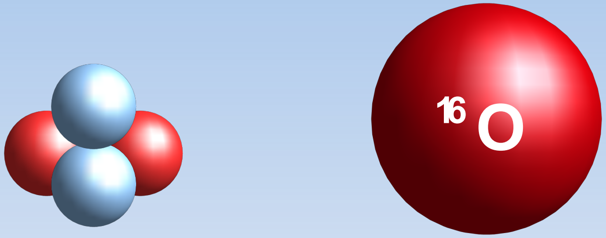
FLORIDA STATE UNIVERSITY
1851

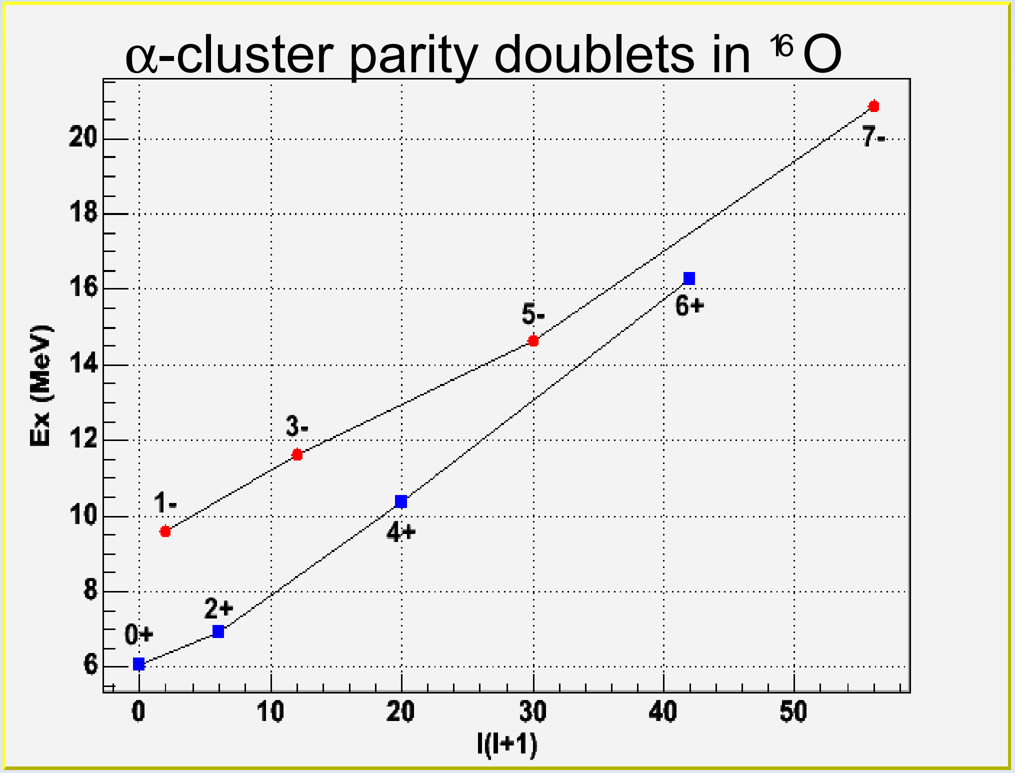
Clustering phenomena in ^{18}O

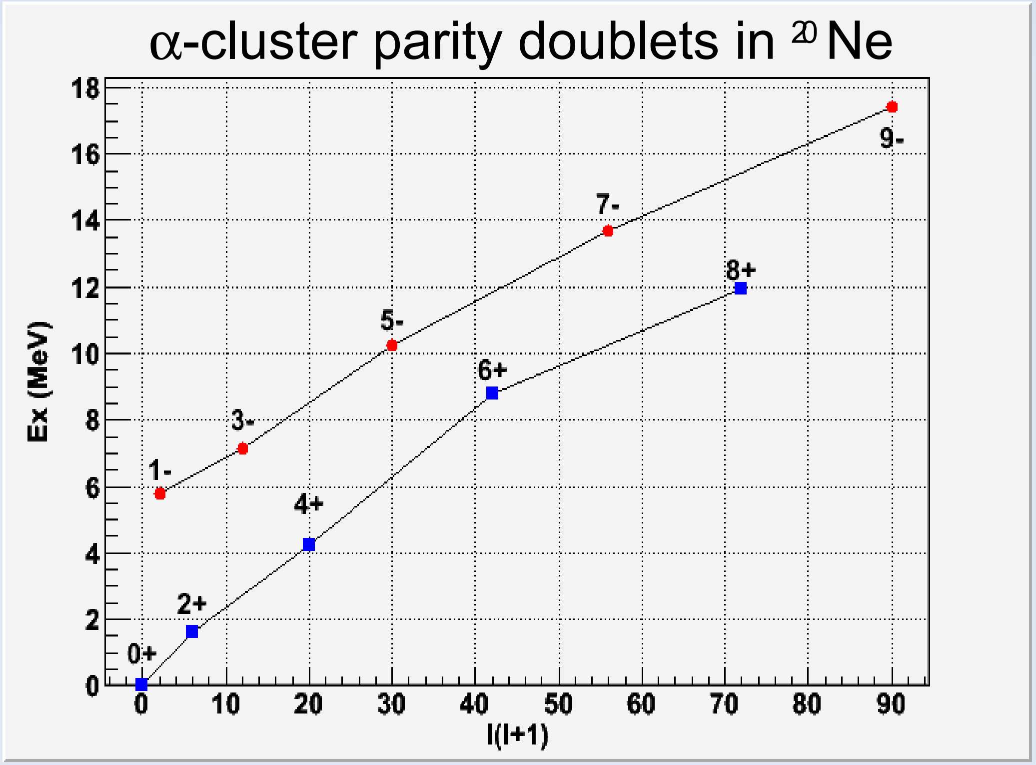
Melina Avila

Santa Tecla, September 22, 2011

α-structure of N=Z

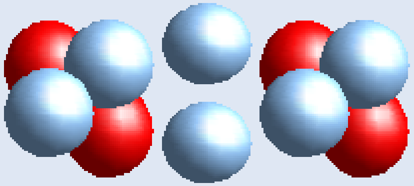



α-cluster parity doublets in ^{16}O


α-cluster parity doublets in ^{20}Ne

α-structure of N≠Z

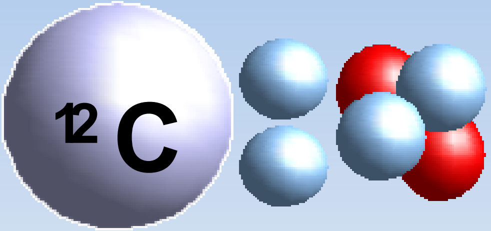
- The α-clustering in N≠Z nuclei is less studied
- Instrumental to understad the interplay between α-clustering and single particle degrees of freedom.
- Exotic Molecular type configurations have been predicted



^{10}Be

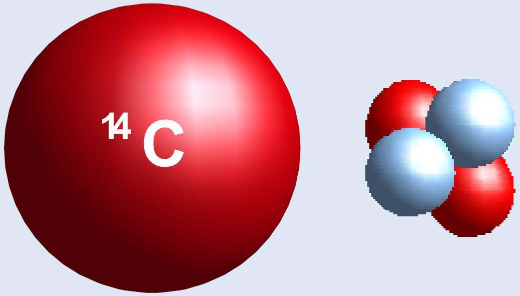
W. von Oertzen,
Z. Phys. A354 (1996)

Why ^{18}O is important?



Molecular Type State

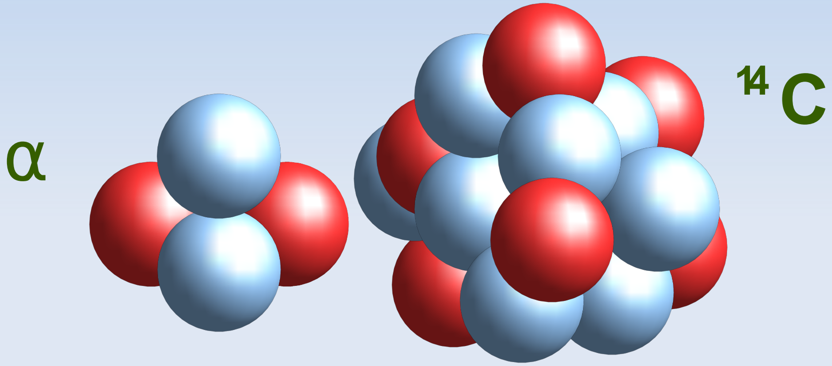
Shell model Structure



Cluster model Structure

$^{14}C(\alpha,\alpha)^{14}C$ elastic scattering

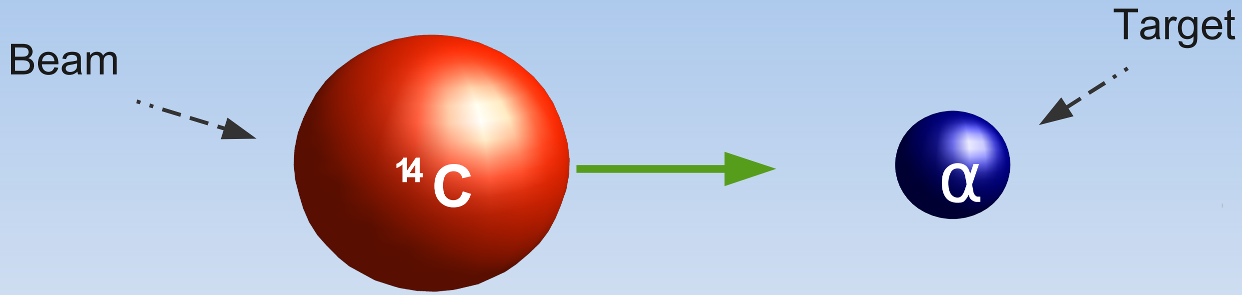
The structure of ^{18}O at exitation energies above the α-decay threshold was studied using $^{14}C+\alpha$ elastic scattering.



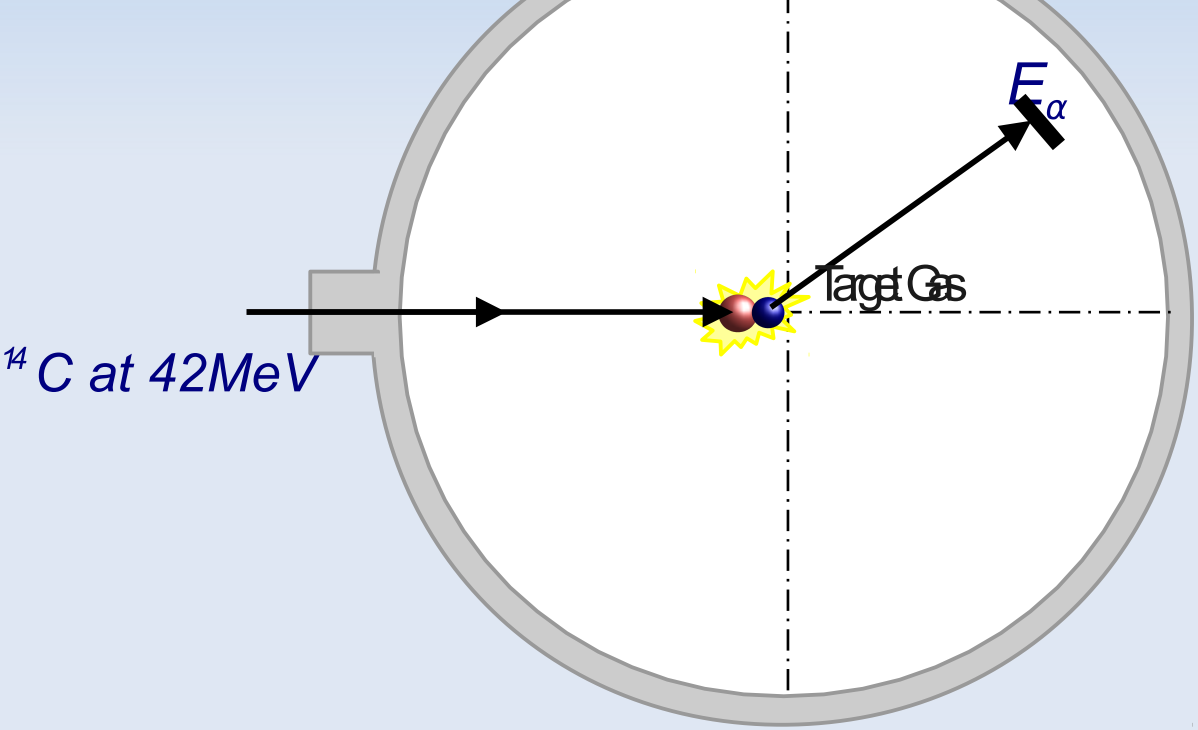
^{14}C beam was produced by John D. Fox Superconducting Linear accelerator facility at Florida State University. $E(^{14}C) = 42$ MeV.

Excitation function of resonance elastic scattering of $^{14}C+\alpha$ was measured using Method of Thick Target and Inverse Kinematics (TTIK).

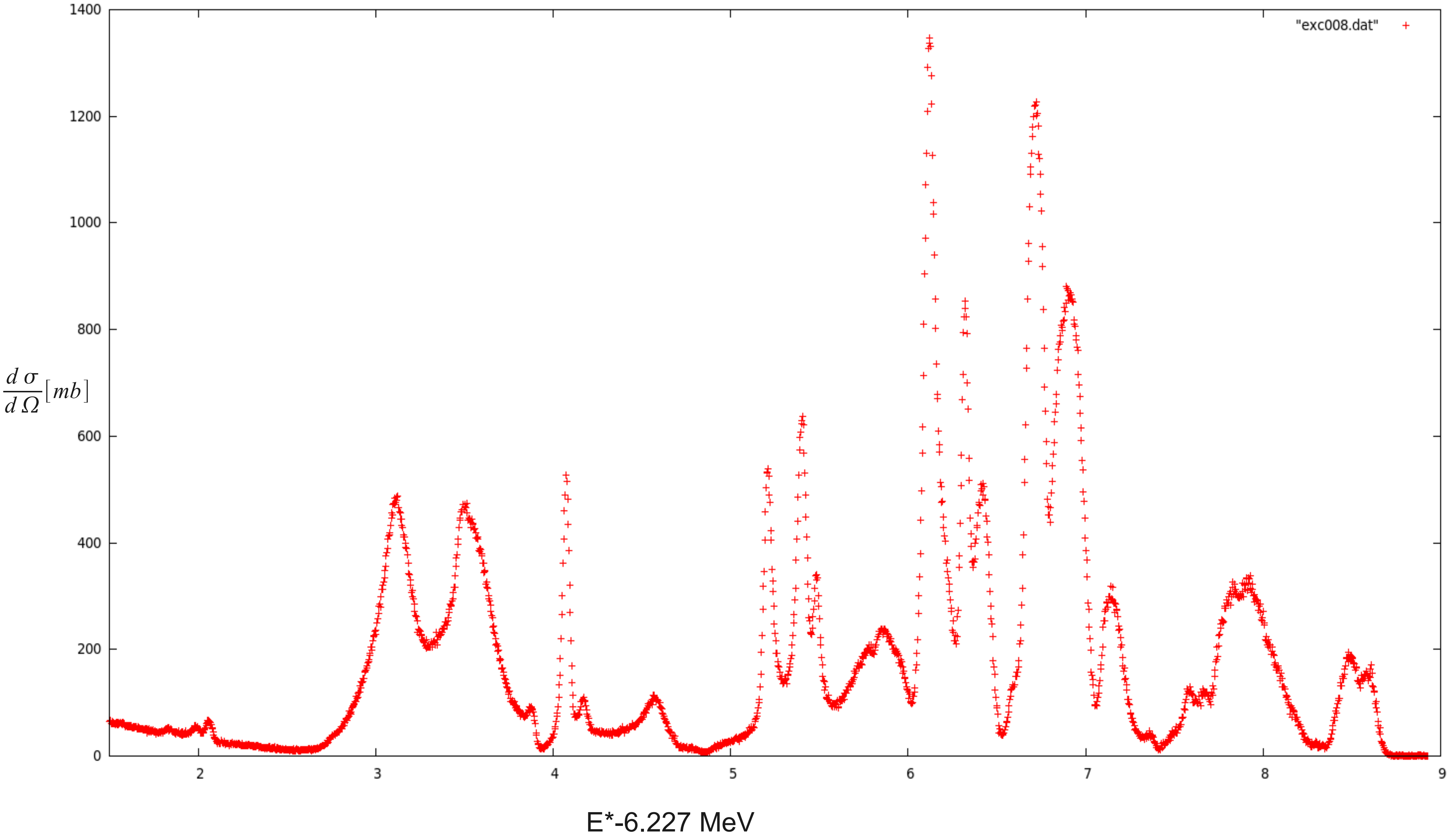
Thick Target and Inverse Kinematics



- Allows to study a range of excitation function without the need to change the initial energy.
- More efficient experiment
- Less time consuming



