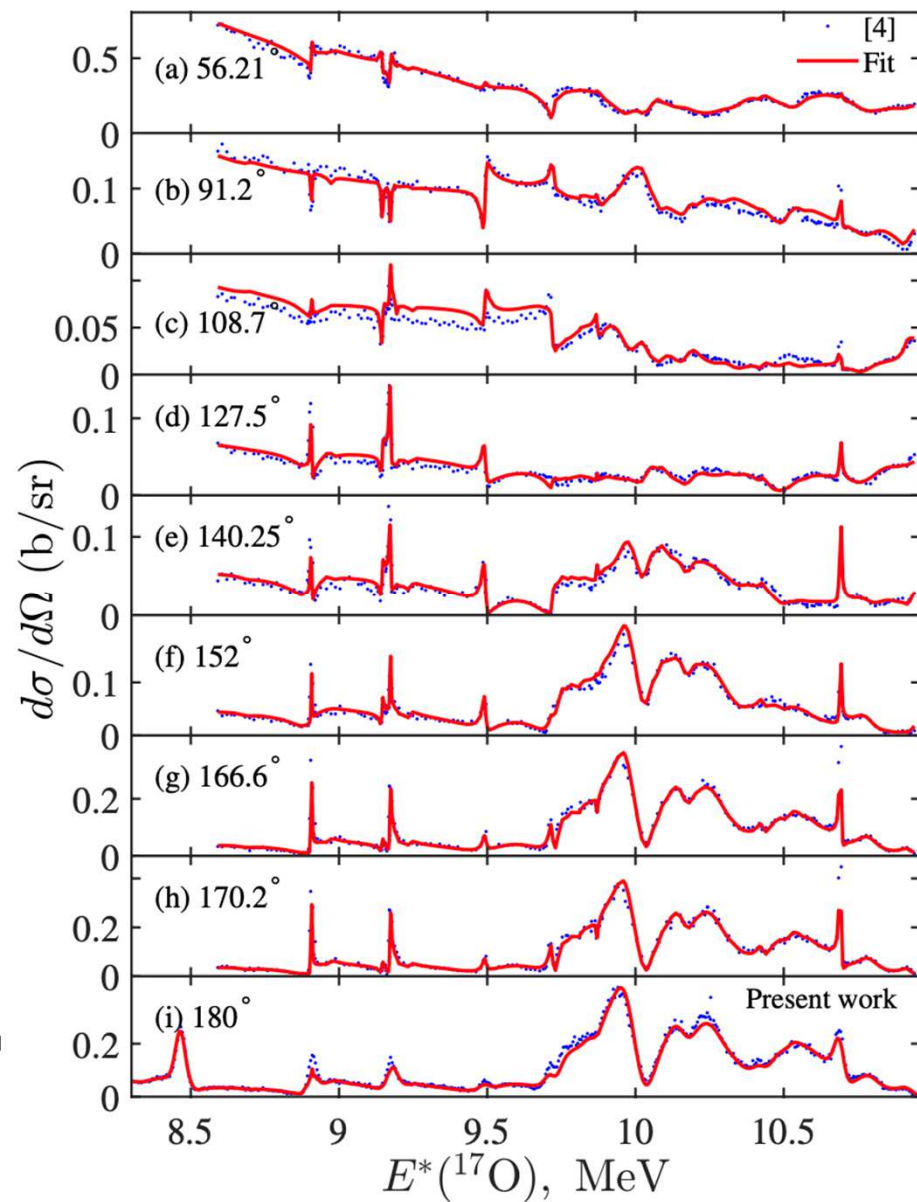
The detailed excitation functions for ¹³C(α,α) elastic scattering and the additional TTIK measurements were analyzed using the R matrix approach.



α cluster states in ¹⁶O and ¹⁷O.

The centroid experimental energies used for α cluster states in ¹⁷O, the length of the lii is proportional to the sum of the reduced widths for the shown spin

V. Z. Goldberg, A. K. Nurmukhanbetova, A. Volya et al., *Phys. Rev C* in print
M. Heil, R. Detwiler, R. E. Azuma et al., *Phys. Rev. C* 78, 025803 (2008).

