The Institute of Nuclear Physics
Ministry of Energy of the Republic of Kazakhstan

Joint Institute for Nuclear Research
SCIENCE BRINGING NATIONS TOGETHER

NATIONAL RESEARCH CENTER
"KURCHATOV INSTITUTE"

INVESTIGATION OF EXOTIC STATES IN LIGHT NUCLEI

D.M. Janseitov

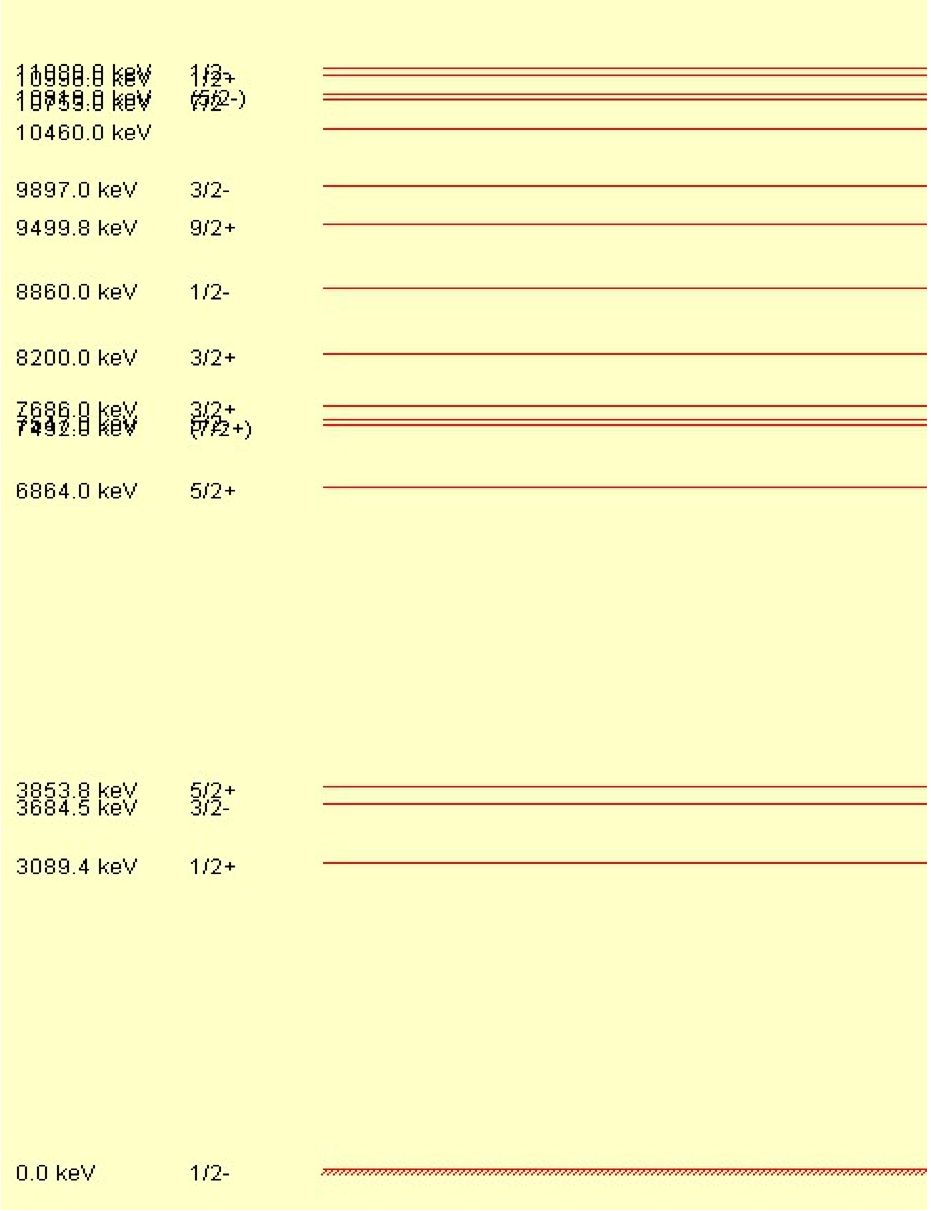
.

DUBNA 2017

Relevance

Why ^{13}C ?

Until now, the neutron halo has been observed almost exclusively in the ground states of some radioactive nuclei. ^{13}C nucleus is a good example of a "normal" core, which is well described in the framework of the shell model. The ^{13}C level diagram was reliably determined up to excitation energies of ~ 10 MeV.



Relevance

Search for a neutron halo in the excited state of the ^{13}C nucleus

The halo is most likely to be detected in nuclear states in which the valence neutron occupies an s-orbit, since the absence of a centrifugal barrier can lead to a significant increase in the radius. In the ^{13}C and ^{9}Be nuclei, such states are known near neutron thresholds ($1/2^+$, 3.09 MeV and 1.68 MeV, respectively).

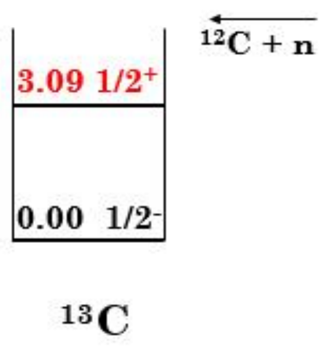
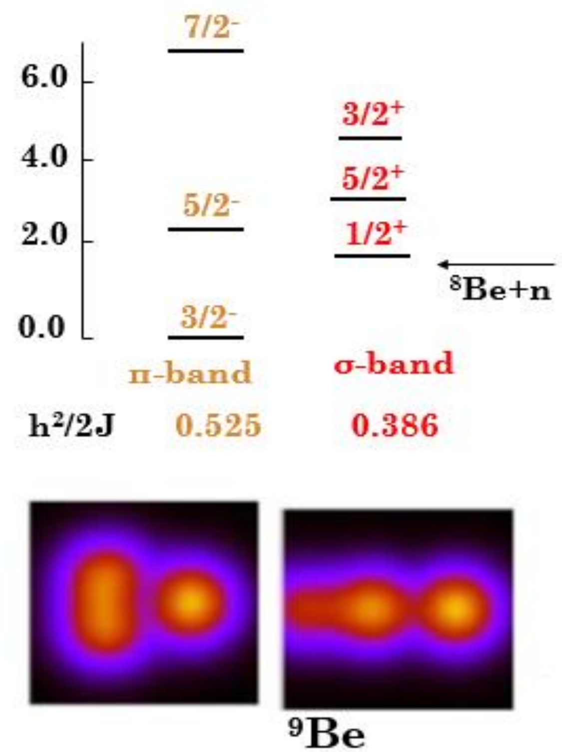