Experimental data



R-Matrix analysis

- multi-level, multi-channel approach

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_{\lambda} - E}$$

The elastic scattering data was fit using an R-Matrix analysis consisting of 3 open channels, $^{14}C(\alpha,\alpha)$, $^{14}C(\alpha,n)^{17}O$, and $^{14}C(\alpha,n)^{17}O^{*}$

α + $^{14}C(0^{+}$,g.s.)
n + $^{17}O(5/2^{+}$,g.s.)
n + $^{17}O(1/2^{+}$,0.87)

$$\Gamma_{tot} = \Gamma_{\alpha} + \Gamma_{n}$$
$$\Gamma_{\alpha} = 2P\gamma_{\alpha}^{2}$$

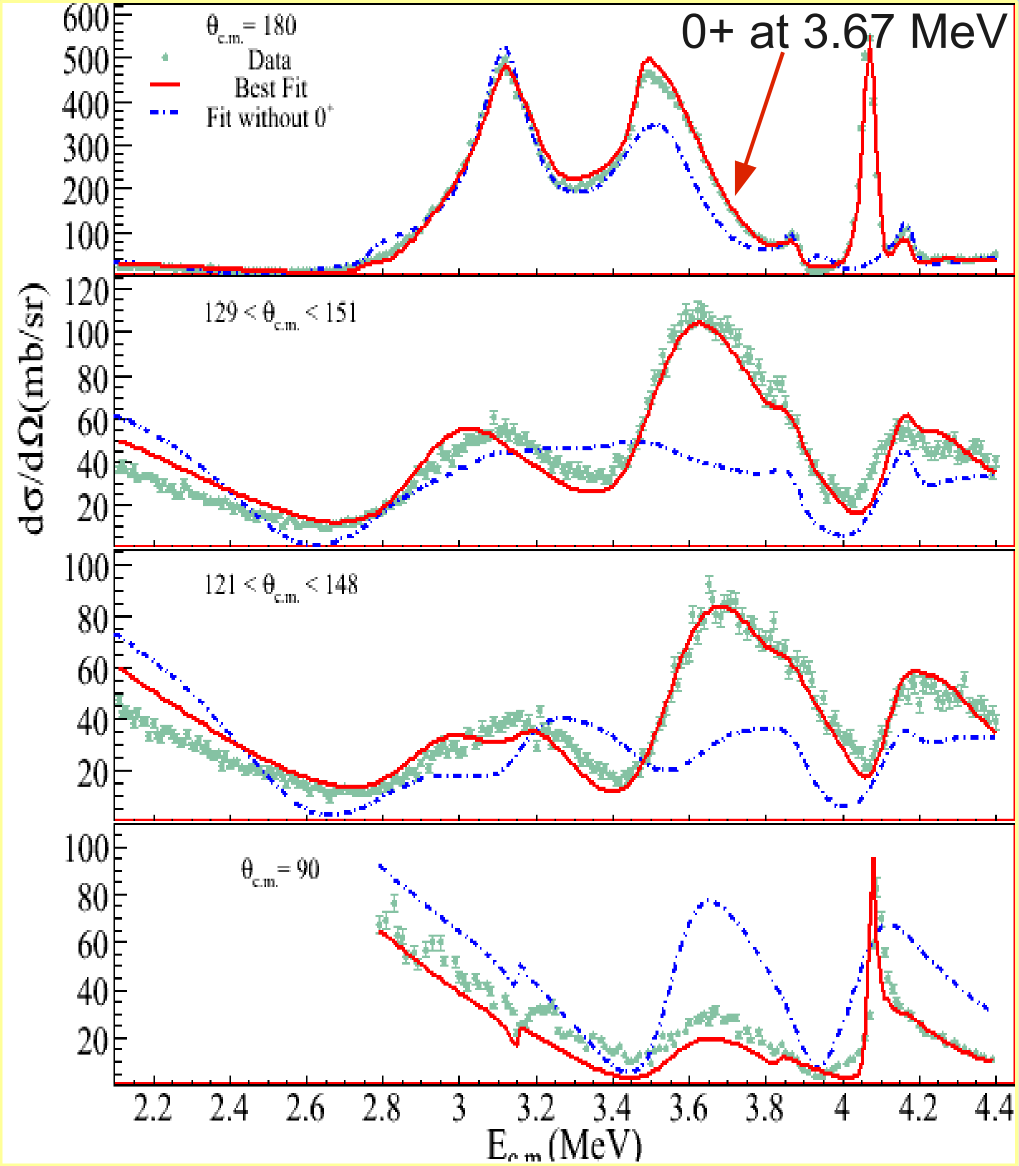
$$\theta_{\alpha}^{2} = \frac{\Gamma_{\alpha}}{\Gamma_{sp}}$$

Γ_{sp} Was obtained using Potential model calculations

[Robson, PRL 42 (1979)]

Resonances in ^{18}O observed via ^{14}C+α

E.D. Johnson, et al., EPJA, 42 135 (2009)



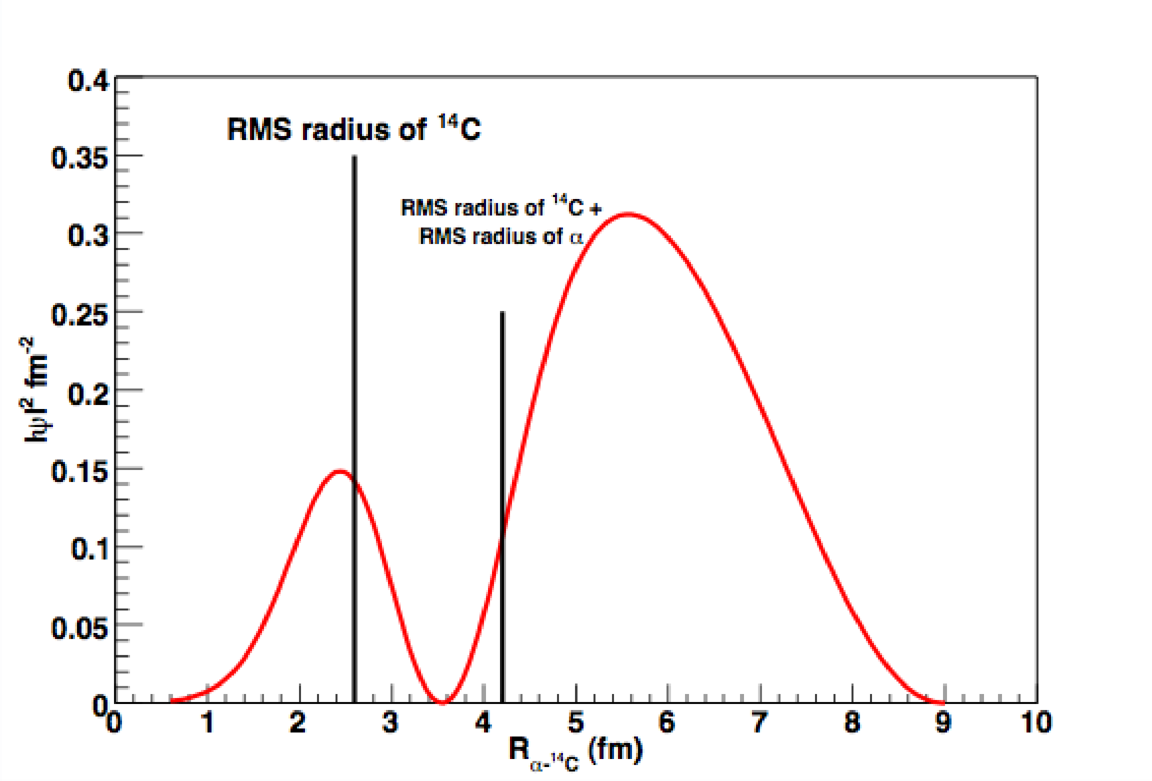
0+ at 3.67 MeV

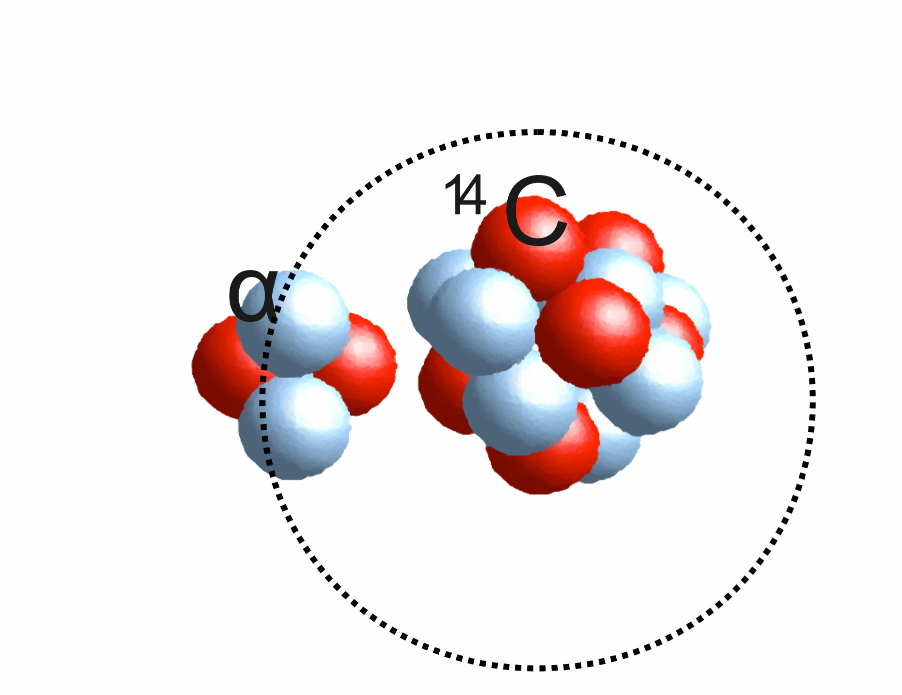
16 States were used to fit the data

E* (MeV)	Jπ	Γtot(keV)	Γα(keV)	Θα^2
8.04	1-	2	2	0.02
8.21	2+	1	1	<0.01
8.29	3-	8	2	0.09
8.78	2+	70	1	<0.01
8.98	2+	60	4	0.01
9.17	1-	240	205	0.24
9.36	2+	24	1	<0.01
9.39	3-	155	103	0.47
9.69	3-	56	0.1	<0.01
9.79	2+	263	167	0.20
9.76	1-	740	658	0.48
9.9	0+	2100	2100	1.20
10.1	3-	17	12	0.02
10.3	4+	23	16	0.08
10.34	2+	111	20	0.02
10.4	3-	48	17	0.02

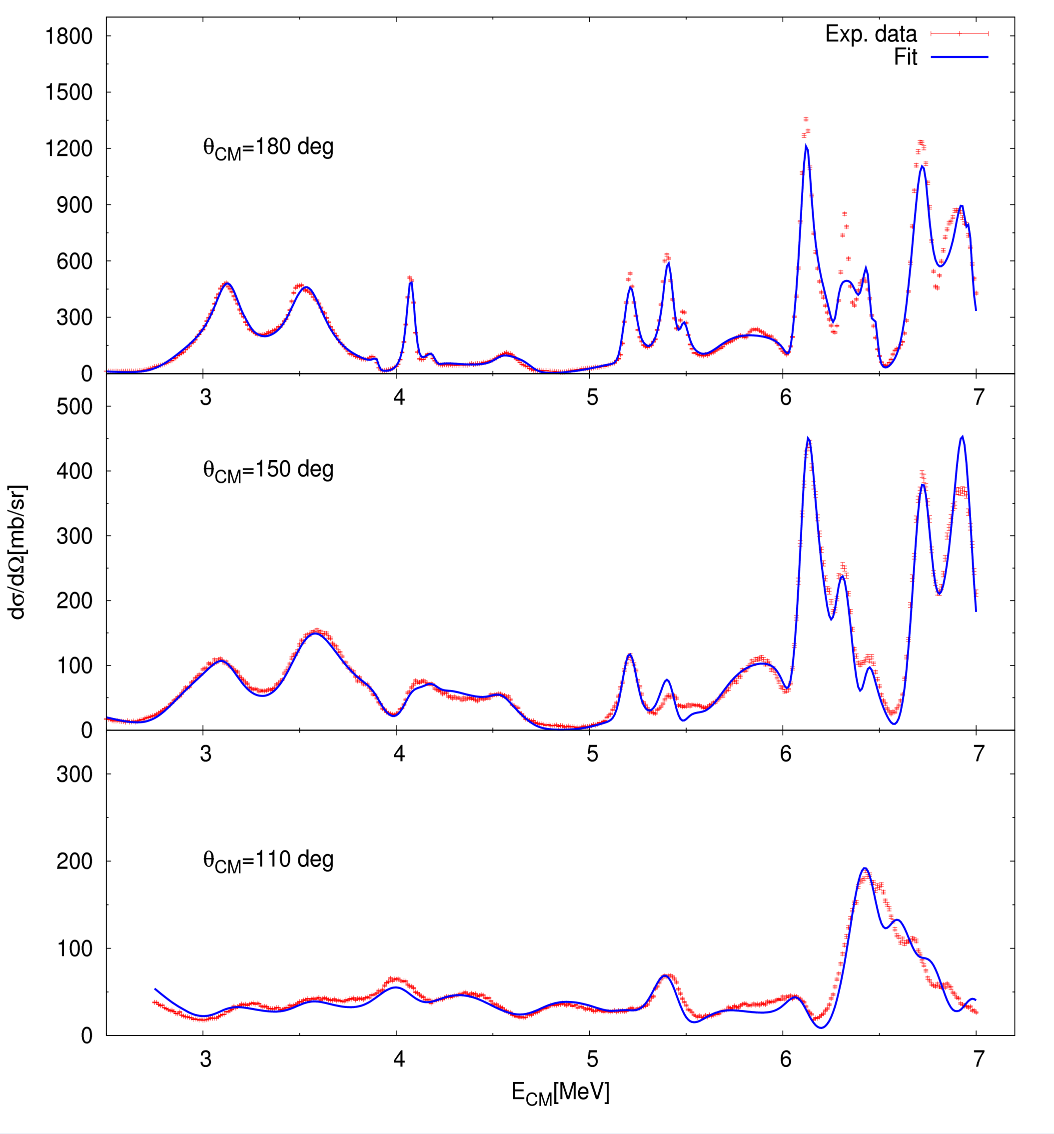
0^+ α halo state in ^{18}O

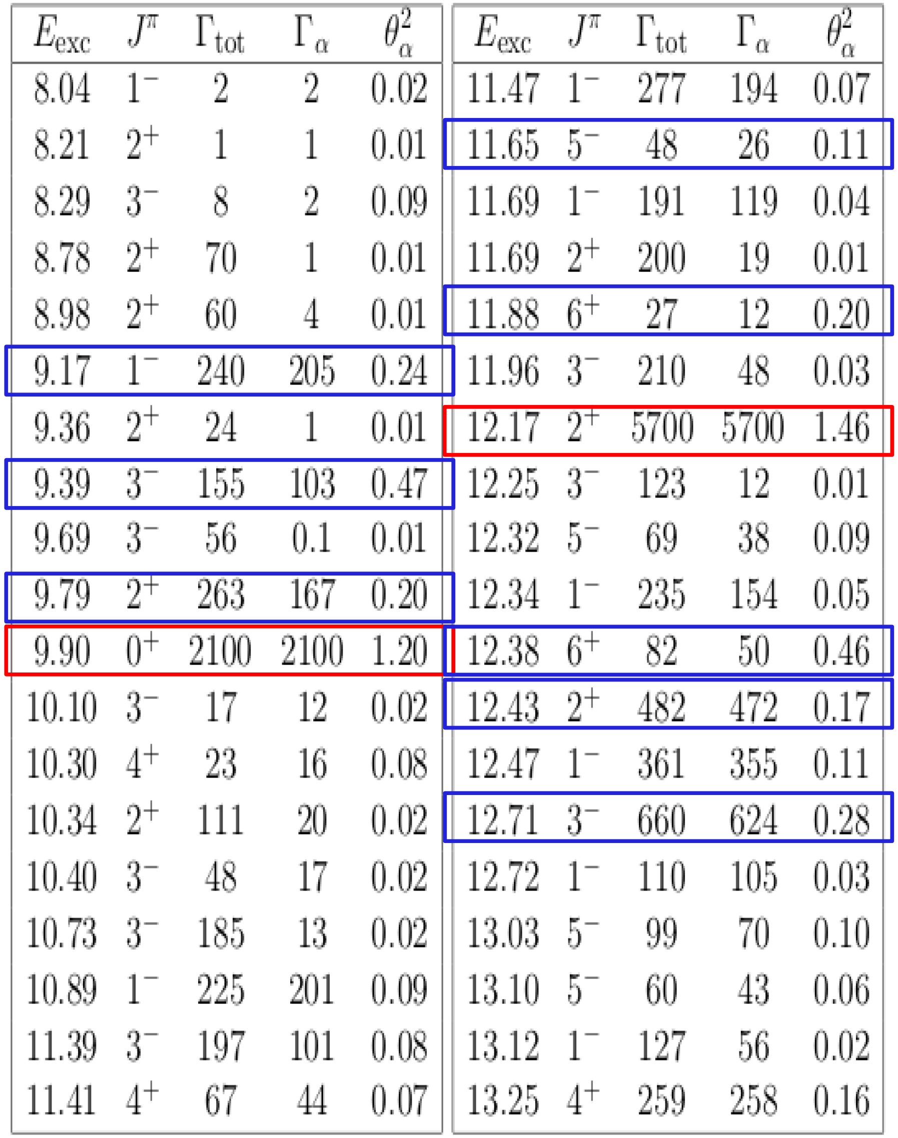
0^+ at 3.7+/-0.3 MeV (~10 MeV ^{18}O excitation energy) with width of ~2 MeV is necessary to fit the α+^{14}C data.
This width corresponds to purely α particle state.