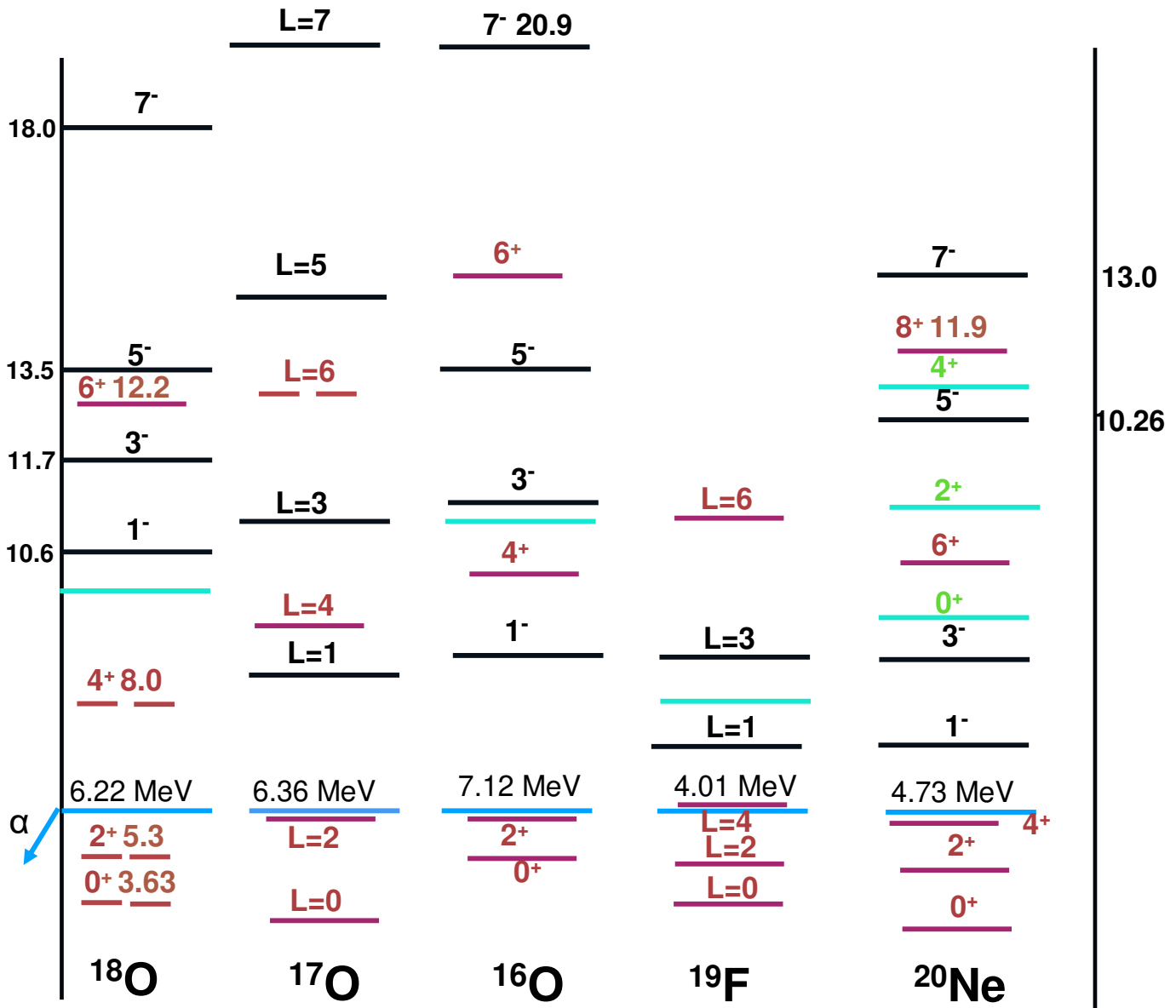


α cluster states in light nuclei

Centroids of α cluster states are shown for ^{17,18}O and ¹⁹F nuclei

$$E = \frac{\sum E_{\alpha i} \times \theta_{\alpha i}}{\sum \theta_{\alpha i}} \quad \overline{\sum \theta_{\alpha i}} \sim 0.75$$

For the ¹⁸O nuclei, the excitation energies are shown on left ordinate.