Fig. from T.Togashi et al., Int. J. Mod. Phys. E17 (08) 2081



Three types of neutron halo

The neutron is in the s-state

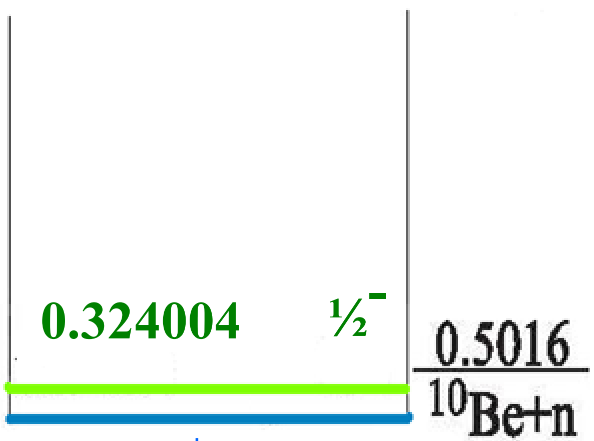
The discrete spectrum

In the continuum

Ground state

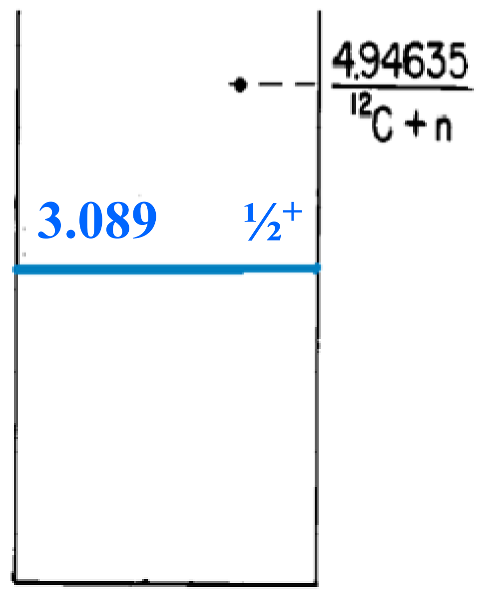
Excited state

Excited states



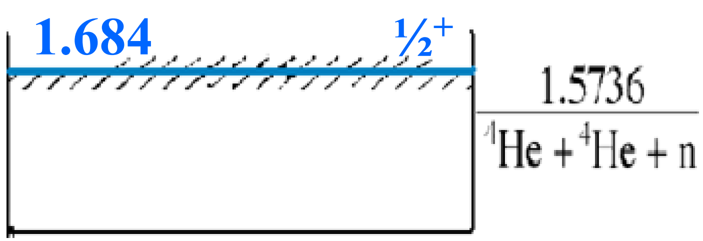
$J^\pi=1/2^+$; T=3/2

^{11}Be



$J^\pi=1/2^-$; T=1/2

^{13}C



$J^\pi=3/2^-$; T=1/2

^{9}Be

I. Tanihata et al., PRL,55,2676(1985)

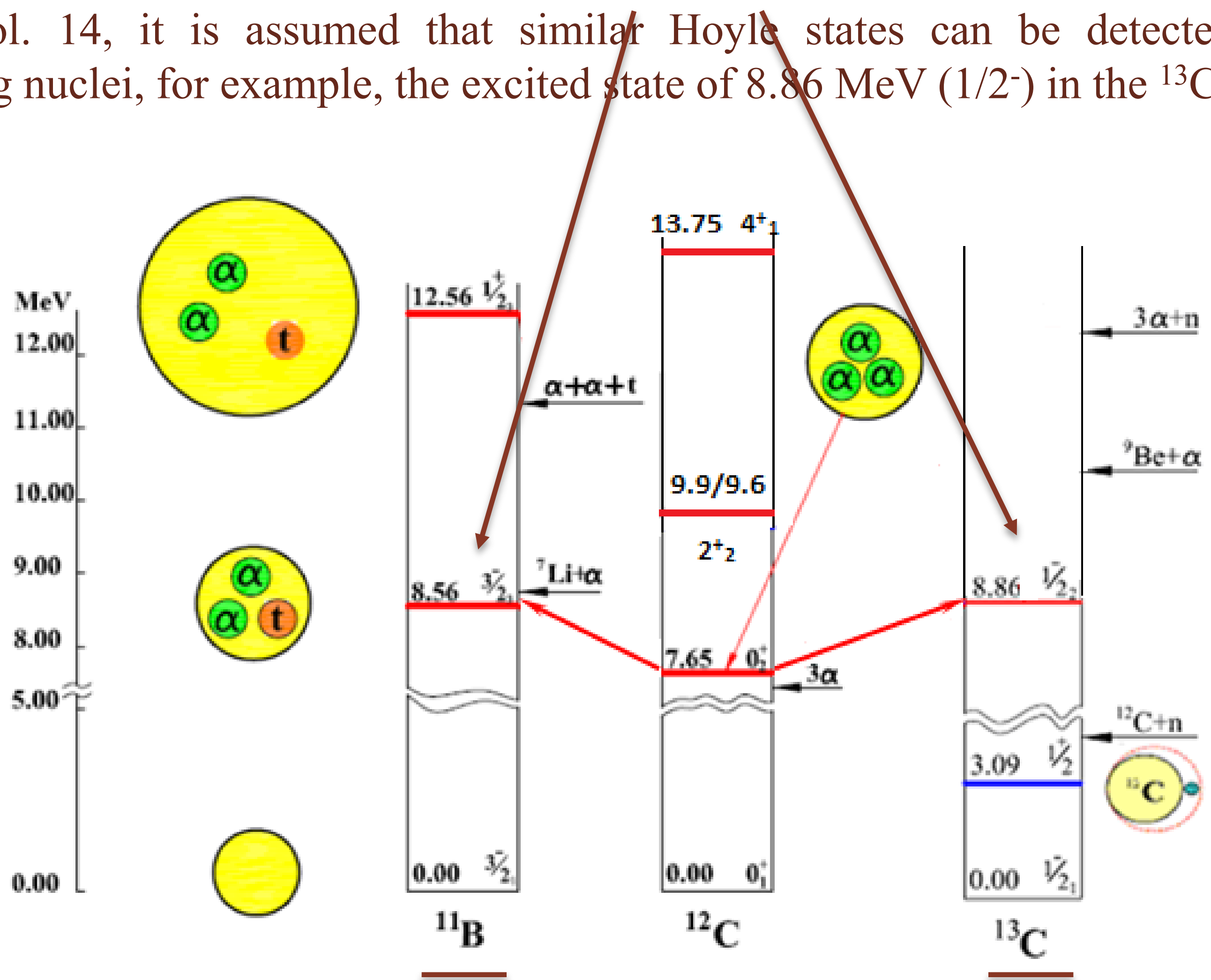
Z.H.Liu et al.,PR C64, 034312(2001),
T.Belyaeva et al., PR C90,064610(2014)

Ogloblin et al.,PR C84,054601(2011)