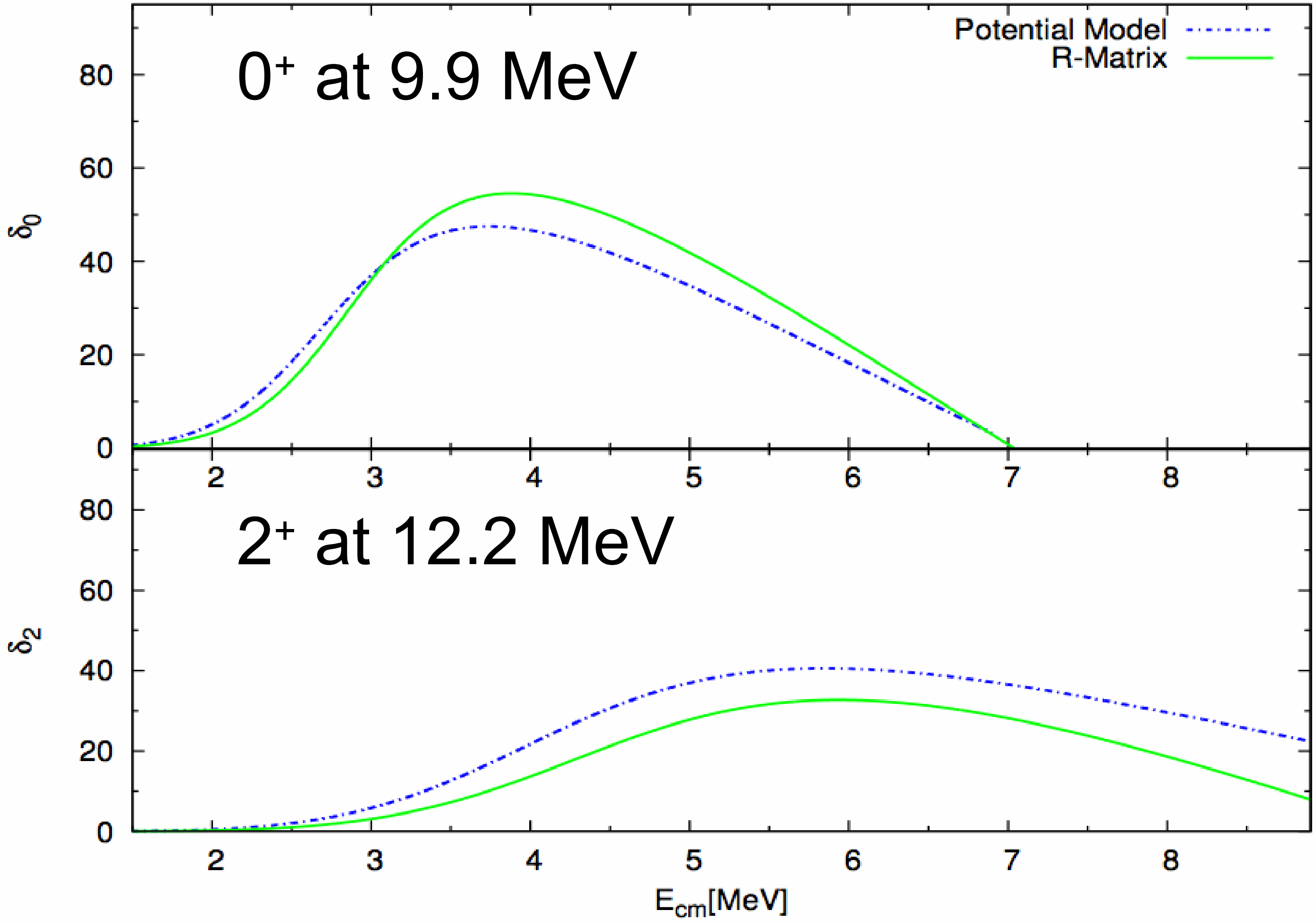
Experimental fit



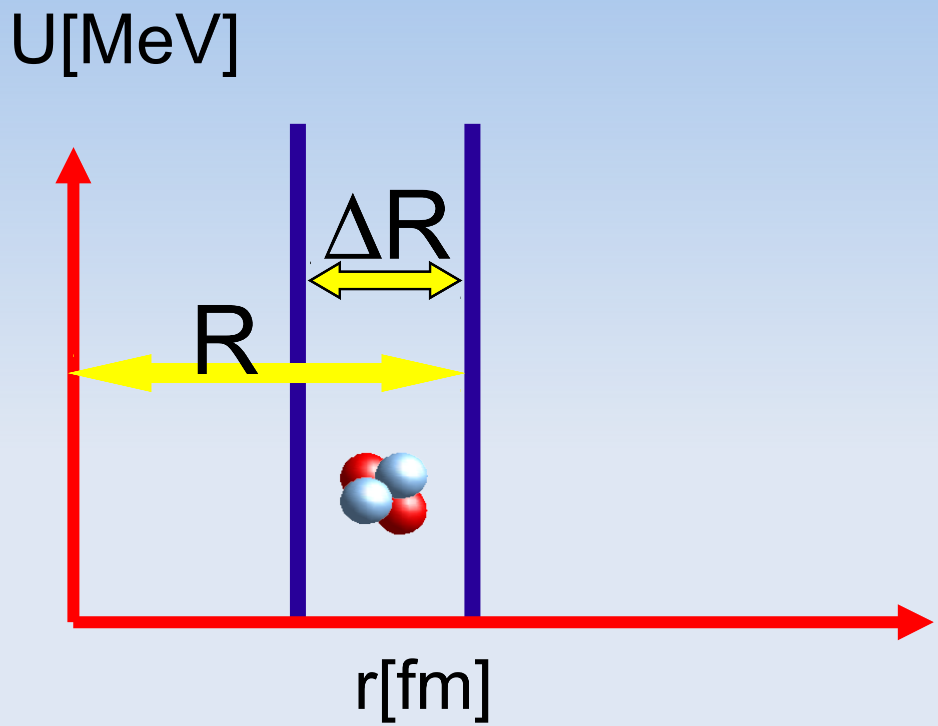


$E_{\rm exc}$	J^π	$\Gamma_{\rm tot}$	Γ_α	θ^2_α	$E_{\rm exc}$	J^π	$\Gamma_{\rm tot}$	Γ_α	θ^2_α
8.04	1^-	2	2	0.02	11.47	1^-	277	194	0.07
8.21	2^+	1	1	0.01	11.65	5^-	48	26	0.11
8.29	3^-	8	2	0.09	11.69	1^-	191	119	0.04
8.78	2^+	70	1	0.01	11.69	2^+	200	19	0.01
8.98	2^+	60	4	0.01	11.88	6^+	27	12	0.20
9.17	1^-	240	205	0.24	11.96	3^-	210	48	0.03
9.36	2^+	24	1	0.01	12.17	2^+	5700	5700	1.46
9.39	3^-	155	103	0.47	12.25	3^-	123	12	0.01
9.69	3^-	56	0.1	0.01	12.32	5^-	69	38	0.09
9.79	2^+	263	167	0.20	12.34	1^-	235	154	0.05
9.90	0^+	2100	2100	1.20	12.38	6^+	82	50	0.46
10.10	3^-	17	12	0.02	12.43	2^+	482	472	0.17
10.30	4^+	23	16	0.08	12.47	1^-	361	355	0.11
10.34	2^+	111	20	0.02	12.71	3^-	660	624	0.28
10.40	3^-	48	17	0.02	12.72	1^-	110	105	0.03
10.73	3^-	185	13	0.02	13.03	5^-	99	70	0.10
10.89	1^-	225	201	0.09	13.10	5^-	60	43	0.06
11.39	3^-	197	101	0.08	13.12	1^-	127	56	0.02
11.41	4^+	67	44	0.07	13.25	4^+	259	258	0.16

Phase shift calculations



Infinite surface potential

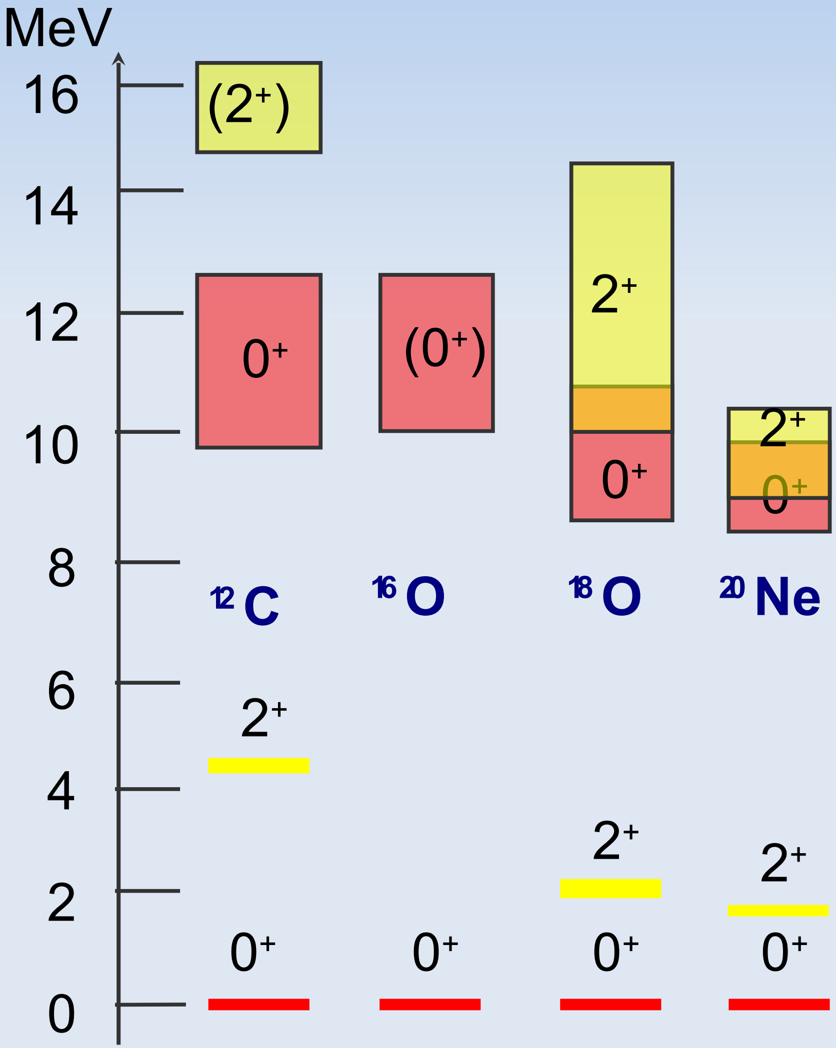


This approach was used for qualitative classification of cluster states in ^{16}O and ^{20}Ne by *V.Z. Goldberg, et al, Sov. J. Nucl. Phys., 19, 253 (1974)*

Excitation energyof n=2 0^+ state should be ~11 MeV

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

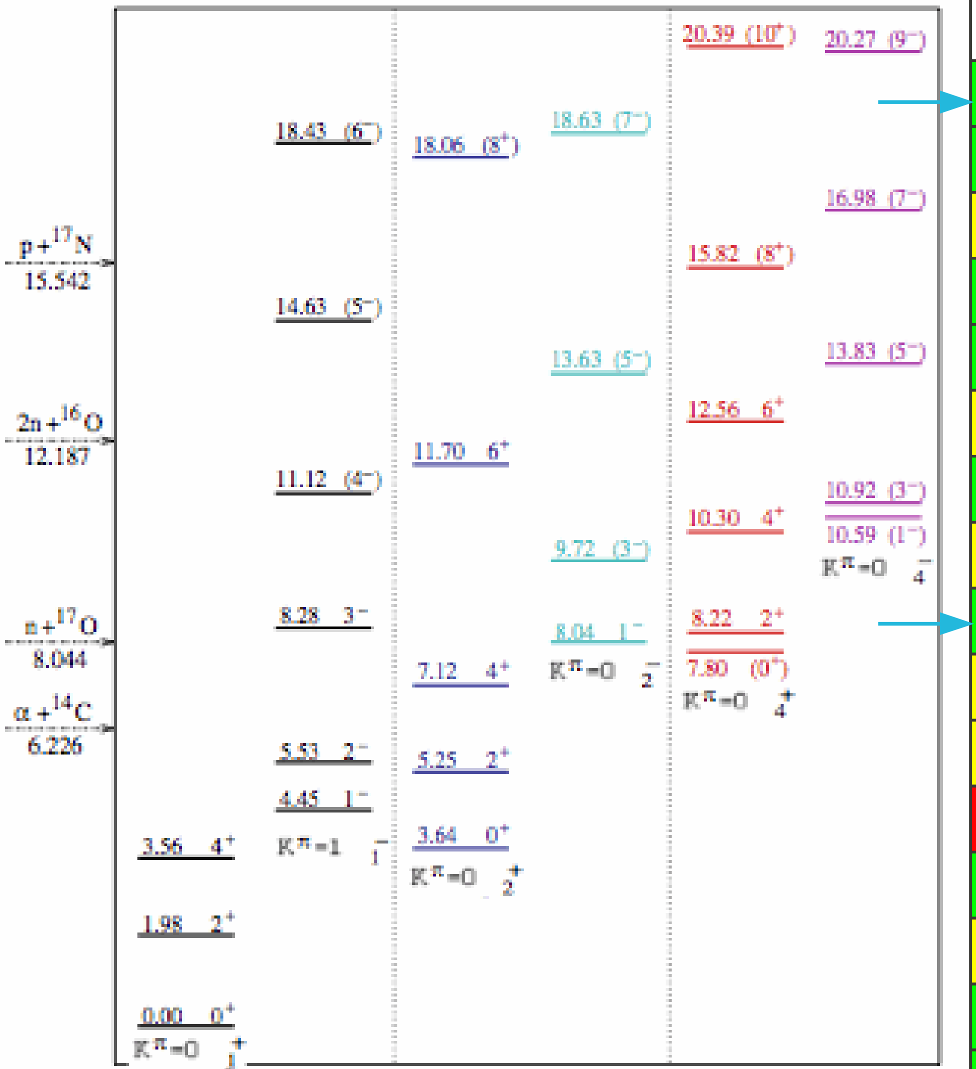
“α-halo” states in light nuclei



^{12}C:
0^+ at 11.25 MeV, Γ=2.5 MeV
H. Fynbo, et al., Nature 433 (2005) 136

^{20}Ne:
0^+ at 8.6 MeV, Γ=1.47 MeV
2^+ at 8.9 MeV, Γ=1.2 MeV
H. Shen, et al., NIM B 90 (1994) 593
L.C. McDermott, et al., PR 118 (1960) 175

Negative parity rotational band



W. von Oertzen, et al.,
EPJ A43, 17 (2010)
12C(7Li,p)

E* (MeV)	Jπ	Γtot(keV)	Γα(keV)	Θα^2
8.04	1-	2	2	0.02
8.21	2+	1	1	<0.01
8.29	3-	8	2	0.09
8.78	2+	70	1	<0.01
8.98	2+	60	4	0.01
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9.79	2+	263	167	0.20
9.76	1-	740	658	0.48
9.9	0+	2100	2100	2.60
10.1	3-	17	12	0.02
10.3	4+	23	16	0.08
10.34	2+	111	20	0.02
10.4	3-	48	17	0.02
11.88	6+	27	12	0.20
12.38	6+	82	50	0.46

These states may play important role in (α,γ); (α,p) and (α,n) reactions relevant for various stellar nucleosynthesis processes.