**Excitation functions
 $\alpha + {}^{12}\text{C}, {}^{16}\text{O}, {}^{18}\text{O}, {}^{20}\text{Ne}$
 elastic scattering
 at 180°**

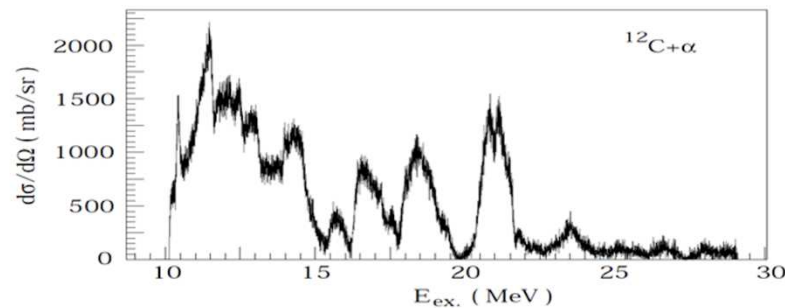
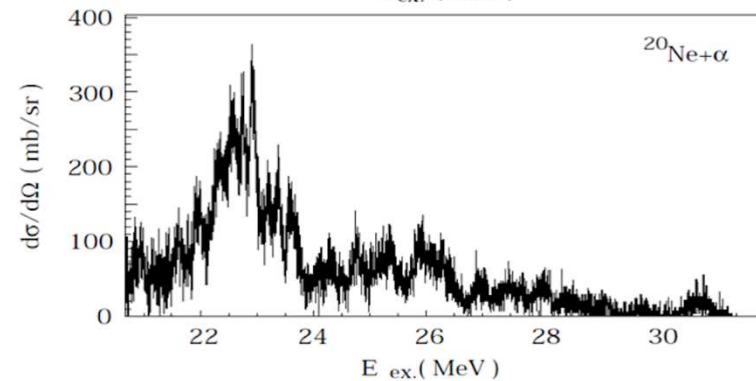
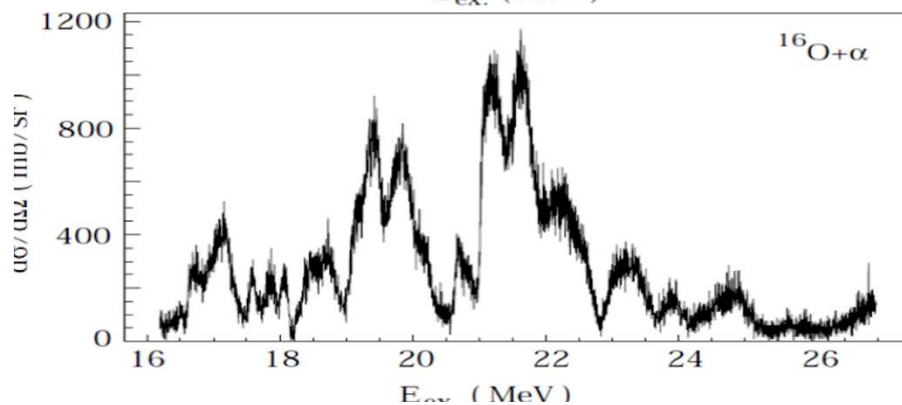
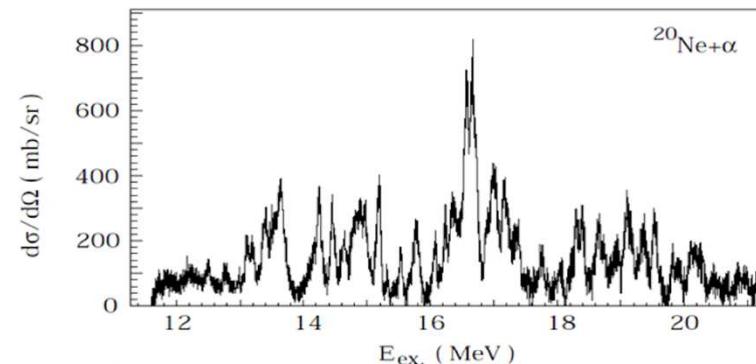
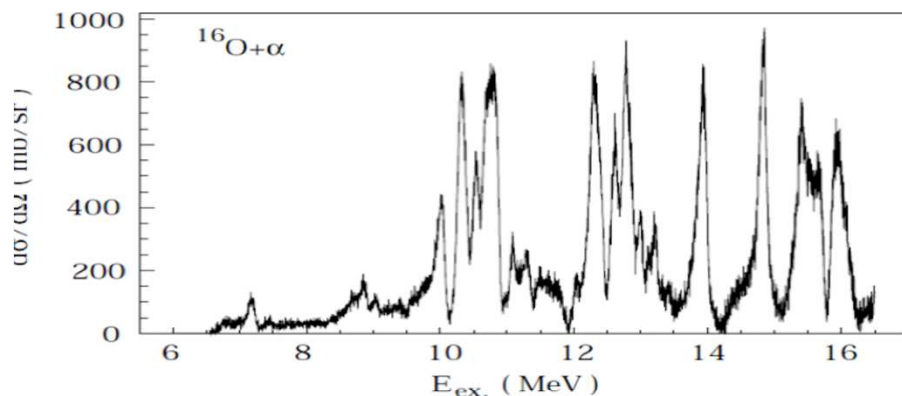
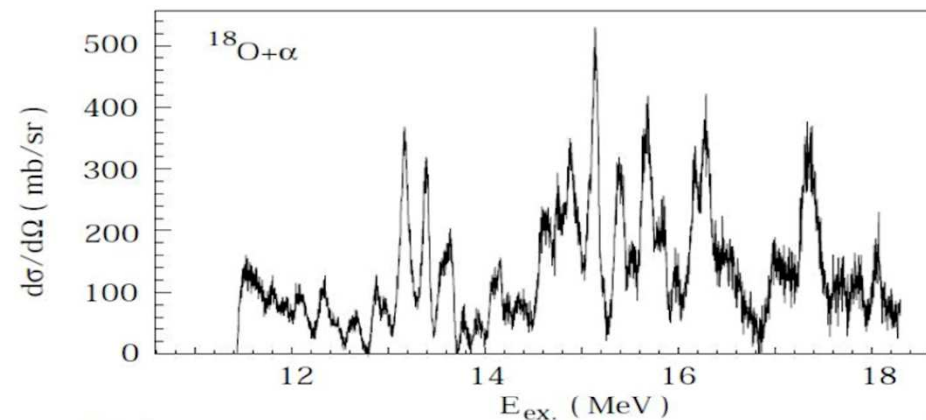
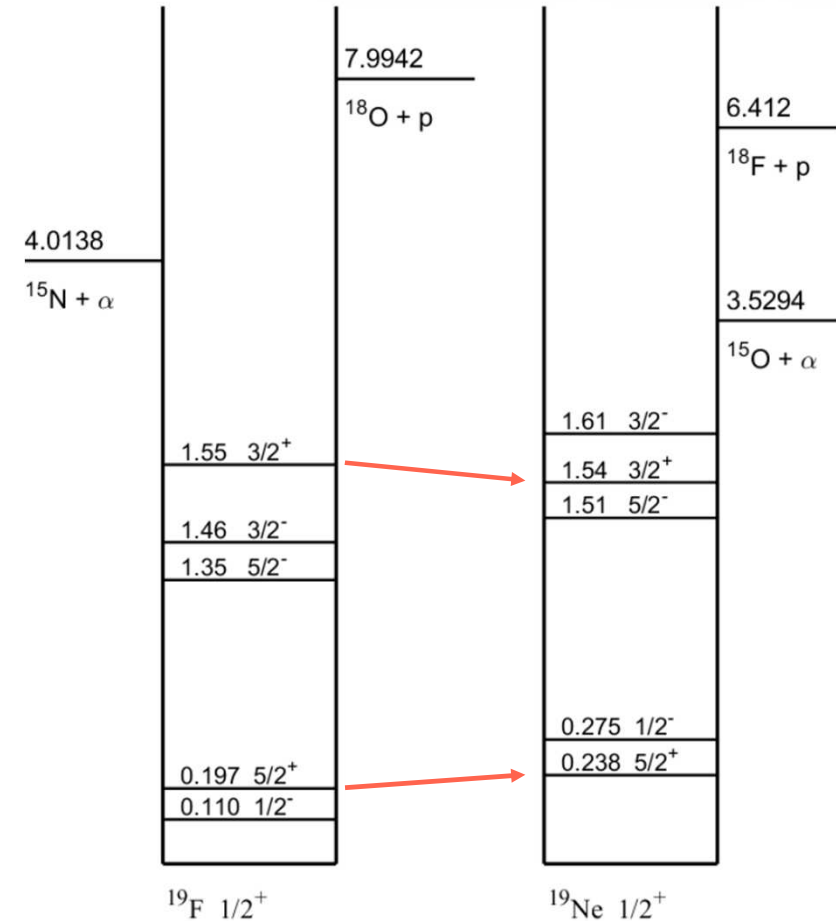