Relevance

Analogues of Hoyle's state

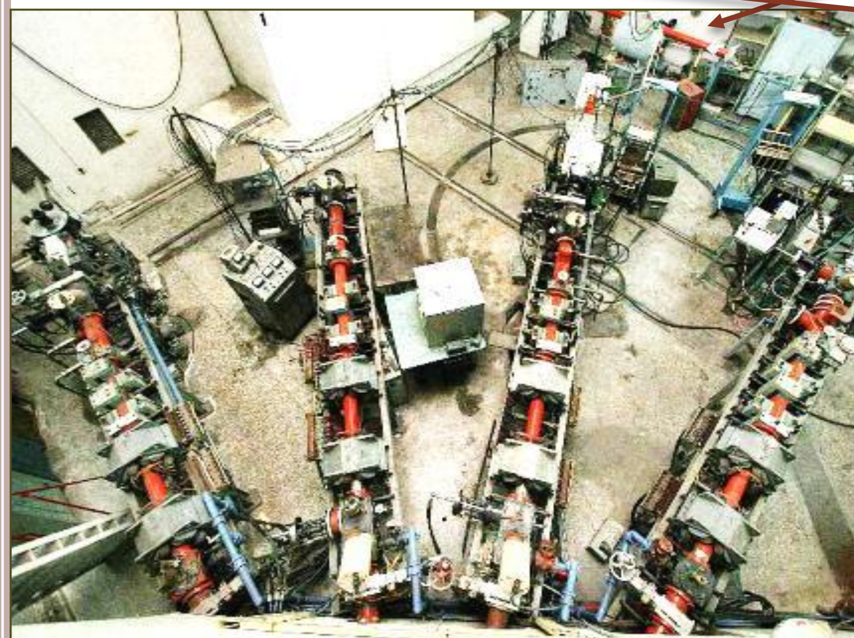
For nuclei with a pronounced cluster structure, the shell model does not reflect a number of their characteristic features. In the paper Milin M. and von Oertzen W // Eur. Phys. J. A-2002.-Vol. 14, it is assumed that similar Hoyle states can be detected in some neighboring nuclei, for example, the excited state of 8.86 MeV (1/2$^-$) in the ^{13}C nucleus.

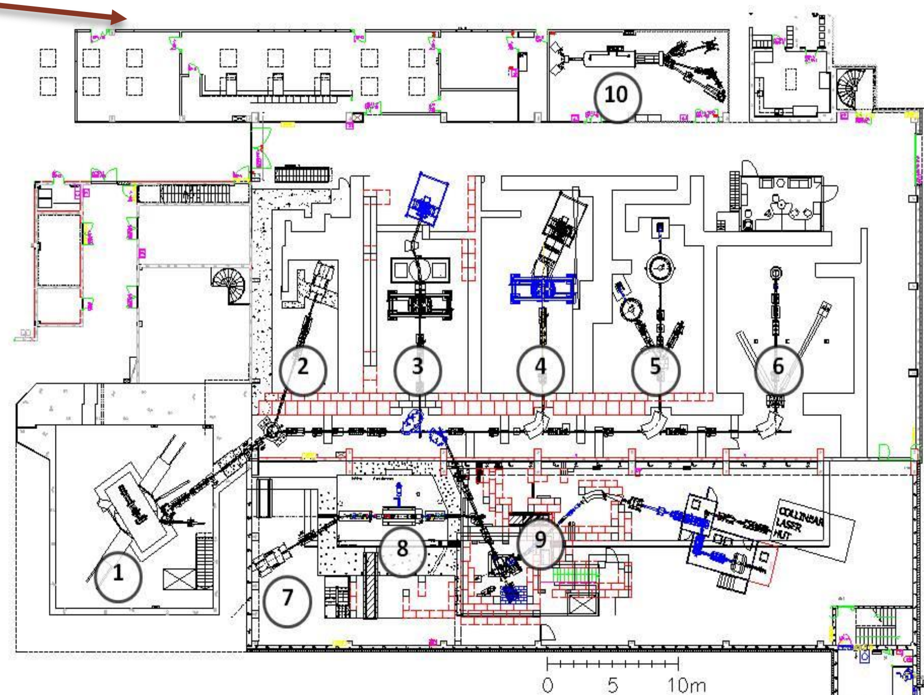


Experiment

A series of collaborative experiments were conducted with the scientists of the Kurchatov Institute (Moscow, Russia) and the University of Jyväskylä (Jyvaskyla, Finland) in order to study the "exotic" state in neutron-rich nuclei (^{9}Be, ^{11}B, and ^{13}C), .

Experiments were carried out on the cyclotrons **U150M** (INP, Kazakhstan) and **K-130** (UY, Finland) at energies of accelerated alpha particles E(α) = 29 and 65 MeV, respectively.

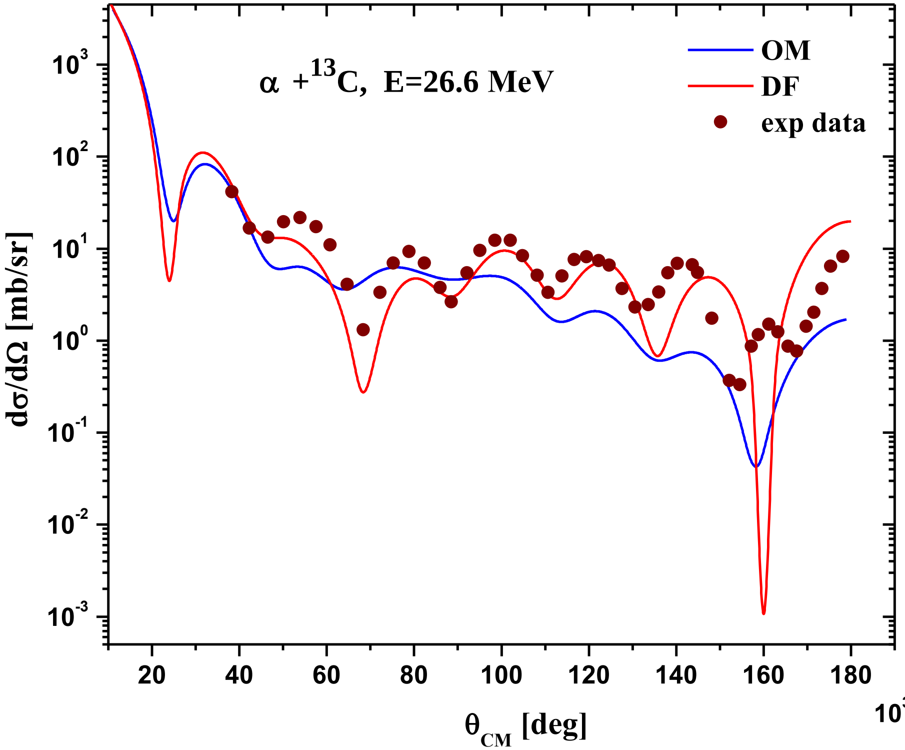




The parameters of optical and double folding potentials of α +^{13}C system at 26.6 – 65 MeV