Like in the mirror nucleus: ^{18}Ne(α,p)

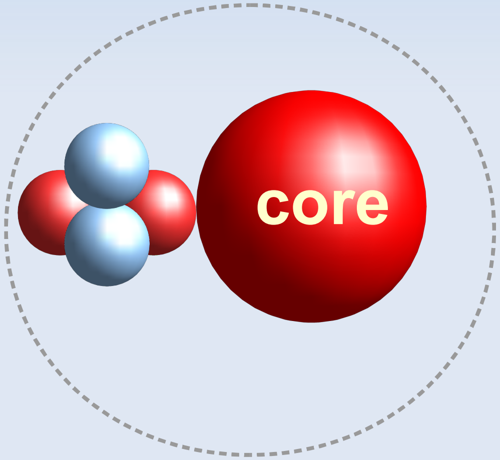
Summary

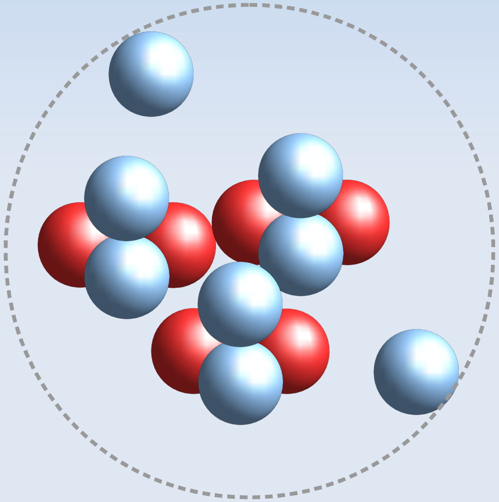
- Several α-cluster states were found in ^{18}O including in the energy range of 2-7 MeV.
- Broad resonances that correspond to pure α-core structures ("α-halo" states) have been known to exist in ^{12}C, ^{20}Ne and now observed in ^{18}O.
- It is speculated that "α-halo" states are common phenomena for light nuclei.
- Potential model was able to predict these broad states.

Thank you!

Clusters in nuclear matter

- Protons and neutrons inside the nucleus form into one or more clusters

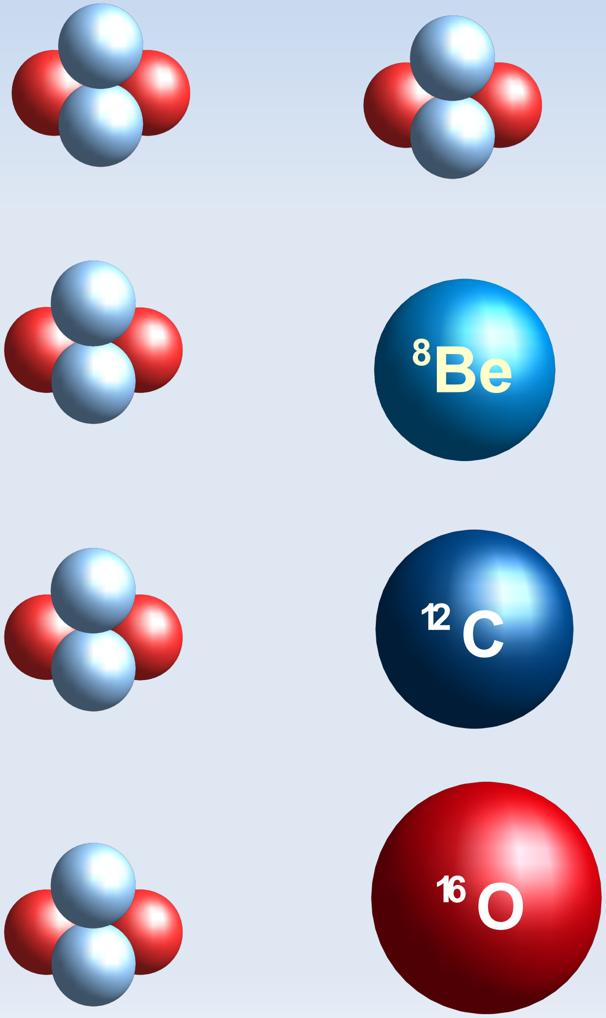




α-structure for N=Z

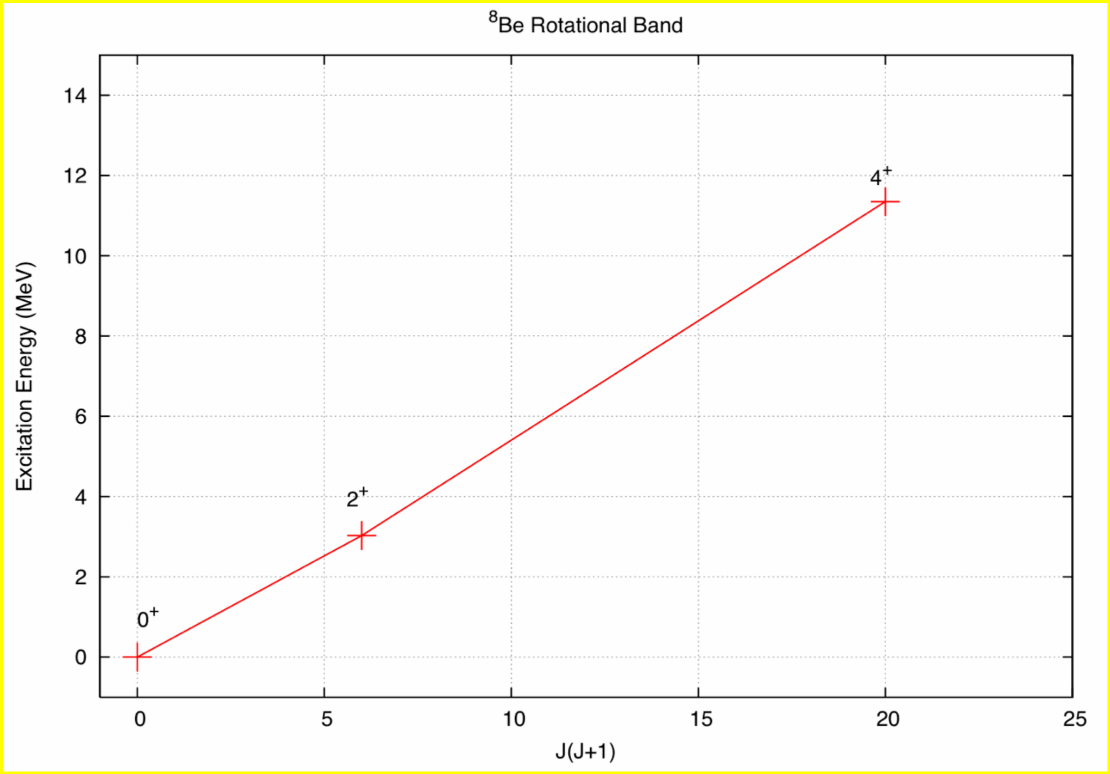
Well known alpha clusters in :

- ^{8}Be
- ^{12}C
- ^{16}O
- ^{20}Ne.

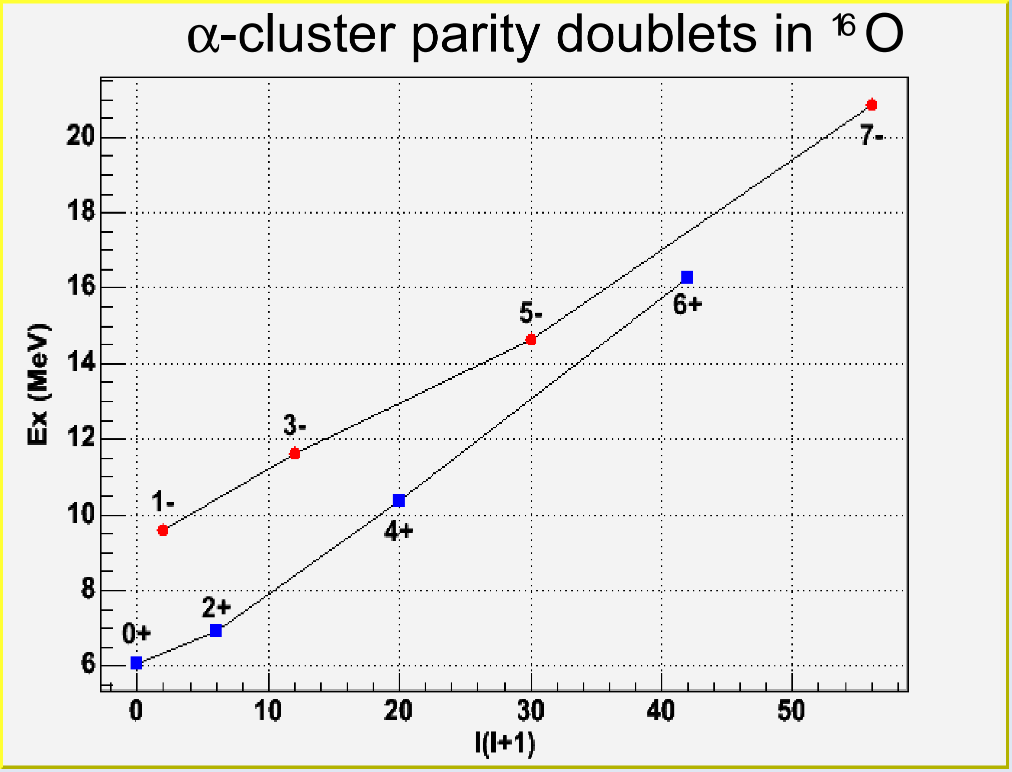


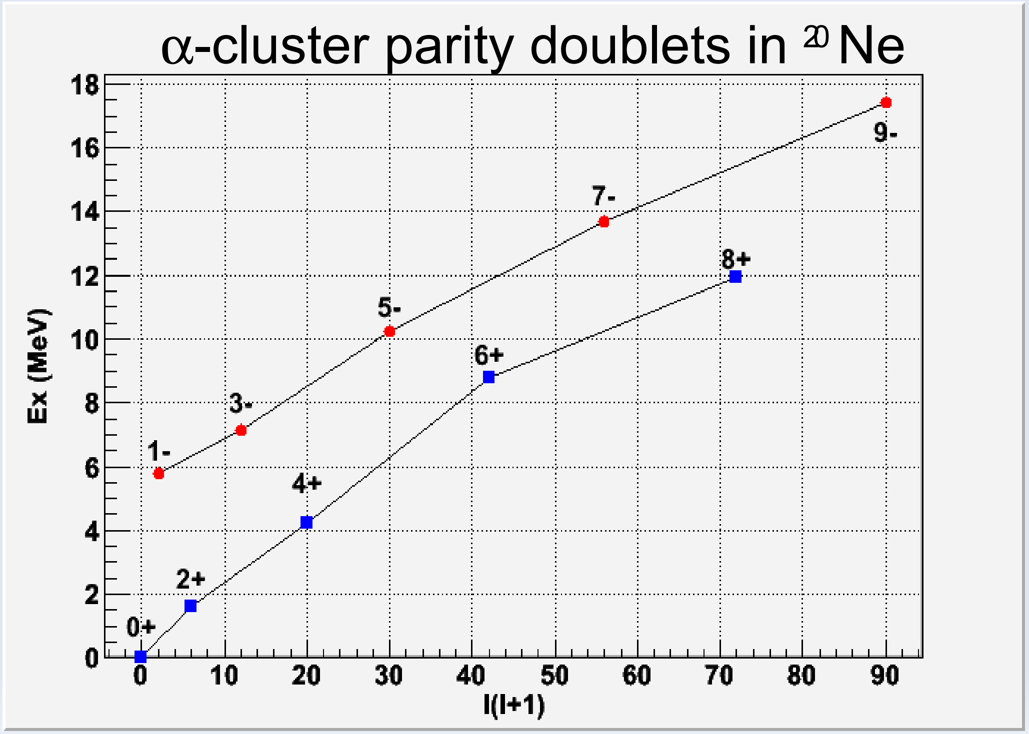
Rotational Bands

^{8}Be Rotational Band



Rotational bands

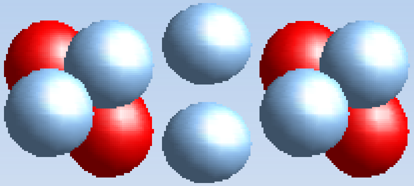




α-structure of N≠Z

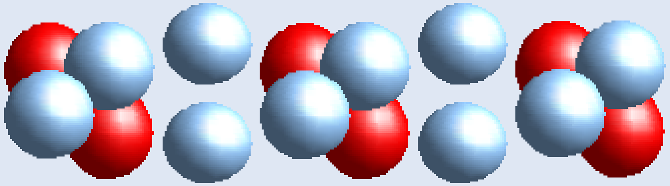
- The α-structure of N≠Z in not well known
- Instrumental to understad the interplay between α-clustering and single particle degrees of freedom.
- Useful to understand Molecular type states

Clustering in N≠Z nuclei. Molecular type states

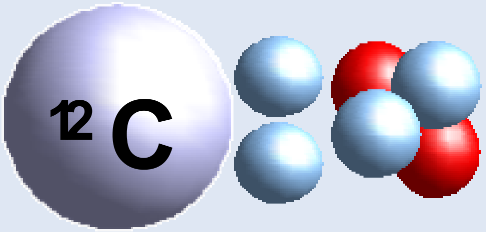


^{10}Be

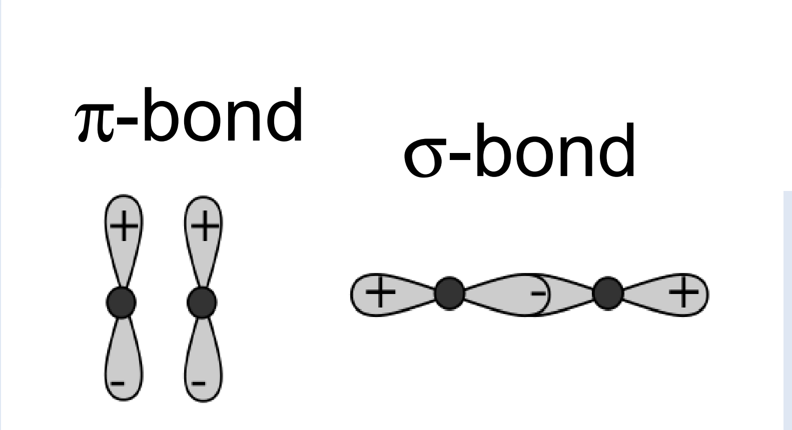
W. von Oertzen,
Z. Phys. A354 (1996)



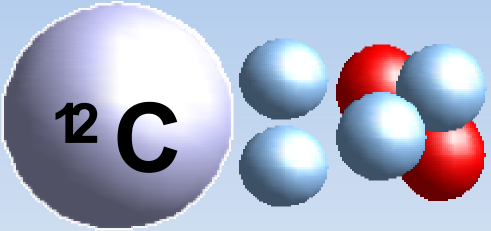
^{16}C



^{18}O

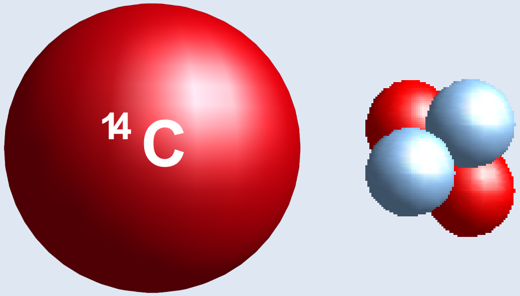


Why ^{18}O is important?