Рис. 3.1: Функция возбуждения упругого рассеяния ${}^{12}\text{C} + \alpha$, измеренная под углом 180° в с.п.м.

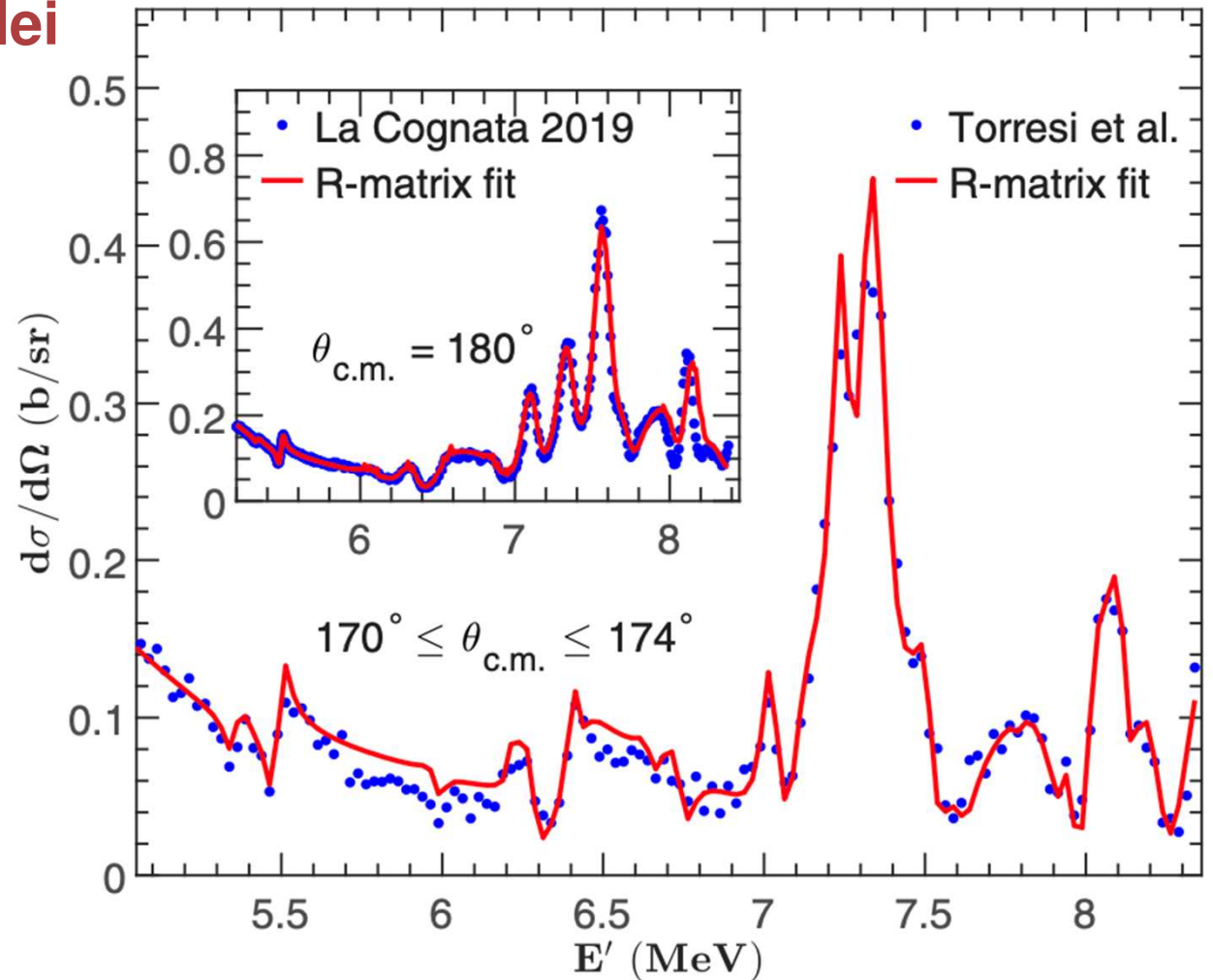


V.Z.Goldberg,
 V.I.Duchanov,
 A.E.Pachomov et. al.,
 Phys.Atomic Nuclei 60,
 1061 (1997)

Alpha clusters in mirror nuclei



^{17}O . $d3/2^+$ $E^*=5.085$; famous $1/2^+$ at 6.356
 ^{17}F . $d3/2^+$ $E^*=5.003$; famous $1/2^+$ at 6.56



Excitation function for the $\alpha + ^{15}\text{O}$ elastic scattering, points show data from Torresi et al. Inset shows the mirror excitation function for $\alpha + ^{15}\text{N}$ scattering.

Summary

Alpha cluster structure is an exciting research field.

- 1** Alpha-cluster structure does not disappear in light $N \neq Z$ nuclei. The sum of the reduced widths for the corresponding levels in these nuclei is close to the reduced widths of the analogous alpha-cluster states in ^{16}O , while the centroids of the excitation energies of the alpha-cluster states in $N \neq Z$ nuclei form quasi-rotational bands.
- 2** There is no theoretical description of the alpha cluster structure in light nuclei especially at high excitation energies. The distribution of α -cluster states present a natural challenge for theory. A new challenge is associated with the description of Coulomb shifts in mirror nuclei.
- 3** All major experimental methods remain important, but improvements are needed to provide more detailed data at high excitation energies as well as in the regions close to the alpha threshold and below it.
- 4** Resonance reactions with radioactive beams are expected to be very important for extending our knowledge of cluster structure into new regions of nuclei and for obtaining new data on Coulomb shifts.

Merci de votre attention

Thank you for fruitful and hot discussions!!~



Alexandr Volya



Aliya Nurnukhabetova



Grigorii Rogachev

Summary

Alpha cluster structure is an exciting research field.

1. Alpha-cluster structure is persistent in $N \neq Z$ nuclei; it distributed over larger number of states while centroids of these states of these states

2. There is no good theoretical description of the alpha cluster structure especially at high excitation energies.

New results stimulated various theoretical activity in the field.