E, MeV	Model	V, MeV	r_V, fm	a_V, fm	N_r	W, MeV	r_W, fm	a_W, fm	J_v, MeVfm³	J_w, MeVfm³	r_c, fm
26.6	OM	148.32	1.112	0.736		12.844	1.6	0.267	321	66	1.28
	DF				0.97	18.635	1.6	0.267	399.3		1.28
29	OM	147.22	1.112	0.736		12.844	1.6	0.731	318.5	73	1.28
	DF				0.98	12.844	1.6	0.731	402.5		1.28
35	OM	138.95	1.112	0.8		14.125	1.6	0.15	312	71	1.28
	DF				0.99	14.125	1.6	0.15	404.6		1.28
48.7	OM	133	1.112	0.79		14.79	1.6	0.639	297.3	82	1.28
	DF				0.97	14.79	1.6	0.639	392.6		1.28
50	OM	131.8	1.112	0.79		14.41	1.6	0.761	294.7	83	1.28
	DF				0.97	14.41	1.6	0.761	391.6		1.28
54.1	OM	129.5	1.112	0.795		14.21	1.6	0.8	290.5	82	1.28
	DF				0.96	14.21	1.6	0.8	386.6		1.28
65	OM	123	1.112	0.8		14.97	1.6	0.76	277	86	1.28
	DF				0.98	14.97	1.6	0.76	390.7		1.28

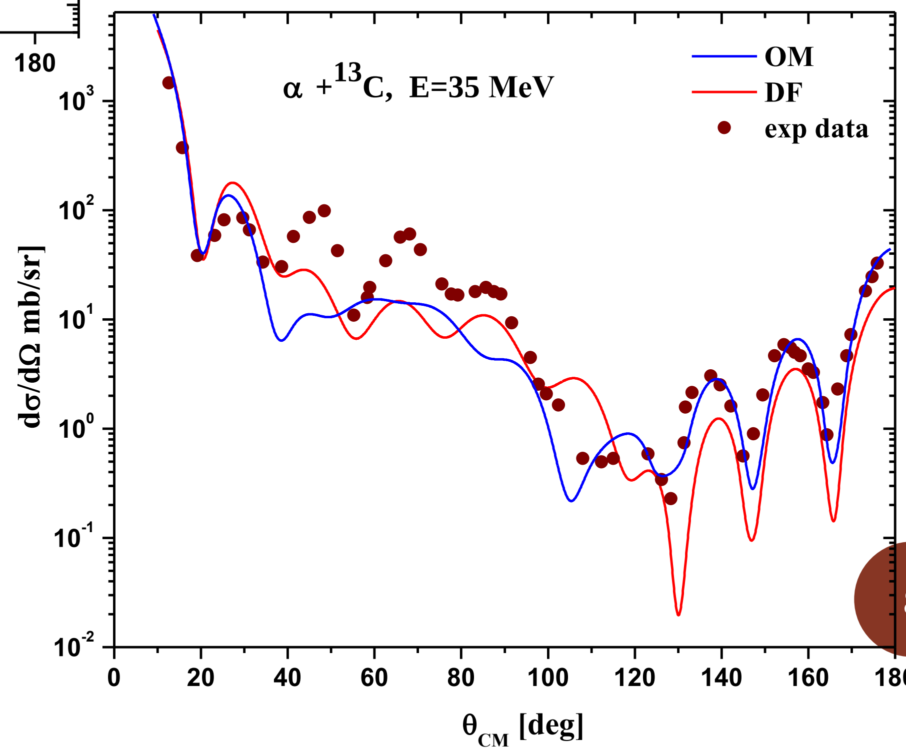
Elastic scattering of alpha particles from ^{13}C nuclei

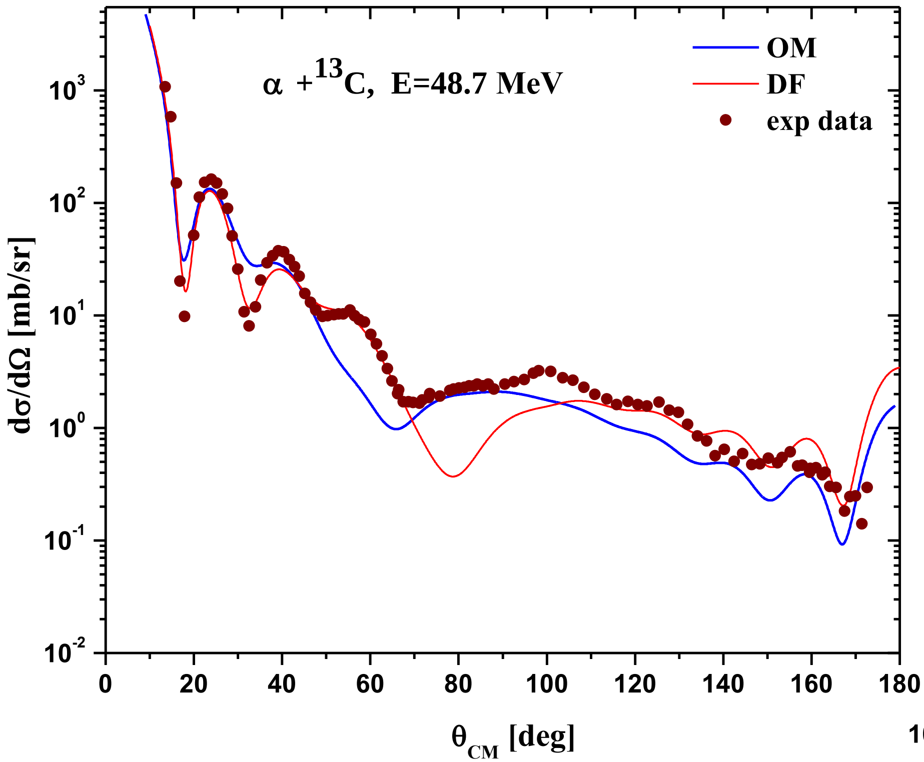


B.I Kuznetsov, P.E. Ovsyannikova, I.P. Chernov // Yadernaya Fizika, V15, p.673(1972)

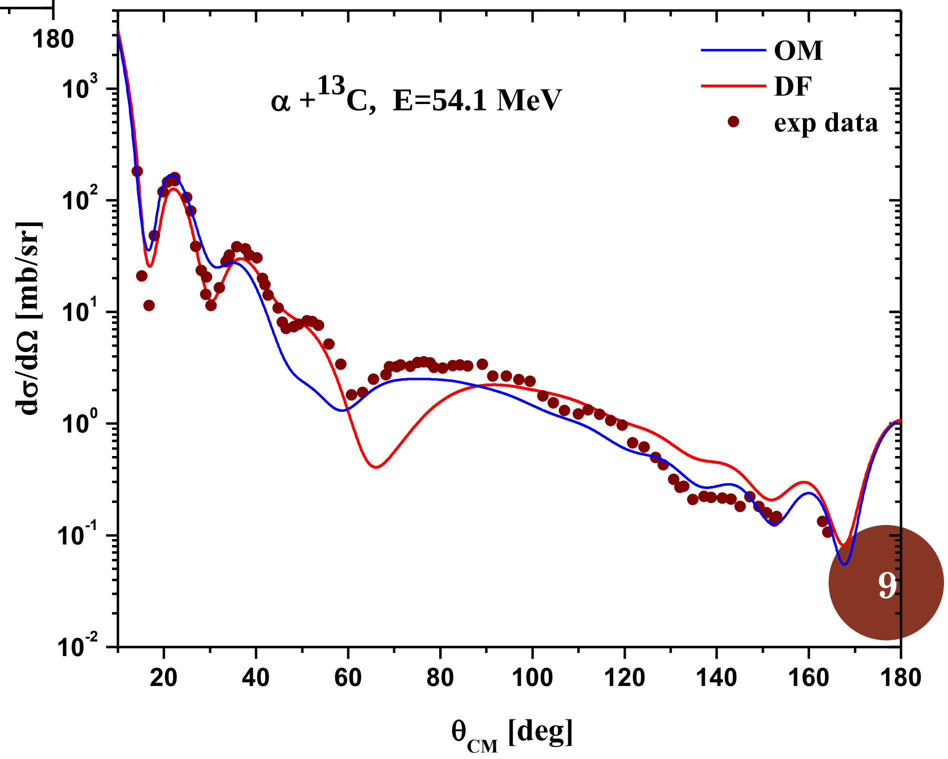
←

S.V.Artemov, G.Kim, G.A.Radyuk // Izv. Rossiiskoi Akademii Nauk, Ser.Fiz V65, p.1579 (2001) →