Molecular Type State

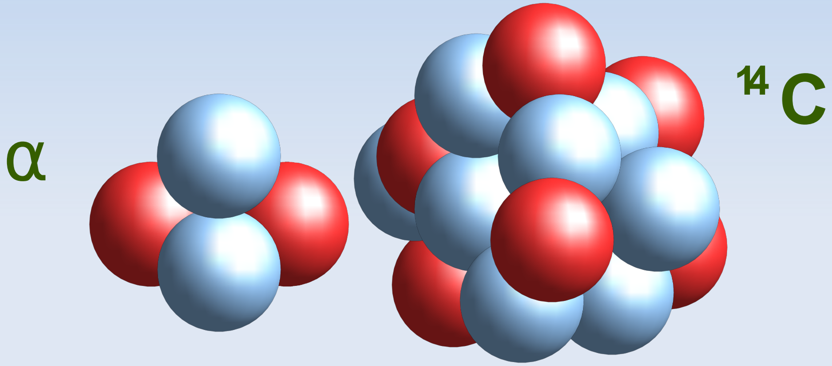
Shell model Structure



Cluster model Structure

$^{14}C(\alpha,\alpha)^{14}C$ elastic scattering

The structure of ^{18}O at exitation energies above the α-decay threshold was studied using ^{14}C+ α elastic scattering.



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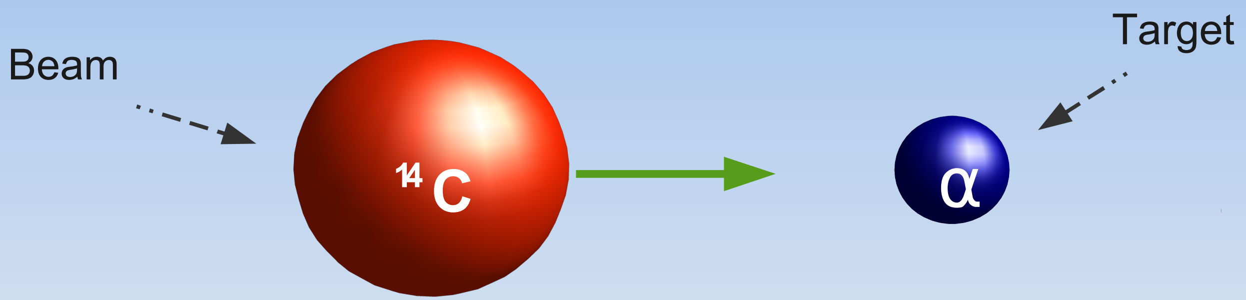
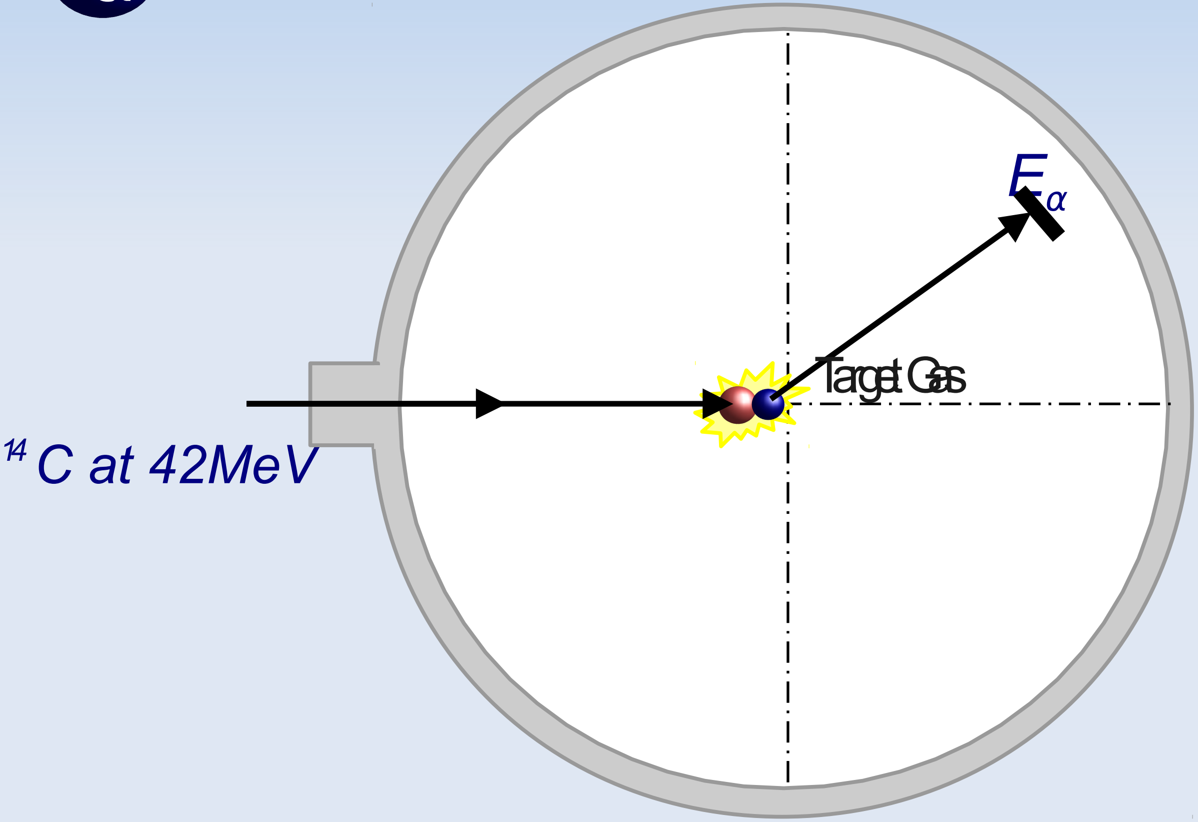
Excitation function of resonance elastic scattering of ^{14}C+α was measured using Method of Thick Target and Inverse Kinematics (TTIK).

Thick Target and Inverse Kinematics

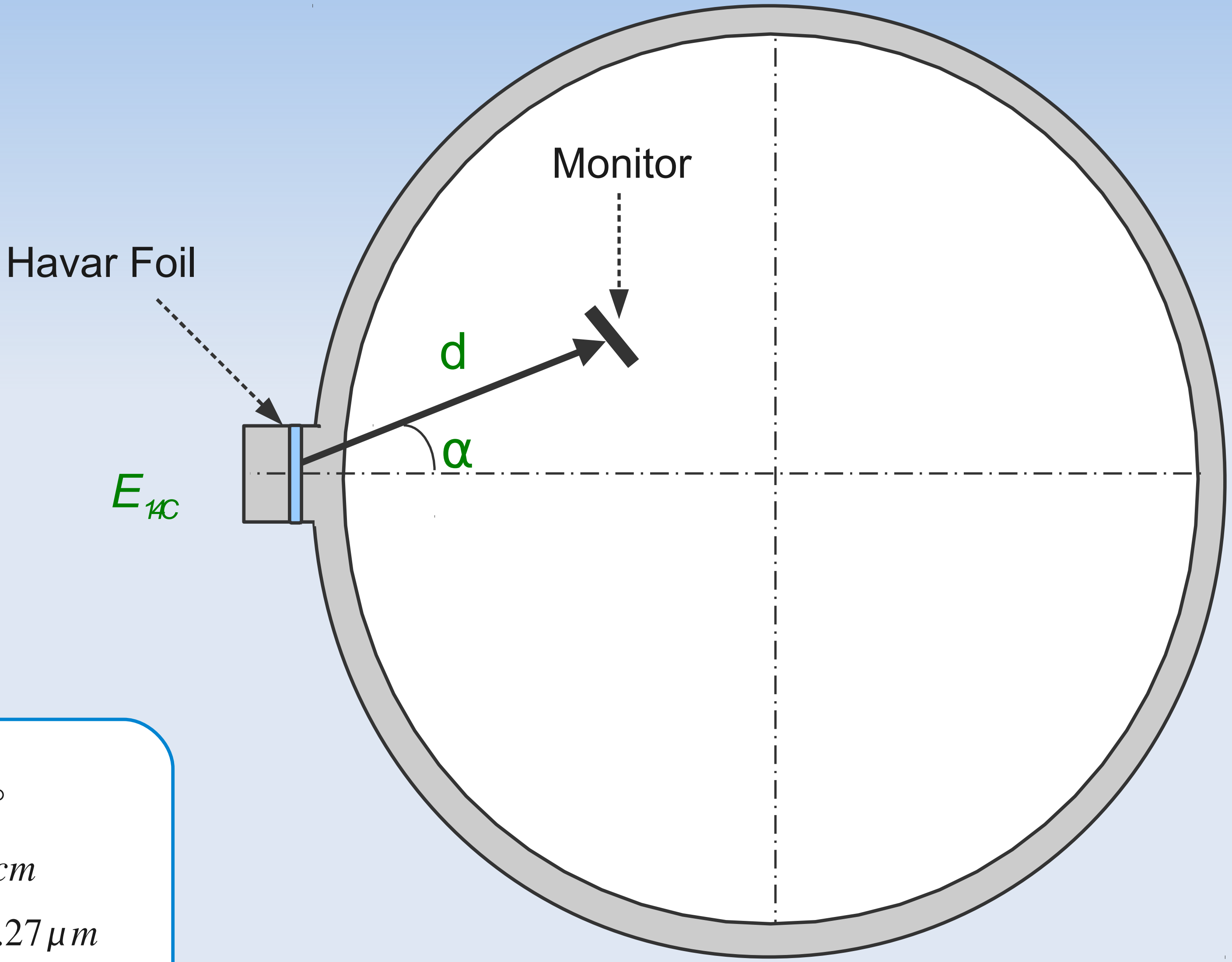


- Allows to study a range of excitation function without the need to change the initial energy.
- More efficient experiment
- Less time consuming



What about beam intensity?

Determination of the beam intensity



$$\alpha = 15°$$

$$d = 22\,cm$$

$$t_{foil} = 1.27\,\mu m$$

Determination of the beam intensity

$$\left(\frac{d\sigma}{d\Omega_{cm}}\right) = \left(\frac{\alpha \hbar c Z_1 Z_2}{4 E_{cm}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

$$\left(\frac{d\sigma}{d\Omega_{cm}}\right) = \frac{1}{I} \frac{N}{k t \Delta\Omega}$$

$$I = \frac{N}{k t \Delta\Omega} \left(\frac{4 E_{cm}}{\alpha \hbar c Z_1 Z_2}\right)^2 \sin^4(\theta/2)$$

R-Matrix analysis

The elastic scattering data was fit using an R-Matrix analysis consisting of 3 open channels, 14C(α,α), 14C(α,n)17O, and 14C(α,n)17O*

$\alpha + {}^{14}C(0^+, g.s.)$

$n + {}^{17}O(5/2^+, g.s.)$

$n + {}^{17}O(1/2^+, 0.87)$

R-Matrix analysis

External region: Channels

Internal Region: Compound Nucleus

Introduced parameters: E, l, γ_α

(Energy, angular momentum, reduced width)

$$R_{cc'} = \sum_\lambda \frac{\gamma_{\lambda c}\gamma_{\lambda c'}}{E_\lambda - E}$$

$$\gamma_{\lambda\alpha} \sim \langle \psi_{18O} | (\psi_{14C} \otimes \psi_\alpha) \rangle$$

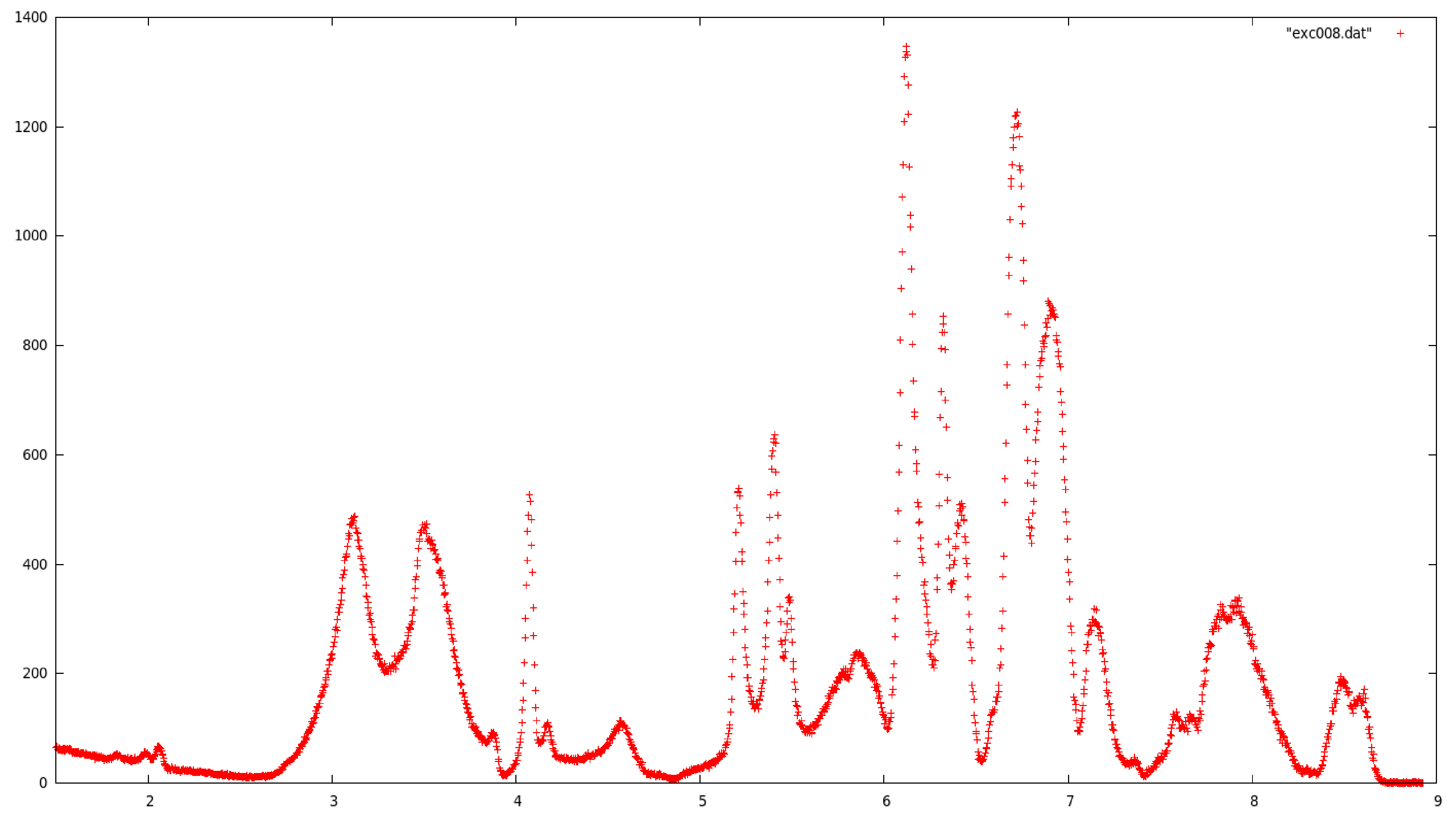
$$\gamma_{sp}^2 = \frac{\hbar^2}{\mu R^2}$$