3. We expect the modifications for the methods.

4. Development of experimental studies of the alpha cluster structure using rare beams is expected

Merci de votre attention



Alexandr Volya



Aliya Nurnukhabetova



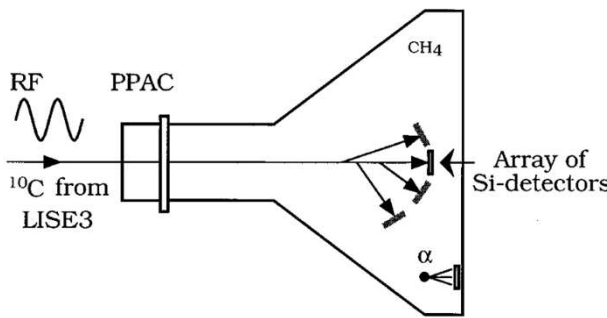
Grigorii Rogachev

Thank you

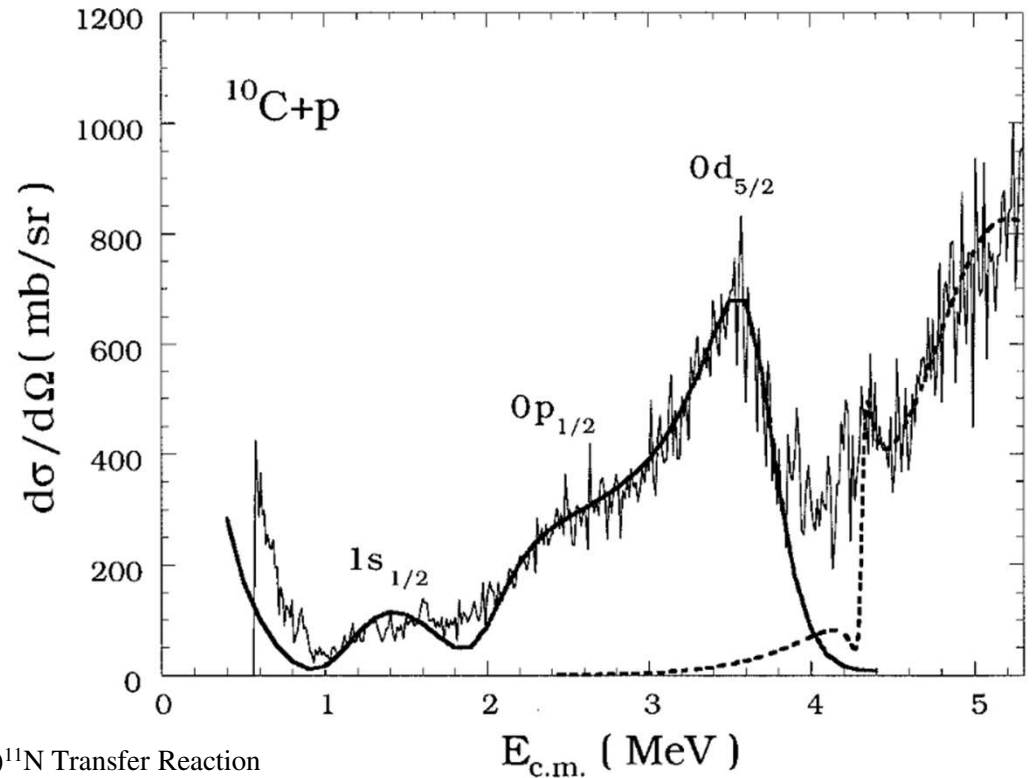
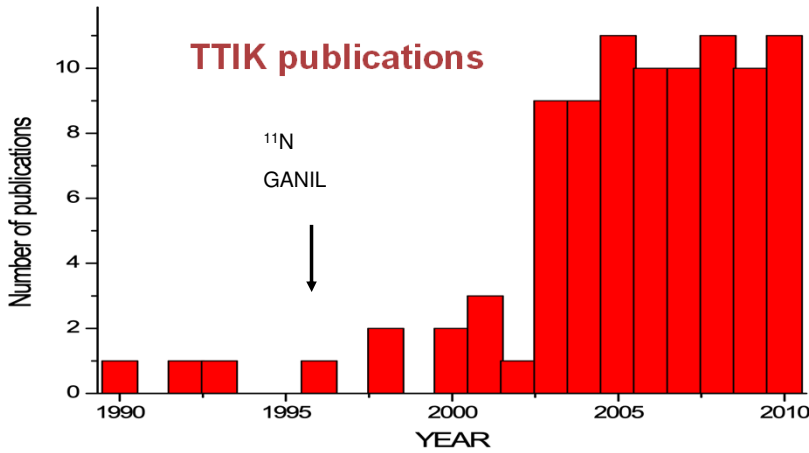
Study of the unbound nucleus ^{11}N by elastic resonance scattering

L. Axelsson, M. J. G. Borge, S. Fayans et al., Phys.Rev. C54, R1511 (1996)

From the fragmentation products a secondary beam of ^{10}C , with kinetic energy of 110 MeV and energy spread $\Delta E \sim 1.5$ MeV was extracted