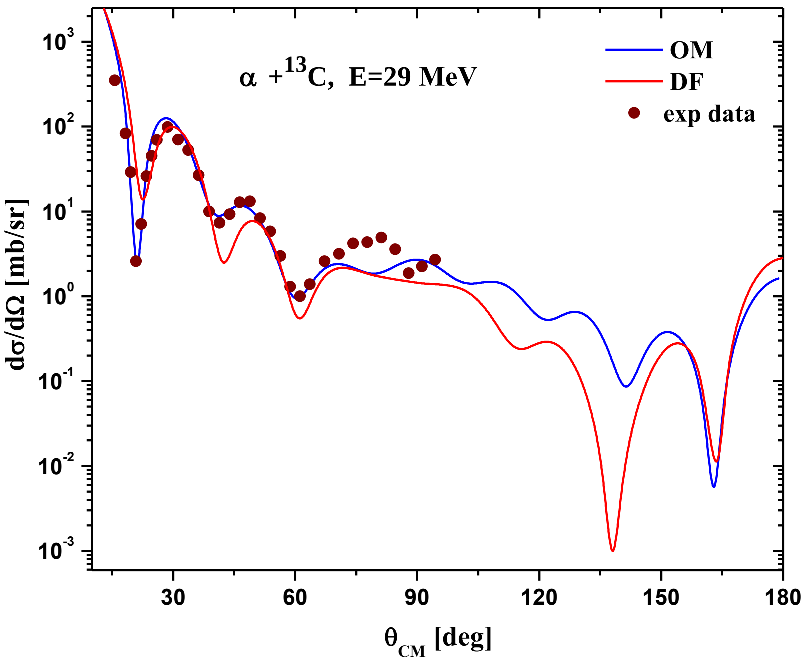




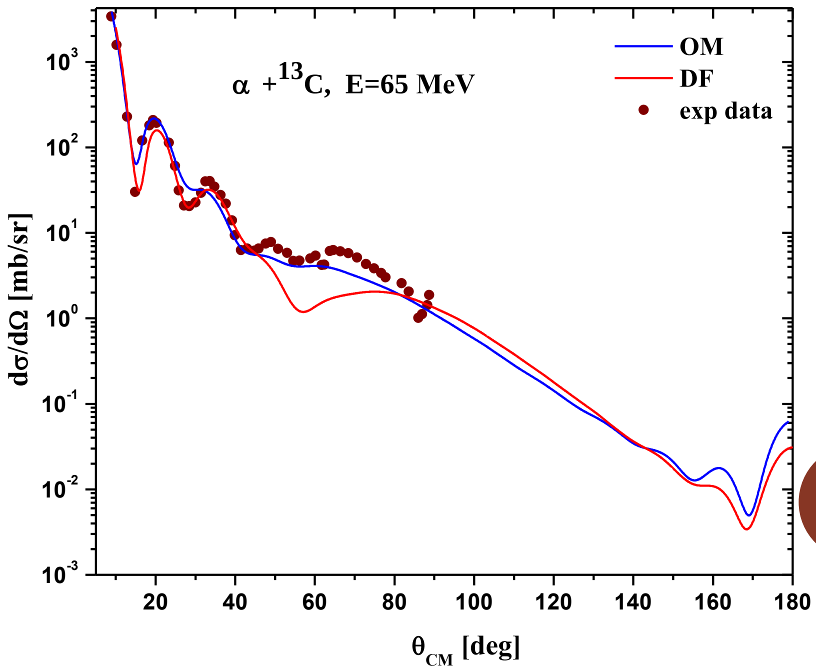
H.Abele. et al. // Zeitschrift fur Physik, Atomic nuclei, V.326, p. 373 (1987)



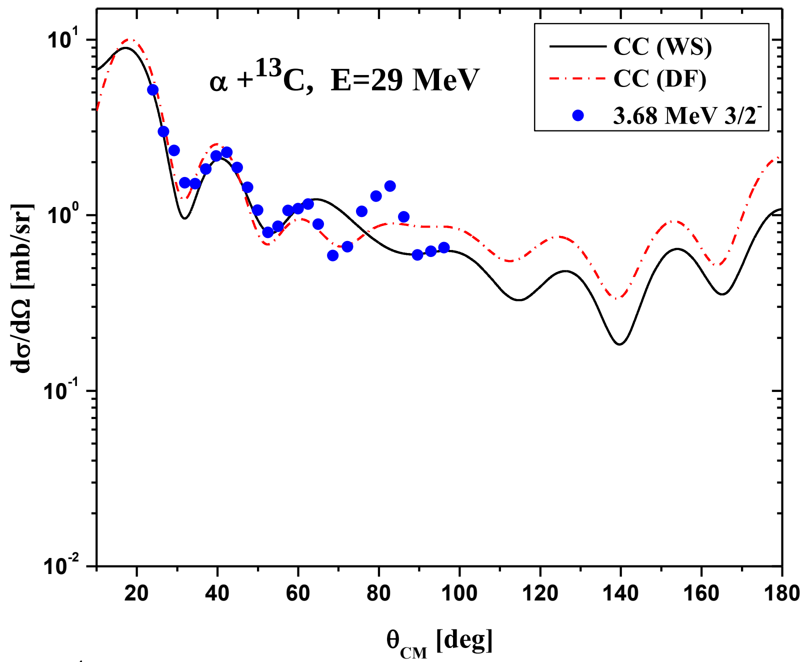
Results



Experimental data at energies 29 and 65 MeV.