$$\theta_\alpha^2 = \frac{\gamma_\alpha^2}{\gamma_{sp}^2}$$

$$\Gamma_{tot} = \Gamma_\alpha + \Gamma_n$$

$$\Gamma_\alpha = 2P\gamma_\alpha^2$$

Experimental data



Resonances in ^{18}O observed via ^{14}C+α

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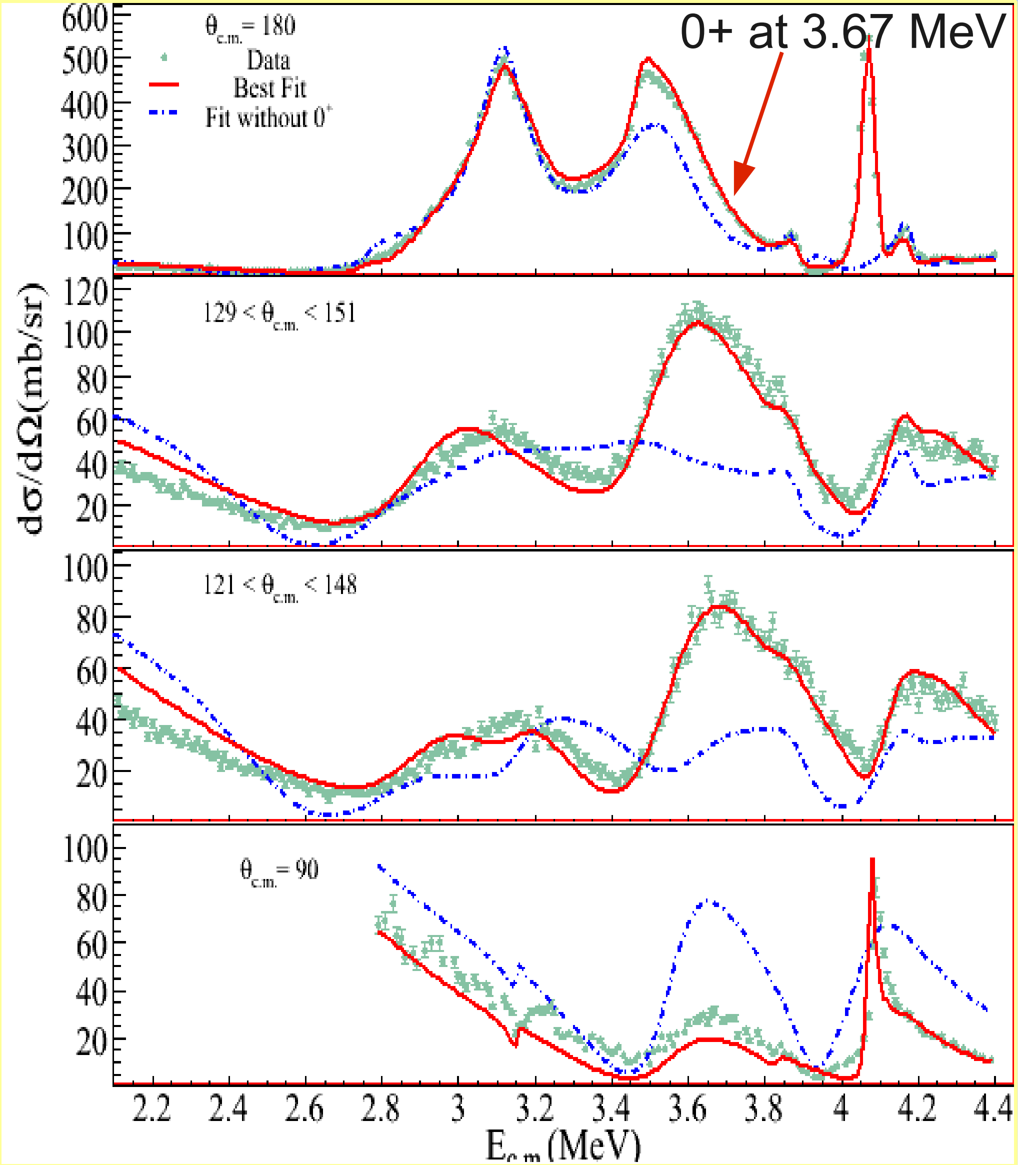

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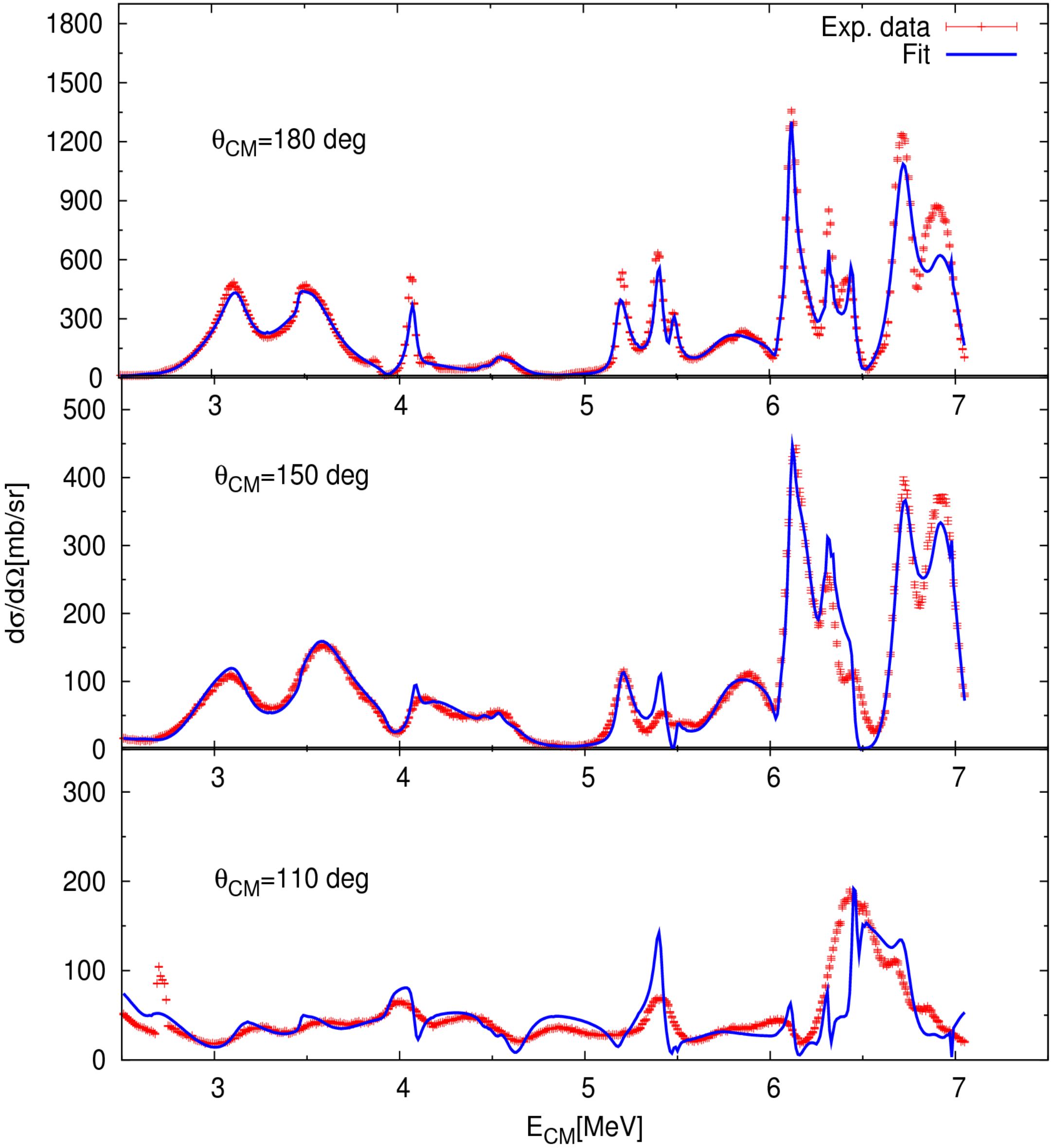
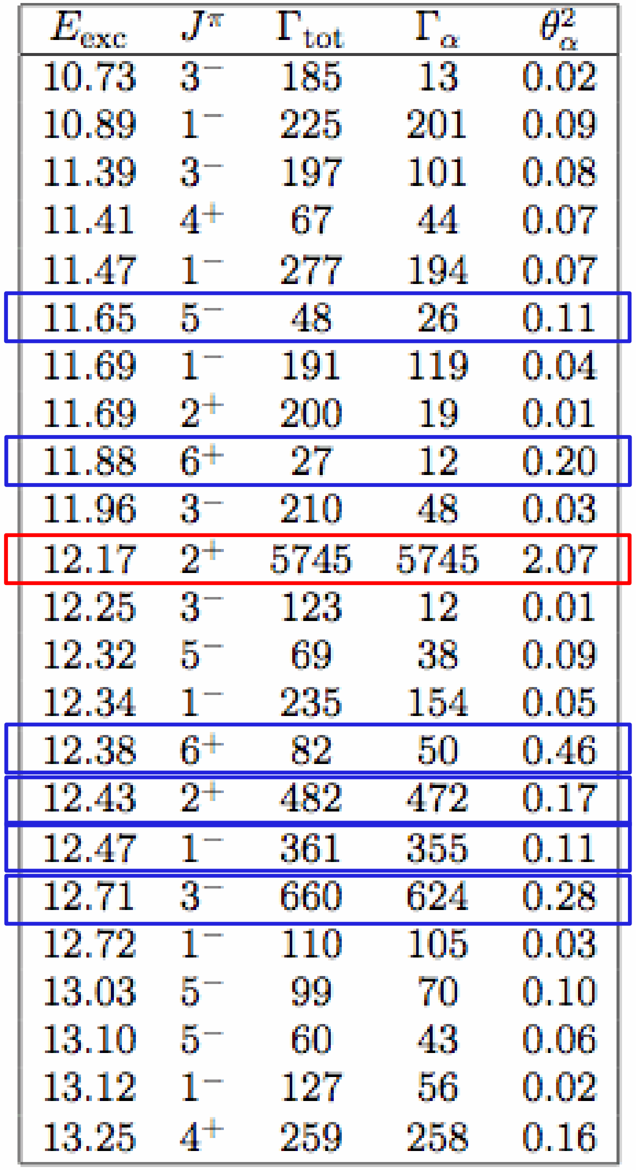
Experimental fit





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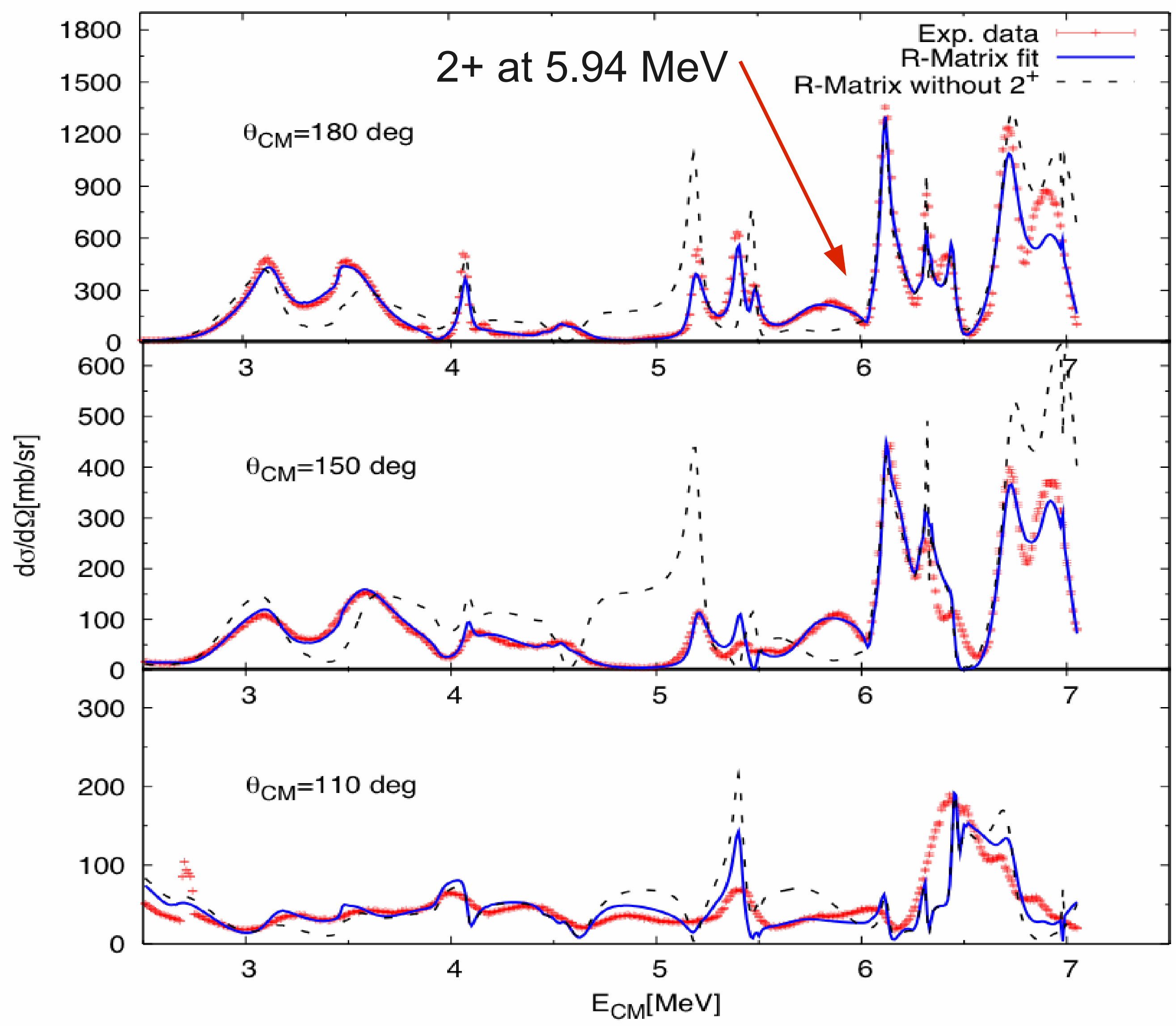
12.72	1^-	110	105	0.03
13.03	5^-	99	70	0.10
13.10	5^-	60	43	0.06
13.12	1^-	127	56	0.02
13.25	4^+	259	258	0.16

Broad 2^+


2+ at 5.94 MeV

Broad States

J^{π}	E_{exc} (MeV)	Γ_{α}(MeV)	Θ^{2}_{α}
O+	9.9	2.1	2.6
2+	12.17	5.7	2.1

$\Theta^{2}_{\alpha}>1$?

More realistic potential is needed to describe α-core states

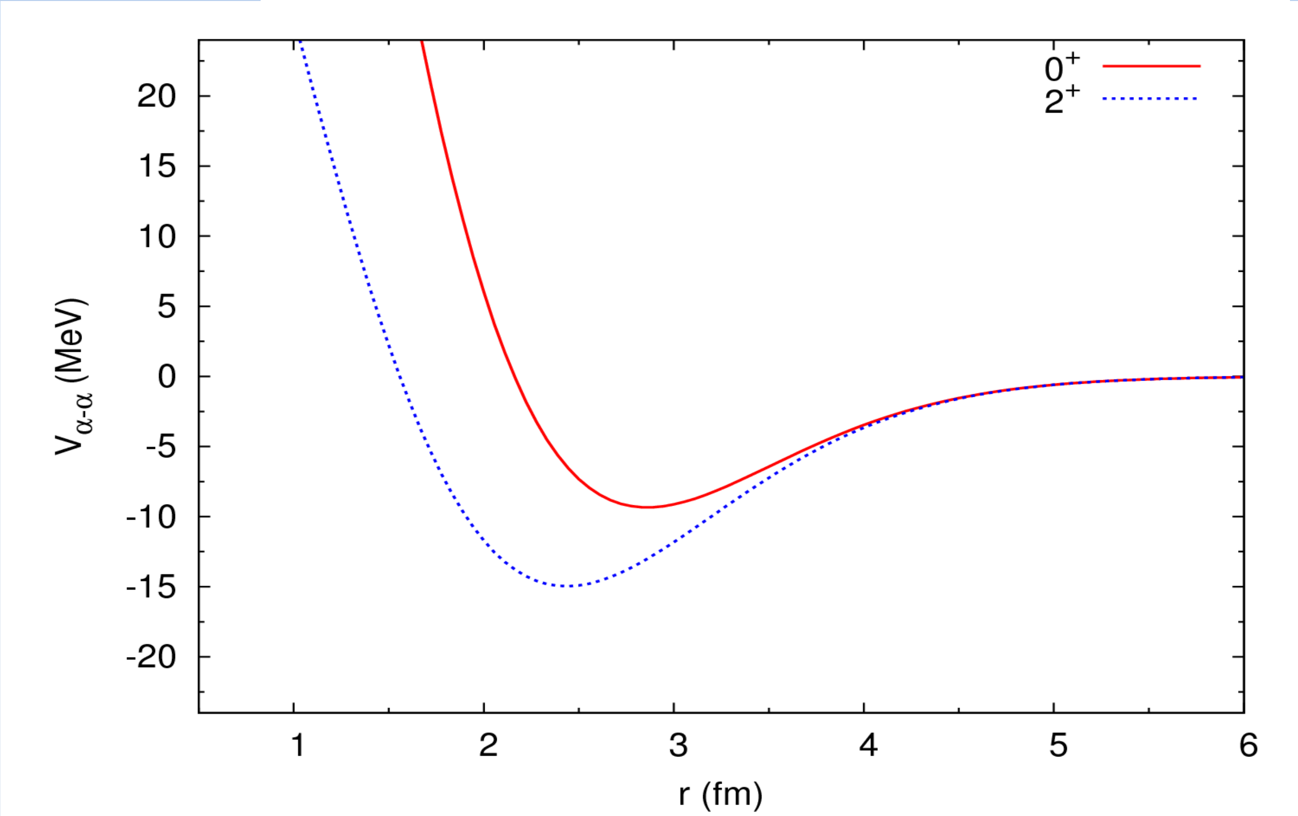
$$\gamma^{2}_{sp}=\frac{\hbar^{2}}{\mu R^{2}}$$