using the LISE3 spectrometer. The beam intensity $\sim$ after a 220 mm thick Be degrader was about 7×10^3 pps. The beam of ^{10}C , separated in the LISE3 spectrometer, enters the scattering chamber via an 80 mg/cm^2 kapton window. The target gas is CH_4 with a pressure chosen to stop the carbon ions in front of the central detector.



The experimental arrangement used in the resonance scattering experiment.



Phys.Rev.Lett. 80, 1601 (1998) Spectroscopy of the Unbound Nucleus ^{11}N by the $^{12}\text{C}(^{14}\text{N}, ^{15}\text{C})^{11}\text{N}$ Transfer Reaction

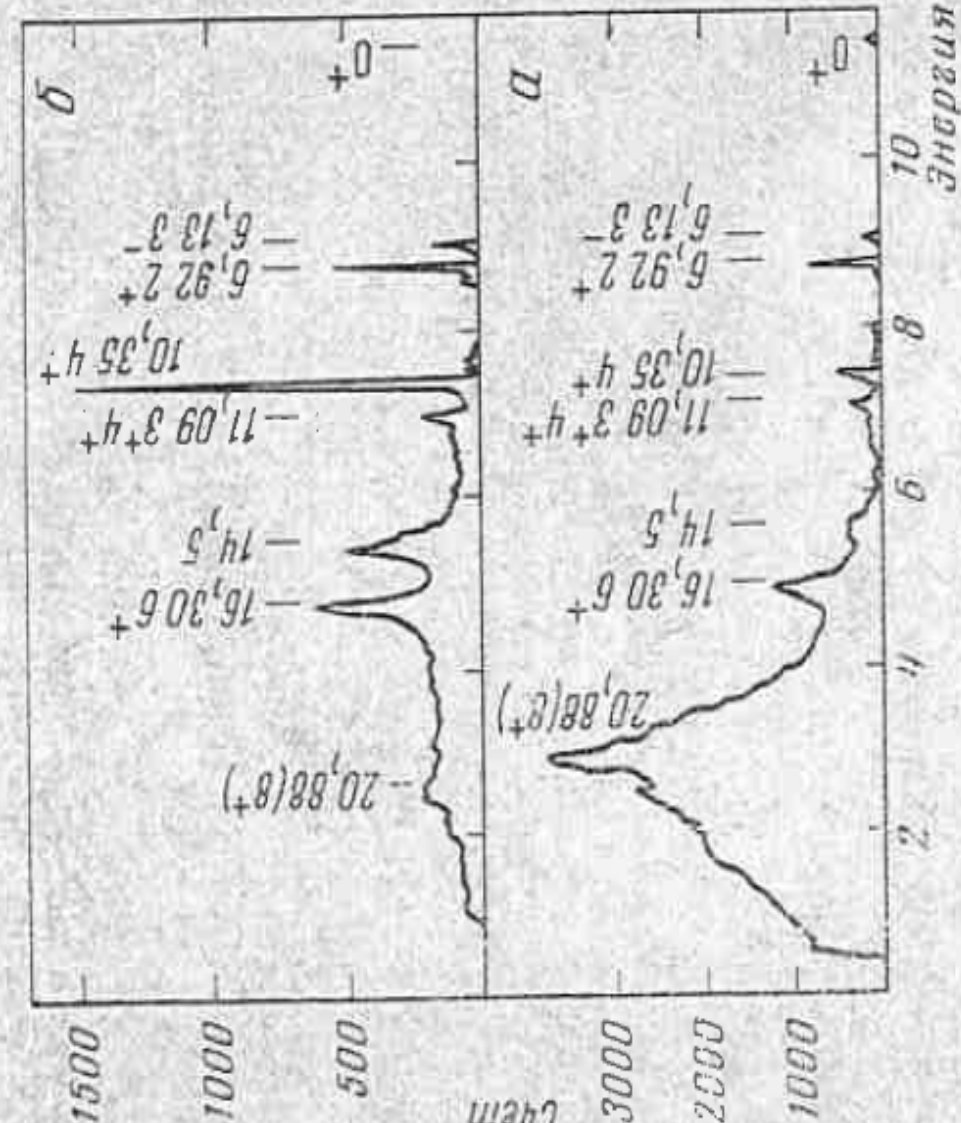
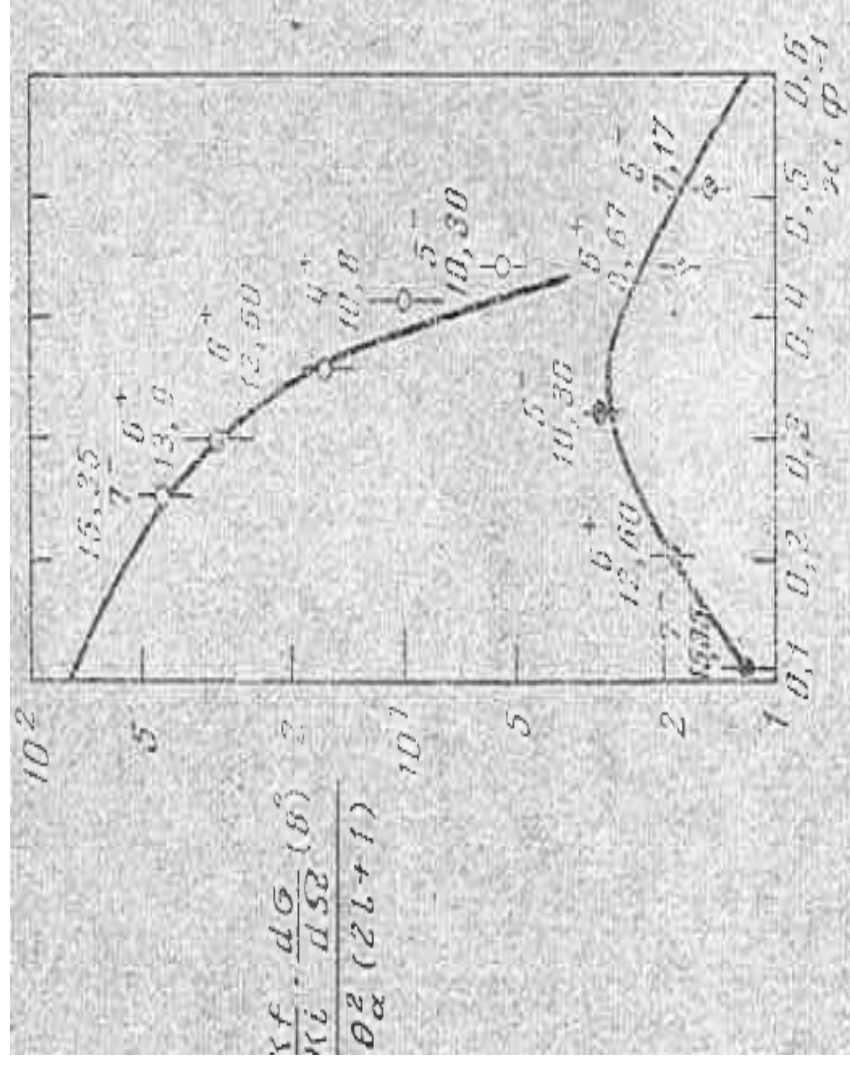