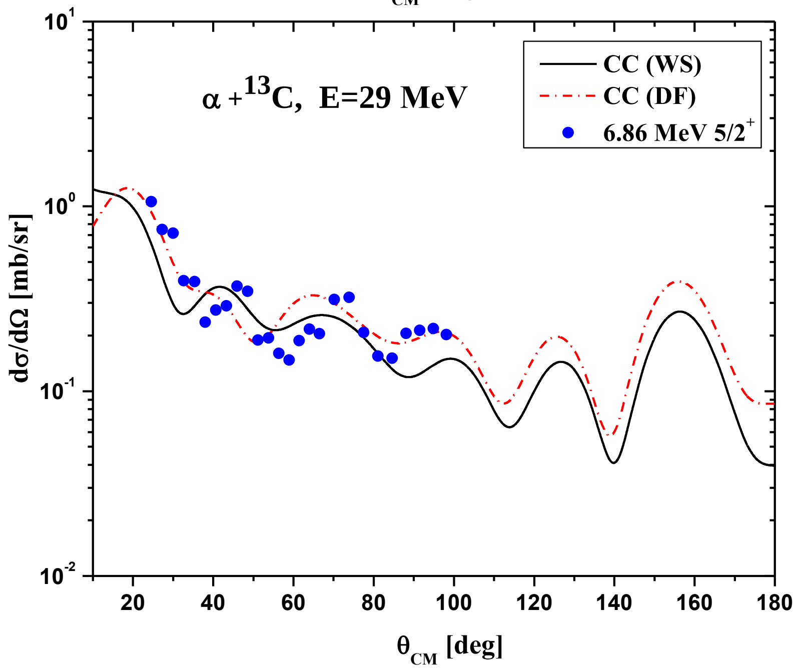
Excited states of ^{13}C

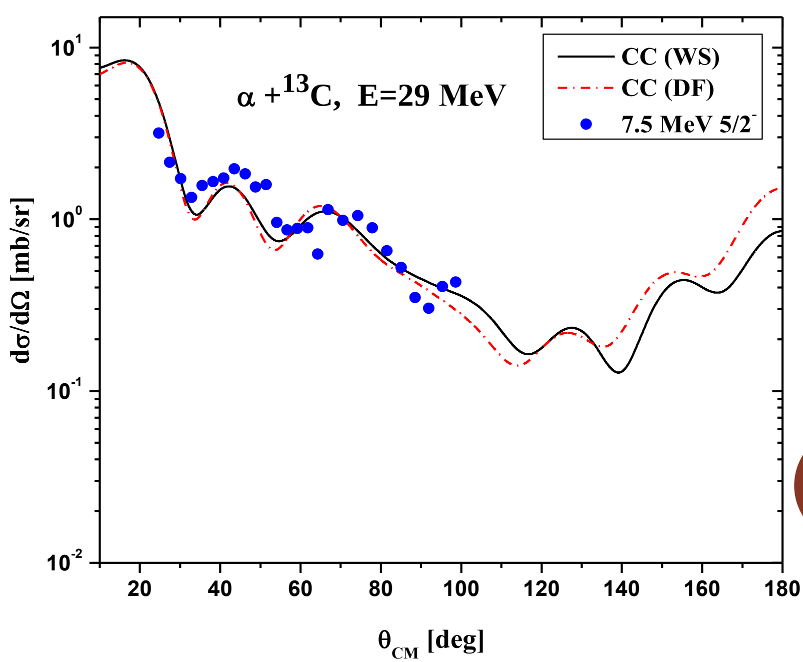


Excited states of ^{13}C nuclei:
$3/2^-$, 3.68 MeV
$5/2^+$, 6.86 MeV
$5/2^-$, 7.5 MeV
at **E=29 MeV**,
calculated within CC method.

Deformation parameters:

E, MeV	Model	β 5/2$^-$	β 5/2$^+$	β 3/2$^-$
29	WS	0.54	0.54	0.54
	DF	0.51	0.51	0.51





The measurement of the radii of the excited state

Asymptotic Normalization Coefficients

Liu Z.H. et al.,PRC 64, 034312(2001)

Modified Diffraction Model

Danilov A.N. et. al. PRC 80, 054603 (2009)

Inelastic Nuclear Rainbow Scattering

Ohkubo S. PRC 70, 041602 (2004)

Modified Diffraction Model

The **modified diffraction model** assumes that the root-mean-square radius R_{rms}(ex.st) of the excited state can be determined through the difference of the diffraction radii of the excited and ground states:

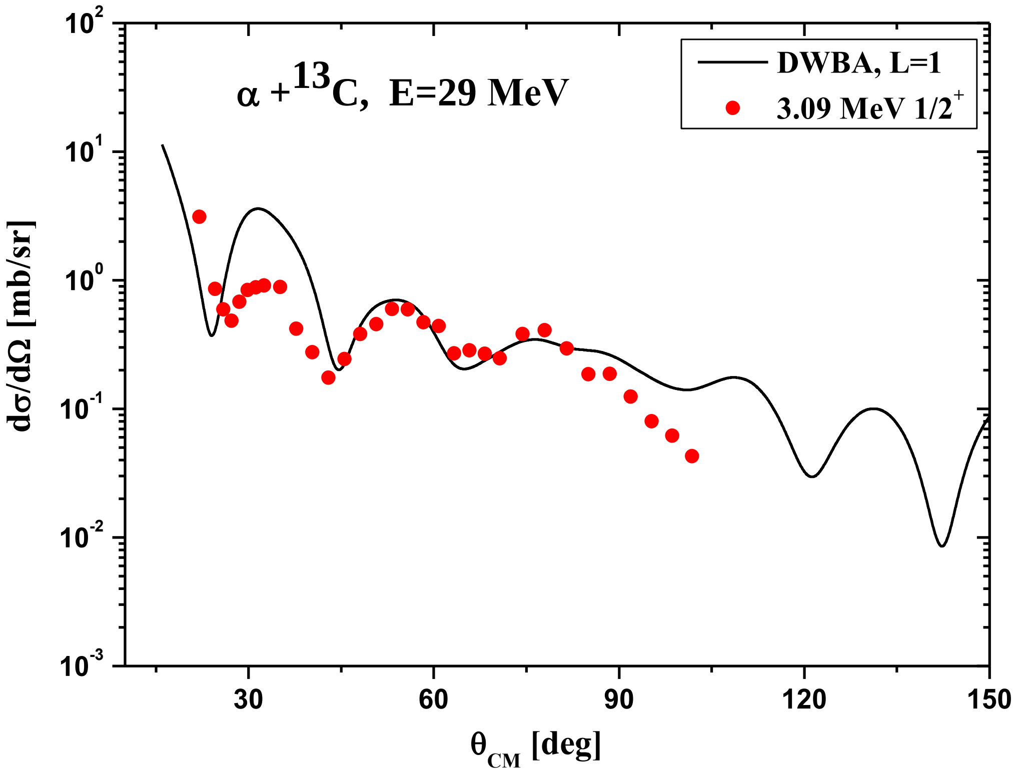
$$\mathbf{R_{rms}\ (ex.st.) = R_{rms}\ (g.s.) + [\mathit{R_{dif}(el)} - \mathit{R_{dif}\ (inel)}]}$$

R_{dif}(el) and **R_{dif}(inel)** are the diffraction radii, are determined from the positions of the minima and maxima of the experimental angular distributions of the inelastic and elastic scattering, respectively.