$$\theta^{2}_{\alpha}=\frac{\gamma^{2}_{\alpha}}{\gamma^{2}_{sp}}$$

Potential model description of α-core states

- ^{8}Be

$$V_{\alpha-\alpha} = -117.2275 e^{-0.2099 r^2} + V_R^{(L)} e^{-0.377 r^2}$$



$V_R^{(0)}$ =255.3 MeV

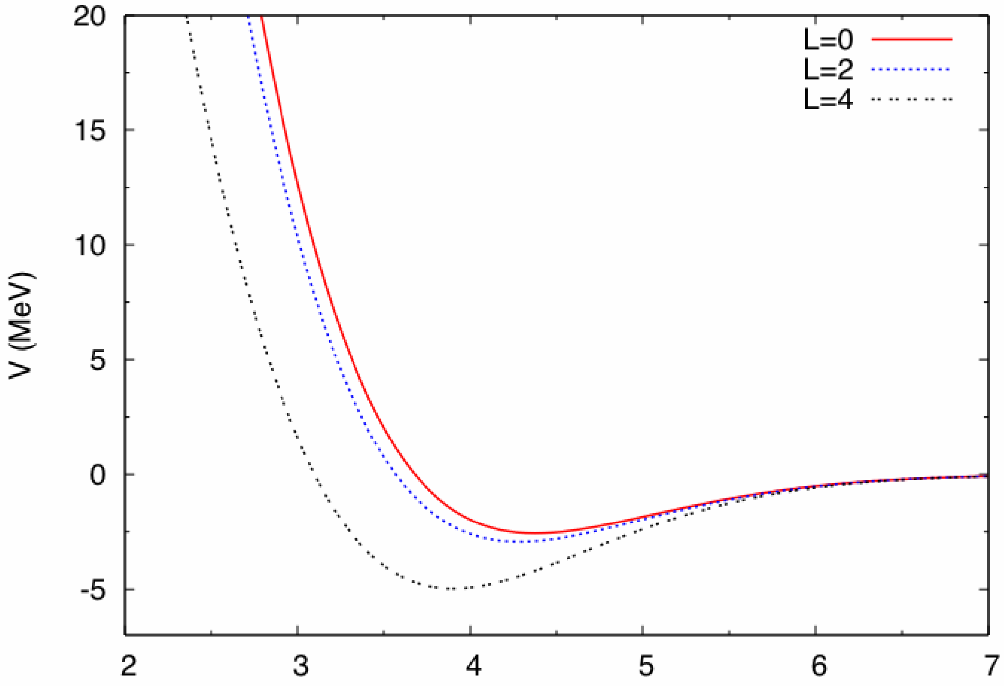
$V_R^{(2)}$ =175.15 MeV

J^π	E_{exc}^{calc} (MeV)	Γ_α^{calc} (keV)	E_{exc}^{exp} (keV)	Γ_α^{exp} (keV)
0^+	0	5.88 eV	0	5.57 eV
2^+	3.03	1934	3.03	1513

Potential model description of α-core states

- ^{20}Ne

$$V(r) = V_A \cdot FCT \cdot e^{-\frac{\left(r^2+R_\alpha^2\right)}{gms}} \left[e^{\frac{2rR_\alpha}{gms}} \left(1-\frac{R_\alpha}{r}\right) + e^{-\frac{2rR_\alpha}{gms}} \left(1+\frac{R_\alpha}{r}\right) \right] + V_{REP} \cdot e^{-r^2/R_{REP}^2}$$



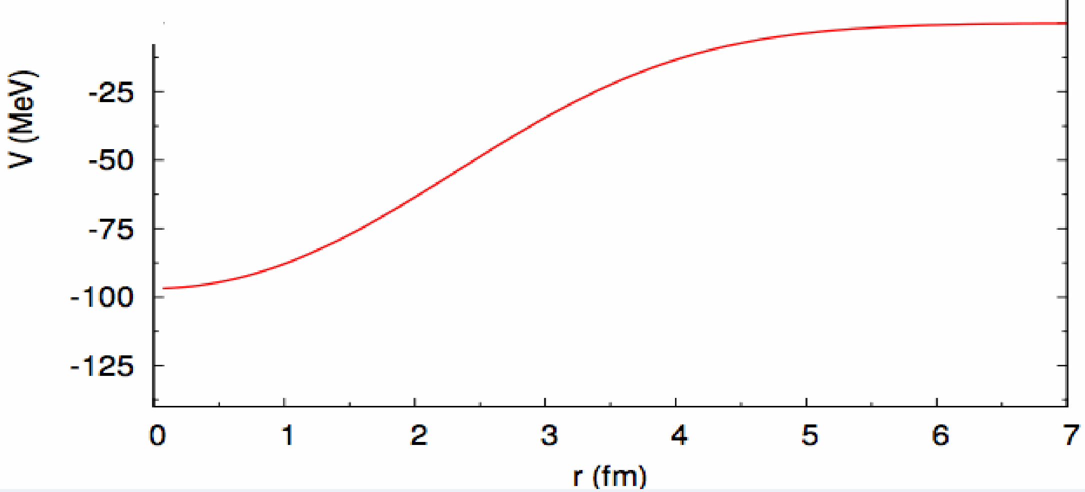
This folding potential reproduces the g.s. of ^{20}Ne bound by 4.73 MeV with respect to α-decay.

$V_R^{(0)}$ =312.56 MeV

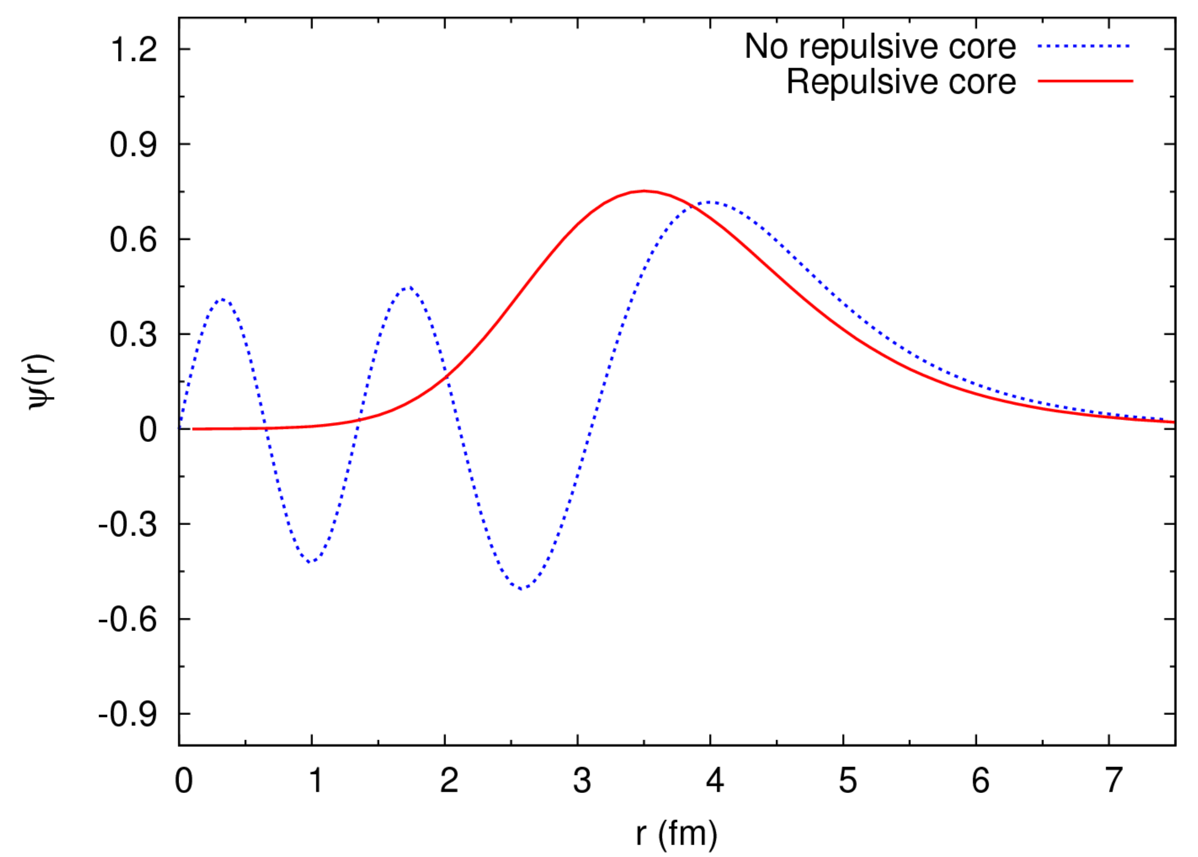
$V_R^{(2)}$ =299.74 MeV

$V_R^{(4)}$ =251.79 MeV

R_c=3.457 fm

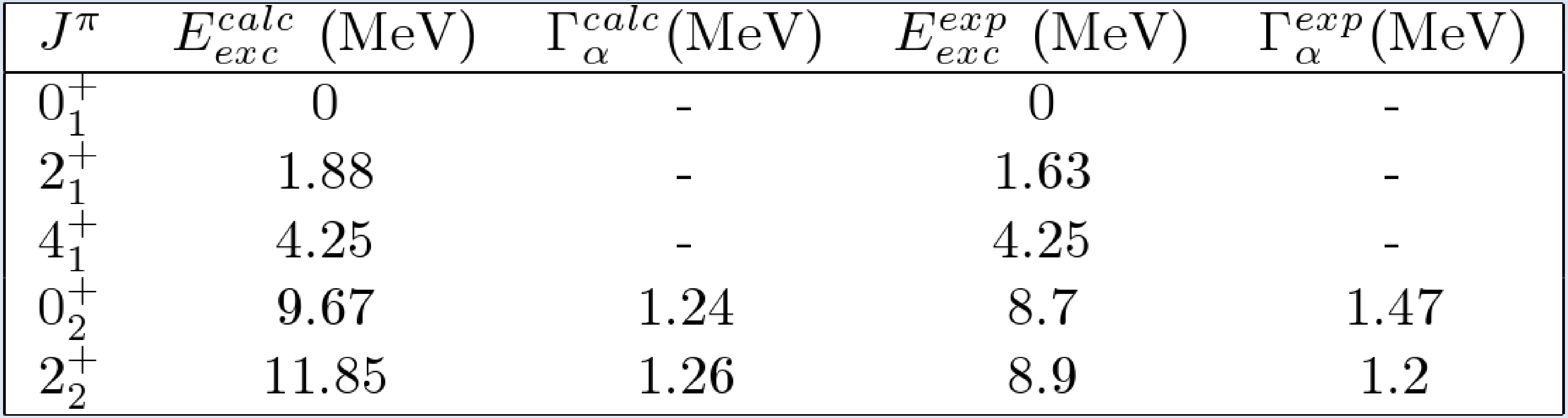


Potential model description of α-core states



Potential model description of α-core states

- 20Ne States using Potential model

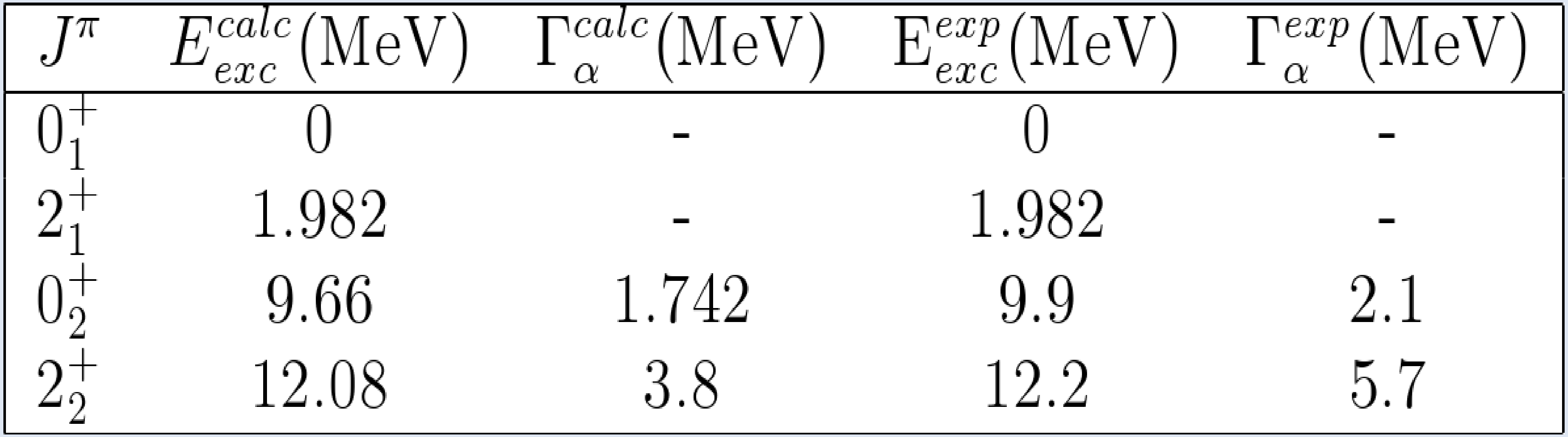


J^{π}	E_{exc}^{calc} (MeV)	Γ_{α}^{calc}(MeV)	E_{exc}^{exp} (MeV)	Γ_{α}^{exp}(MeV)
0_1^+	0	-	0	-
2_1^+	1.88	-	1.63	-
4_1^+	4.25	-	4.25	-
0_2^+	9.67	1.24	8.7	1.47
2_2^+	11.85	1.26	8.9	1.2