рис. 1. Энергетические спектры дейтронов и три-
онов из реакций $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ (a) и $^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$
(б) [7]; $\theta_{\text{п.с.}} = 10^\circ$, $E_{\text{Li}} = 32$ Мэв



3. Сравнение дифференциальных се-
кций возбуждения состояний ^{20}Ne в ре-
акциях $^{16}\text{O}(^6\text{Li}, d)$ (светлые точки) и
 $(^7\text{Li}, t)$ (черные точки) с приведенны-
ми к ним значениями для ^{16}O . Сплошные
линии — кластерные форм-факторы $^{6,7}\text{Li}$ и
 ^{16}O в импульсном представлении [10]

6⁺

6⁺ 13.6

$\alpha + {}^{14}\text{C}$
6.22 MeV

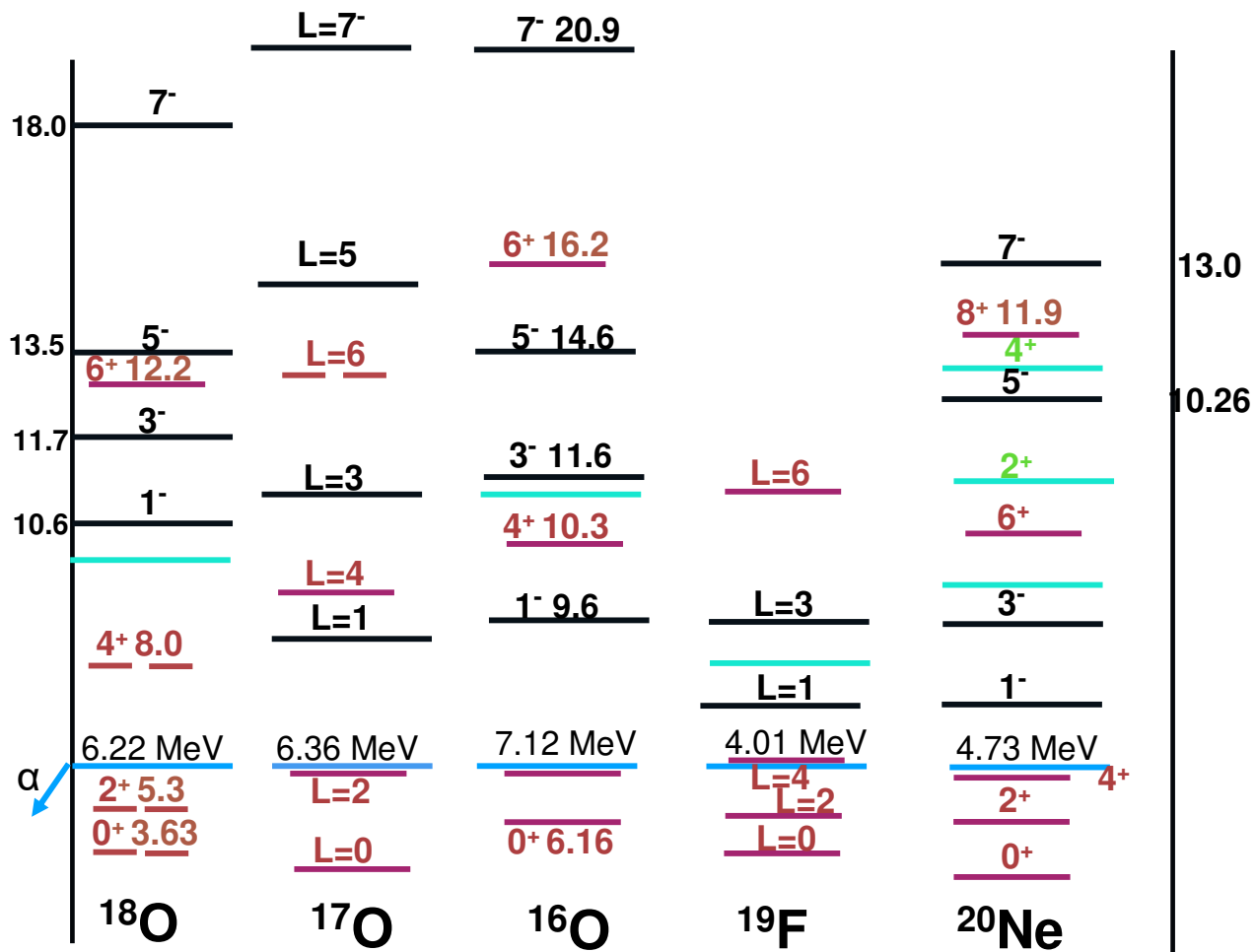


TABLE I: Parameters of Resonances in ^{17}O .

Present work					Ref.[4]			
N	E* (MeV)	Channel	J ^π	Γ (keV)	E* (MeV)	Channel	J ^π	Γ (keV)
1	6.38	α	1/2 ⁺	10 ⁻⁵	6.38	α	1/2 ⁺	1.7 × 10 ⁻⁵
2	6.83	α	5/2 ⁺	1.1 × 10 ⁻⁶	6.83	α	5/2 ⁺	1.1 × 10 ⁻⁵
3	6.94	α	7/2 ⁻	3.3 × 10 ⁻⁶	6.94	α	7/2 ⁻	3.3 × 10 ⁻⁶
4	7.16	α	5/2 ⁻	8.7 × 10 ⁻³	7.16	α	5/2 ⁻	8.7 × 10 ⁻³
5	7.24	α	3/2 ⁺	0.14	7.25	α	3/2 ⁺	0.14
6	7.37	α	5/2 ⁺	330	7.38	α	5/2 ⁺	340.1
7	7.38	α	5/2 ⁻	0.011	7.38	α	5/2 ⁻	0.011
8	7.48	α	3/2 ⁻	2.9 × 10 ⁻³	7.48	α	3/2 ⁻	2.9 × 10 ⁻³
9	7.69	α	7/2 ⁻	0.027	7.68	α	7/2 ⁻	0.027
10	7.92	α	7/2 ⁻	678.3	7.69	α	7/2 ⁻	678.3
11	7.97	α	7/2 ⁻	0.011	7.97	α	7/2 ⁻	0.011
12	8.08	α	7/2 ⁻	-14.5	7.97	α	7/2 ⁻	-14.5
13	8.20	α	1/2 ⁻	335	8.20	α	1/2 ⁻	335
14		α	1/2 ⁻	0.049	7.91	α	1/2 ⁻	0.049
15	8.34	α	1/2 ⁺	2.5	7.91	α	1/2 ⁻	2.5
16	8.40	α	3/2 ⁺	0.03*	8.08	α	3/2 ⁺	0.03*
17		α	3/2 ⁻	0.055	8.08	α	3/2 ⁺	0.055
18	8.47	α	7/2 ⁺	87	8.20	α	3/2 ⁻	87
19	8.50	α	5/2 ⁻	58	8.20	α	3/2 ⁻	58
20	8.69	α	3/2 ⁻	1.5	8.40	α	5/2 ⁺	1.5
21	8.91	α	9/2 ⁻	8.6	8.40	α	5/2 ⁺	8.6
22	8.91	α	3/2 ⁺	4.8	8.47	α	9/2 ⁺	4.8
23				6.8 × 10 ⁻⁶	8.47	α	9/2 ⁺	6.8 × 10 ⁻⁶
24	8.97	α	7/2 ⁻	7.1	8.47	α	7/2 ⁺	7.1
25	9.15	α	1/2 ⁻	-0.42	8.50	α	5/2 ⁻	-0.42
26	9.17	α	7/2 ⁻	2.23	8.50	α	5/2 ⁻	2.23
27	9.19	α	5/2 ⁺	3.36	8.68	α	3/2 ⁻	3.36
28	9.24	α	1/2 ⁺	0.008	8.68	α	3/2 ⁻	0.008
29				0.24	8.90	α	9/2 ⁻	0.24
30	9.49	α	5/2 ⁻	2.29	8.90	α	9/2 ⁻	2.29
31	9.51	α	1/2 ⁺	-0.044	8.91	α	3/2 ⁺	-0.044
32				0.03	8.91	α	3/2 ⁺	0.03
33	9.72	α	7/2 ⁺	17.5	8.91	α	9/2 ⁻	17.5
34	9.73	α	3/2 ⁺	4.81	8.91	α	9/2 ⁻	4.81
35	9.77	α	3/2 ⁺	-2.45	8.96	α	7/2 ⁻	-2.45
36	9.81	α	5/2 ⁻	70	8.96	α	7/2 ⁻	70
37	9.87	α	9/2 ⁺	16.5	9.40	α	3/2 ⁻	16.5
38	9.89	α	1/2 ⁻	20.4	9.49	α	5/2 ⁻	20.4
39	9.97	α	5/2 ⁺	127.8	9.52	α	1/2 ⁺	127.8
40	10.04	α	3/2 ⁺	6.1 × 10 ⁻⁶	9.52	α	1/2 ⁺	6.1 × 10 ⁻⁶
				17.5	9.71	α	7/2 ⁺	17.5
				4.81	9.71	α	7/2 ⁺	4.81
				-2.45	9.72	α	7/2 ⁺	-2.45
				70	9.73	α	3/2 ⁺	70
				16.5	9.73	α	3/2 ⁺	16.5
				20.4	9.78	α	3/2 ⁻	20.4
				127.8	9.78	α	3/2 ⁻	127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				6.1 × 10 ⁻⁶
				17.5				17.5
				4.81				4.81
				-2.45				-2.45
				70				70
				16.5				16.5
				20.4				20.4
				127.8				127.8
				6.1 × 10 ⁻⁶				

TABLE I: (continued).