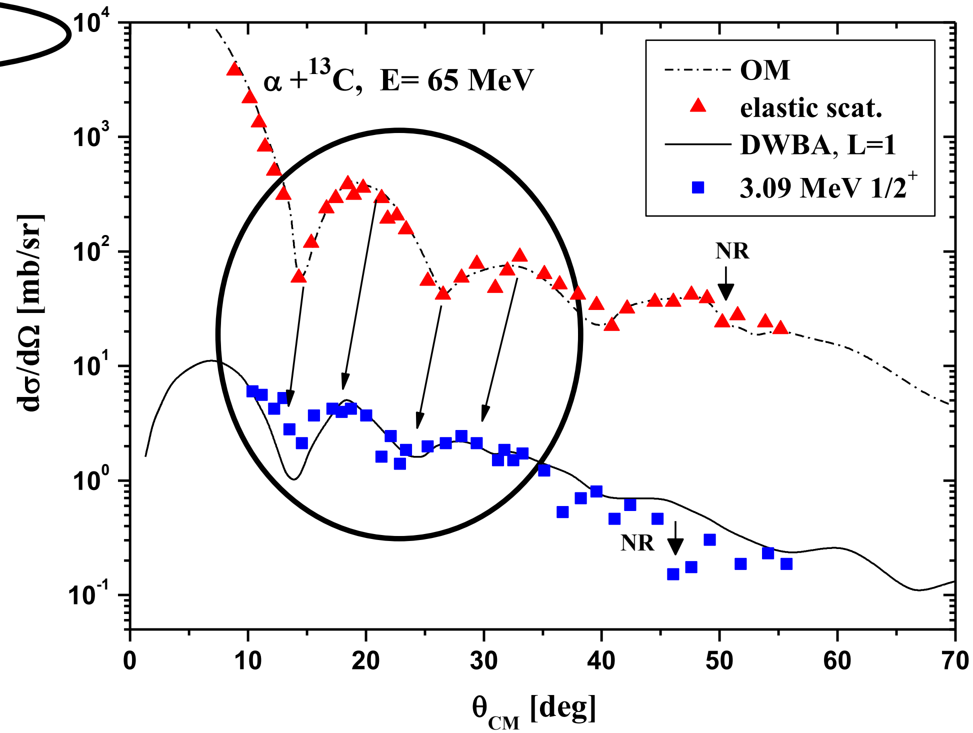
Danilov A.N. et. al. PRC 80, 054603 (2009).

The neutron halo , the excited state 1/2 $^+$, 3.09 MeV

The first excited state of ^{13}C (3.09 MeV (1/2$^+$)) is located at 1.86 MeV below the ^{13}C → ^{12}C + n threshold. Measuring of its radius using MDM is of particular importance for the method as a whole, since it allows us to compare the obtained results with the other independent approaches of the INRS and ANC.



According to the rules of the **Blair** phases, the angular distributions of the elastic and inelastic with the excitation of the $1/2^+$ scattering state should coincide in phase. However, there is a clear systematic shift of the minima and maxima of the inelastic scattering cross section toward smaller angles in comparison with the elastic scattering curve. This type of shift is an **indicator** of the increase in the diffraction radius of the state $1/2^+$, 3.09 MeV.



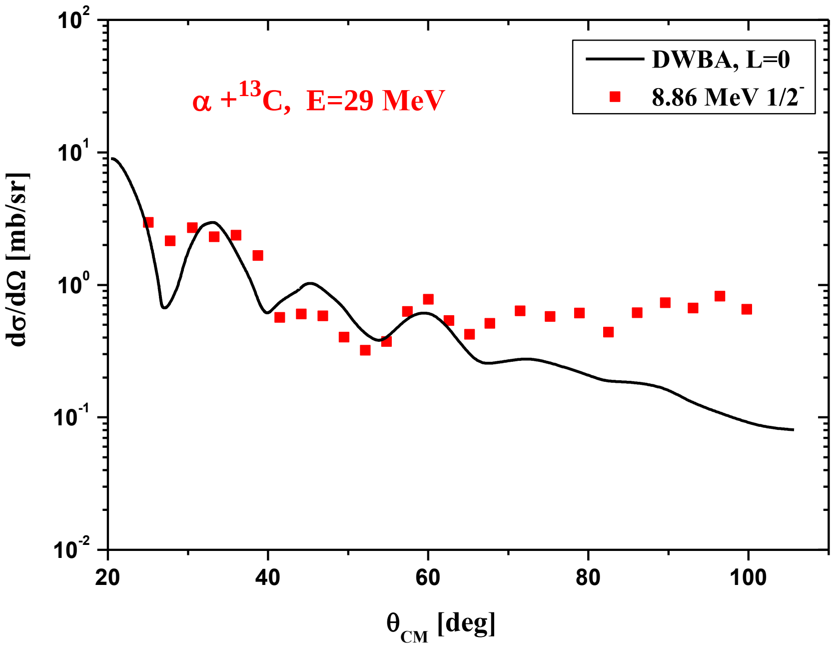
Diffraction and root-mean square radii of **3.09 MeV ($1/2^+$)** excited state of **^{13}C** nuclei calculated within MDM

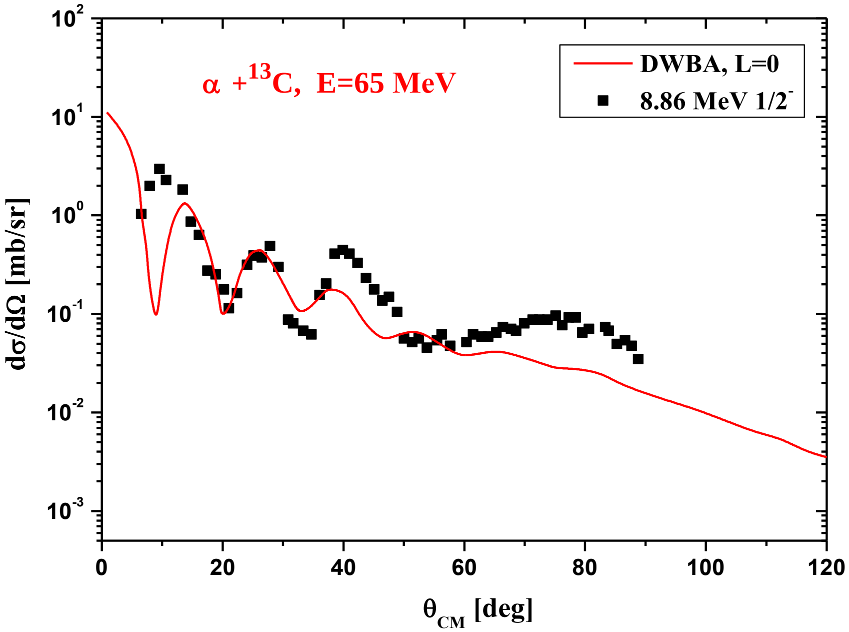
E^*, MэB, I^{π}	R_{dif}, fm	R_{rms}, fm	E_{α}, MeV
0.00, $1/2^-$	5.31±0.07	2.31	65
3.09, $1/2^+$	5.75±0.07	**2.73±0.07**	29
3.09, $1/2^+$	5.96±0.06	**2.92±0.07**	65

Austern N. and Blair J.S. Calculation of inelastic scattering in terms of elastic scattering // Annals of Physics. - 1965. – Vol.33. - P.15-64.