Potential model description of α-core states

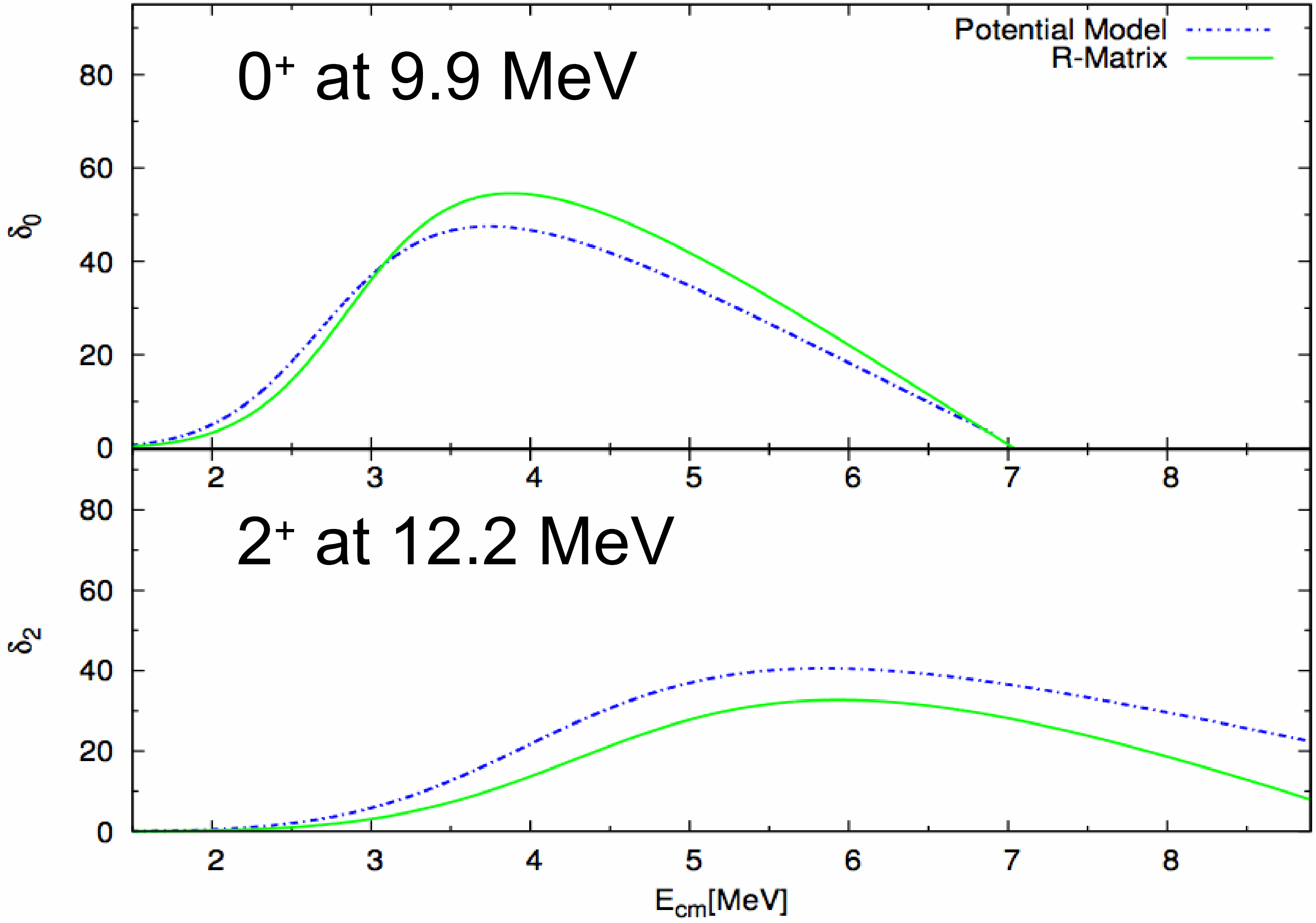
- ^{18}O

States for 18O using the same potential with Rc=3.379 fm

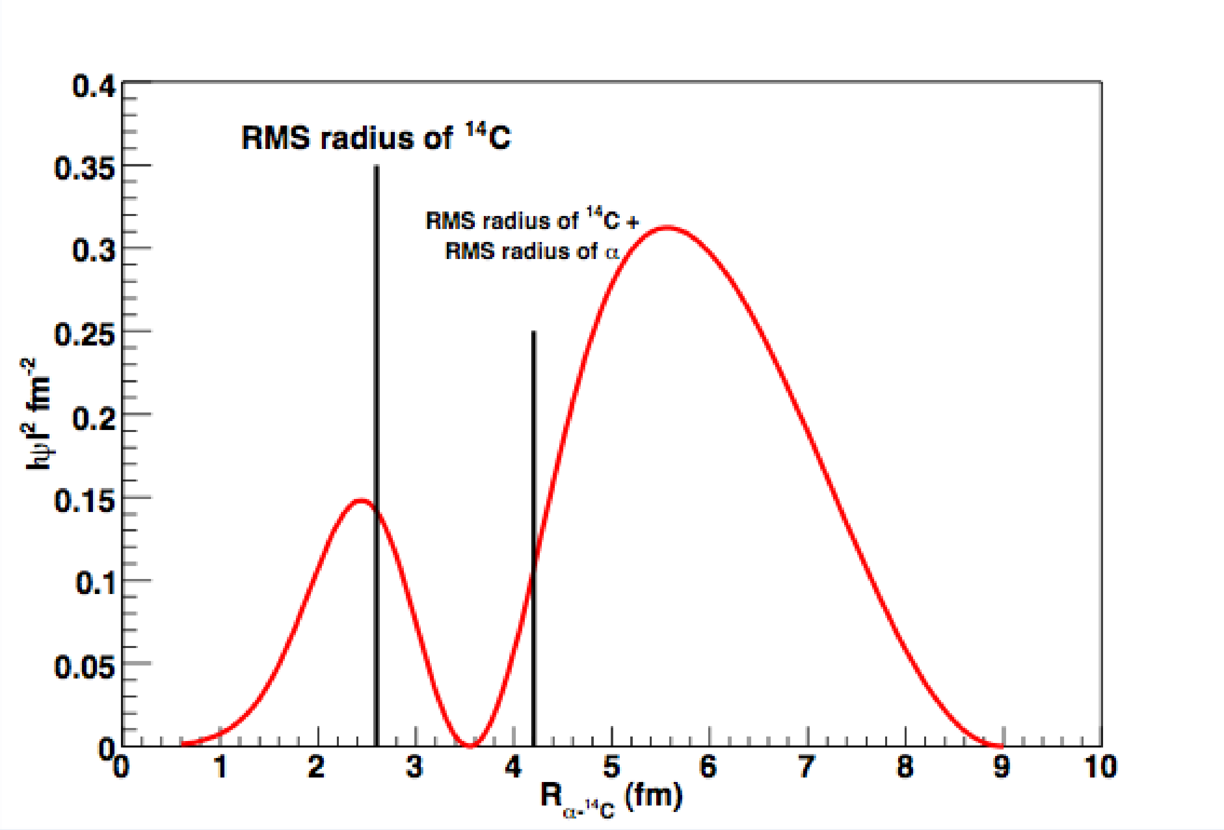


J^π	E_{exc}^{calc}(MeV)	Γ_α^{calc}(MeV)	E_{exc}^{exp}(MeV)	Γ_α^{exp}(MeV)
0_1^+	0	-	0	-
2_1^+	1.982	-	1.982	-
0_2^+	9.66	1.742	9.9	2.1
2_2^+	12.08	3.8	12.2	5.7

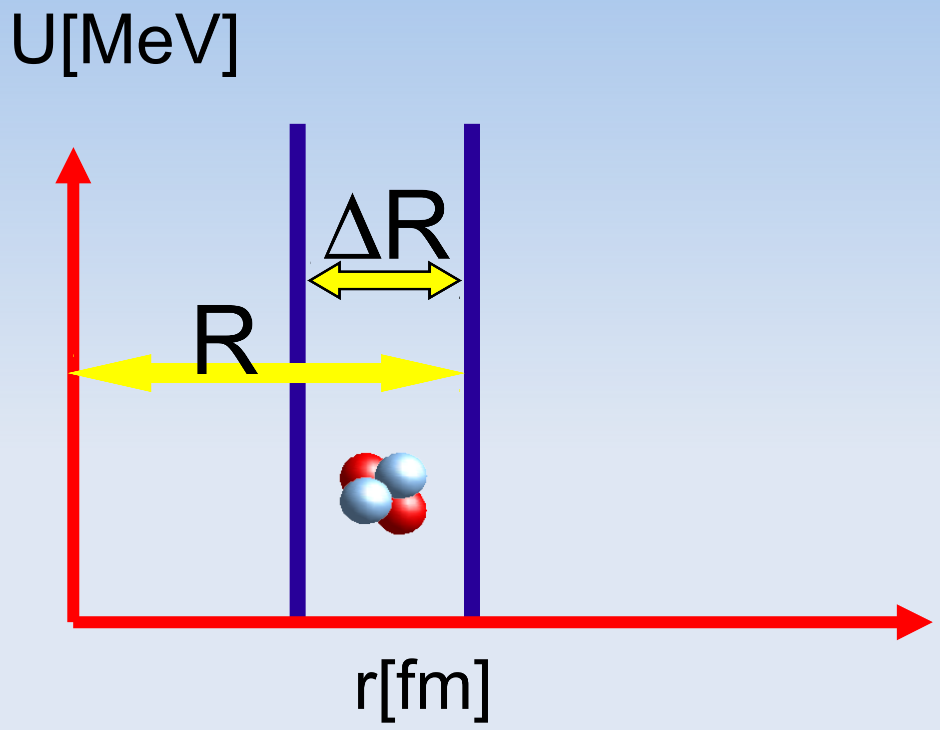
Phase shift calculations



0^+ α halo state in ^{18}O



Infinite surface potential



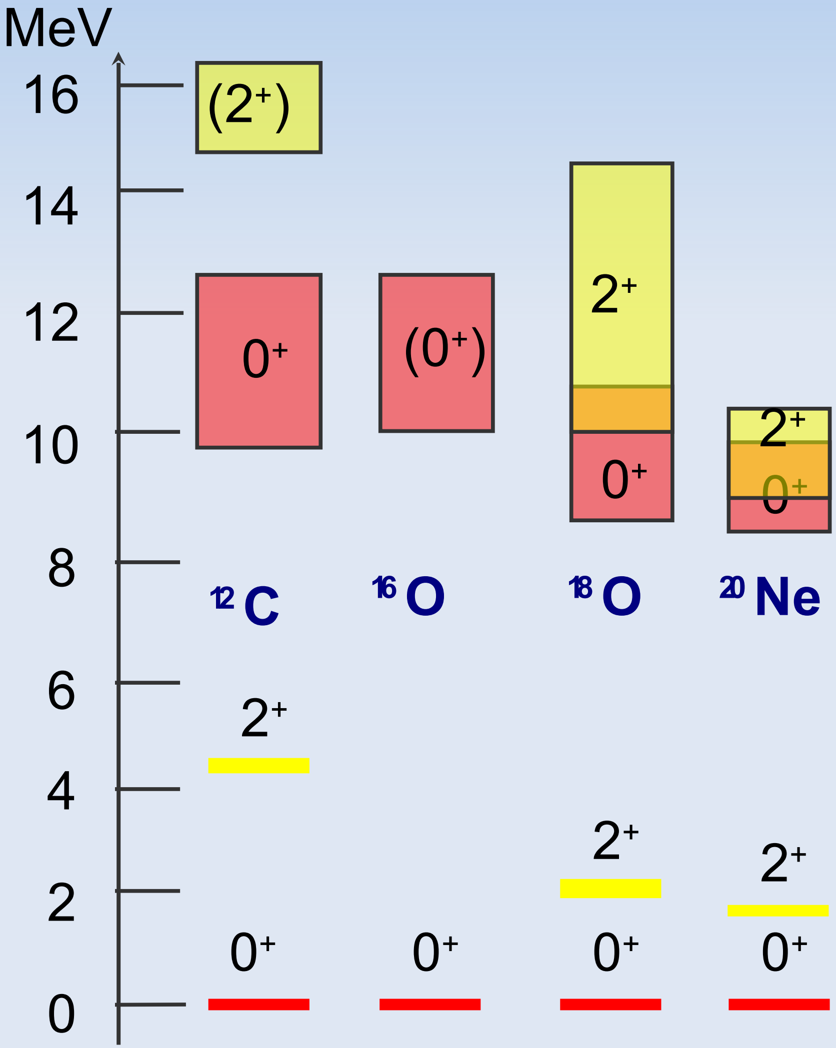
This approach was used for qualitative classification of cluster states in ^{16}O and ^{20}Ne by *V.Z. Goldberg, et al,*
Sov. J. Nucl. Phys., 19, 253 (1974)

Excitation energyof n=2 0^+ state should be ~11 MeV

There should be n=2 2^+ state

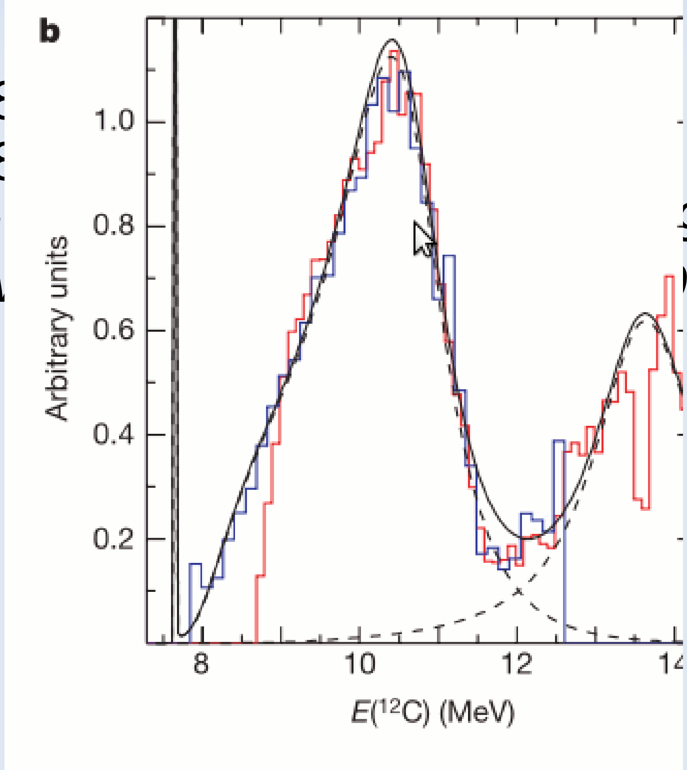
$$E = \frac{n^2\pi^2\hbar^2}{2\mu(\Delta R)^2} + \frac{\hbar^2\ell(\ell+1)}{2\mu R^2}$$

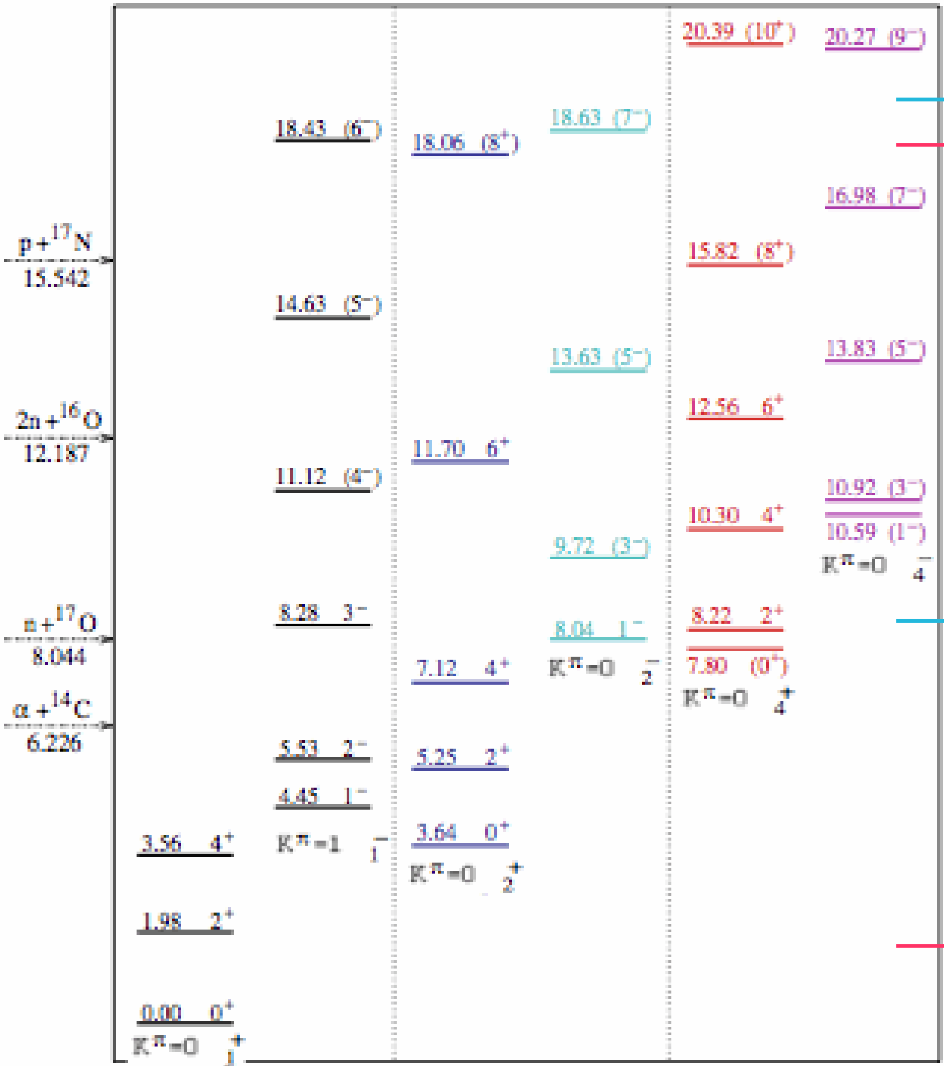
“α-halo” states in light nuclei



^{12}C:
0^+ at 11.25 MeV, Γ=2.5 MeV
H. Fynbo, et al., Nature 433 (2005) 136

^{20}Ne:
0^+ at 8
2^+ at 8
H. Sh *93*
L.C. M *960) 175*





W. von Oertzen, et al.,
EPJ A43, 17 (2010)

12C(7Li,p)

E* (MeV)	Jπ	Γtot(keV)	Γα(keV)	Θα^2
8.04	1-	2	2	0.02
8.21	2+	1	1	<0.01
8.29	3-	8	2	0.09
8.78	2+	70	1	<0.01
8.98	2+	60	4	0.01
9.17	1-	240	205	0.24
9.36	2+	24	1	<0.01
9.39	3-	155	103	0.47
9.69	3-	56	0.1	<0.01
9.79	2+	263	167	0.20
9.76	1-	740	658	0.48
9.9	0+	2100	2100	2.60
10.1	3-	17	12	0.02
10.3	4+	23	16	0.08
10.34	2+	111	20	0.02
10.4	3-	48	17	0.02
11.88	6+	27	12	0.20
12.38	6+	82	50	0.46

Summary

- Broad resonances that correspond to pure α-core structures (“α-halo” states) have been known to exist in ^{12}C, ^{20}Ne and now observed in ^{18}O.
- Several α-cluster states were found in ^{18}O including in the energy range of 2-7 MeV.
- It is speculated that “α-halo” states are common phenomena for light nuclei.
- Potential model was able to predict these broad states.