Present work							Ref.[4]		
N	E* (keV)	Channel	J ^π	Γ (keV)	γ	E* (keV)	Channel	J ^π	Γ (keV)
41	10.08	α	1/2 ⁻	9.3	0.017	10.17	α	1/2 ⁻	9.5
42	10.13	α	5/2 ⁺	16	0.015		n'		26
43		n		54	0.025		n''		4.1 × 10 ⁻⁴
44	10.17	α	5/2 ⁻	-14.5	0.011	10.17	α	5/2 ⁻	4.92
		n		37	0.032		n'		24.5
45	10.20	α	7/2 ⁻	3.3	0.035	10.20	n		2.3 × 10 ⁻⁶
		n		40	0.033		n''		303.3
46	10.21	α	3/2 ⁻	-7.5	0.041		α	5/2 ⁺	-9.7 × 10 ⁻⁶
47	10.27	n	7/2 ⁺	213.5	0.330		n'		0.027
48	10.31	α	7/2 ⁻	3.7	0.023		n''		3.4 × 10 ⁻³
		n''(7/2,0)		-19	0.045				
49	10.32	n	3/2 ⁻	10.75	0.057				
		n		-56					
50	10.33	α	5/2 ⁺	10	0.016	10.36	α	3/2 ⁺	86.5
		n''(5/2,1)		10	0.05		n'		7.1 × 10 ⁻⁷
		n''(7/2,1)		13	0.020		n''		3.4 × 10 ⁻⁴
51	10.34	α	1/2 ⁺	132	0.07		n		1.65
		n		15	0.004		n		1.14
52	10.36	n	3/2 ⁺	95	0.053	10.51	n'		1.3 × 10 ⁻⁶
		n'		-48			n''		
		n''(5/2,1)		9	0.022				
53									
54	10.42	α	7/2 ⁺	-4	0.001		α	5/2 ⁻	-54.2
		n		7	0.013		n		-9 × 10 ⁻⁵
		n''(5/2,1)		3			n'		1.3
		n''(7/2,1)		7			n''		2.36
55	10.51	α	3/2 ⁻	47.5	0.09				
		n'		26.3	0.008				
		n''(5/2,2)		1					
		n''(7/2,2)		6					
56									
57	10.52	α	7/2 ⁺	-61	0.074	10.53	α	7/2 ⁺	74.8
		n		32	0.157		n		-3.05
		n''(5/2,1)		5			n'		22
		n''(7/2,1)		10			n''		0.1
58	10.52	α	5/2 ⁺	-10.6	0.012				
		n		34	0.015				
		n'		5					
		n''(5/2,1)		5					
		n''(7/2,1)		1					
59	10.53	α	5/2 ⁺	10.5	0.005	10.53	α	5/2 ⁺	18.6
		n		-6.1			n'		7.4 × 10 ⁻⁶
		n''(5/2,1)		4.5			n''		
		n''(7/2,1)		1					
60	10.55	α	5/2 ⁺	84	0.075	10.55	α	5/2 ⁺	-1.39
		n		43	0.019		n		13.6
		n'		-10			n'		18.6
		n''(5/2,1)		-0.25			n''		
		n''(7/2,1)		11	0.01				
		n''(5/2,2)		1.7	0.007				
		n''(7/2,2)		21					
61	10.57	α	7/2 ⁻	5	0.01				
		n		2					
62	10.69	α	11/2 ⁺	-0.015	0.190	10.69	α	9/2 ⁺	-6.94
		n		0.2	0.083		n		0.12
		n''(5/2,3)		-0.275			n'		4.8 × 10 ⁻⁵
		α	1/2 ⁻	-3.2	0.002		n''		1.63
63	10.70			-18.7					
		n''(5/2,2)							

TABLE I: (continued).

Present work						Ref.[4]			
N	E* (MeV)	Channel	J ^π	Γ (keV)	γ	E* (MeV)	Channel	J ^π	Γ (keV)
64	10.74	α n n' n''(5/2;2)	1/2 ⁻	145 42 42 71	0.028 0.042				
65	10.79	α n n' n''(5/2;1) n''(7/2;1)	5/2 ⁺	-30 44 38 0.05 -18.5	0.032 0.016	10.78	α n n' n''	3/2 ⁻	82.1 150 0.079 192.4
66	10.80	α n n' n''(5/2;2) n''(7/2;2)	3/2 ⁻	3.5 22.4 -3.5 39 15 7	0.020 0.003				
67						10.83	α n n' n''	1/2 ⁺	107 ⁻⁵ 1.4 × 10 ⁻⁵ 5.74 43.5
68	10.84	α n n' n''(5/2;1)	3/2 ⁺	200 17 -1.5	0.007	10.84	α n n' n''	1/2 ⁻	890.4 28.4 126.2 10.9
69	10.91	α n n' n''(5/2;2)	1/2 ⁺	5 50 29	0.024 0.007				
70	10.92	α n n' n''(5/2;2)	3/2 ⁻	6.5 -11.5 5	0.011				
71	10.94	α n n' n''(5/2;2)	5/2 ⁻	3 64.5 -30 7.5 0.5	0.020				
72						10.92	α n n' n''	5/2 ⁻	10.6 -32.3 1.35 20.9
73	10.96	α n n' n''(5/2;1) n''(7/2;1)	7/2 ⁺	2.5 15 8	0.046				
74	11.03	α n n' n''(5/2;1) n''(7/2;1)	7/2 ⁺	-4 40.5 -4.4 0.005	0.024 0.013	11.03	α n n' n''	5/2 ⁺	33.6 -2.05 4.3 × 10 ⁻⁴ 13.8
75	11.03	α n n' n''(5/2;2)	3/2 ⁻	3.2 2.15 51.8 -15.4 6	0.015				
76	11.06	α n n' n''(5/2;2)	3/2 ⁺	66 0.09 -7.7	0.030				
77	11.07	α n n' n''(5/2;1) n''(7/2;1)	9/2 ⁺	7.7 2.64 0.08 -14.3	0.028 2 × 10 ⁻⁴	11.08	α n n' n''	9/2 ⁺	71.9 23.3 650.6 0.06
78	11.12	α n n' n''(5/2;1) n''(7/2;1)	5/2 ⁺	18.5 0.5 10 7	0.030 2 × 10 ⁻⁴				
79	11.12	α n n' n''(5/2;1) n''(7/2;1)	7/2 ⁺	-2 23 8	0.023				
80	11.20	α n n' n''(5/2;1) n''(7/2;2)	1/2 ⁻	-3 190 -40 -30 10	0.038	11.14	α n n' n''	1/2 ⁻	-618.1 56.8 0.89 2.6 × 10 ⁻³