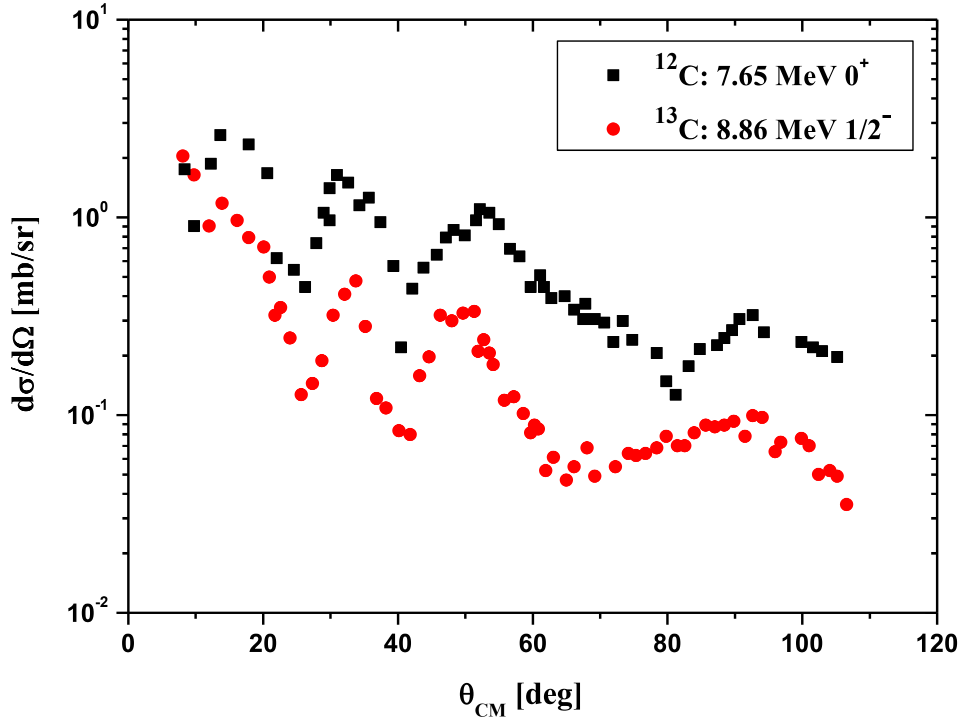
Analogues of Hoyle's state in ^{13}C

Observation of the exotic structure and the anomalously large radius of the Hoyle 0^+ (7.65 MeV) state in the ^{12}C nucleus prompted a number of assumptions that a similar situation can occur in neighboring ^{13}C and ^{11}B nuclei, which differ from ^{12}C, by adding a neutron or by removing the proton, respectively.





For a state of 8.86 MeV (1/2⁻), the minimum of the rainbow (Airy) in comparison with the Hoyle state of 7.65 MeV (0^+_2) is located at a smaller angle. The observed shifts in the positions of airy minima from large angles in inelastic scattering, with respect to elastic scattering, indicate an increase of the radius in this excited state.



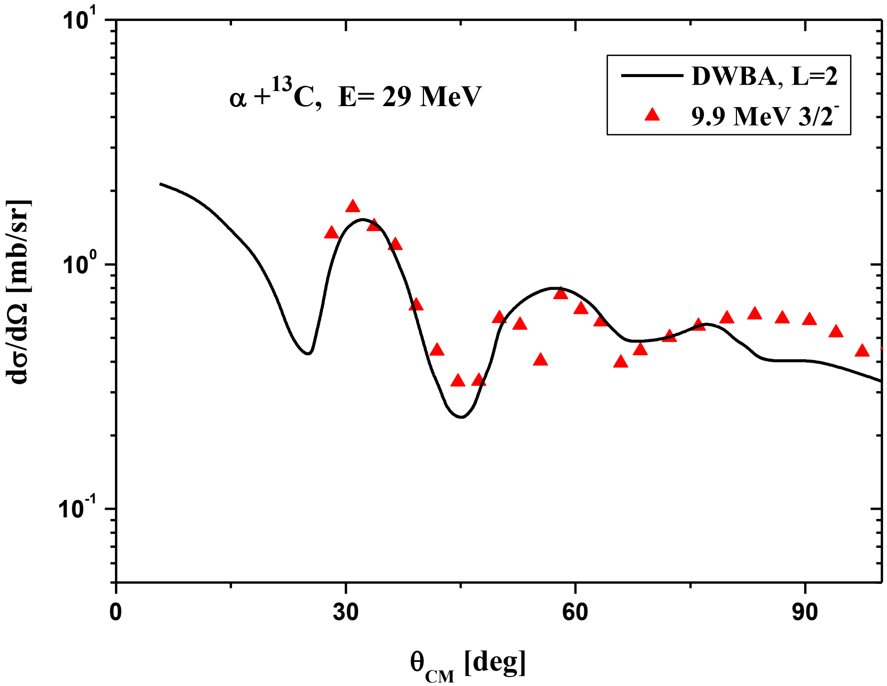
The rms radii of the excited state of the 8.86 MeV (1/2⁻) **^{13}C** nucleus obtained in the framework of MDM in comparison with the 0^+ state of the **^{12}C** nucleus

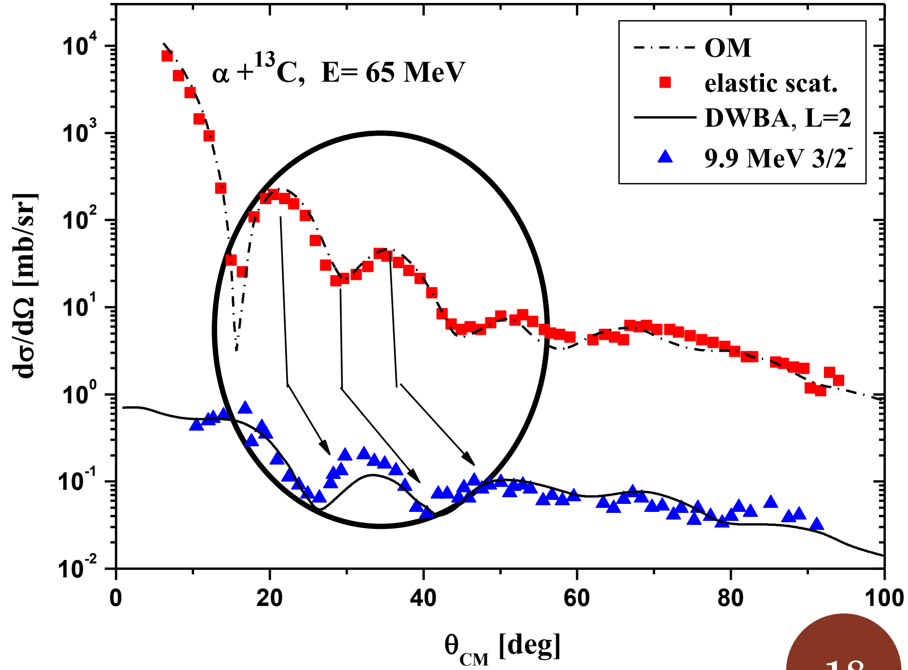
E^*, MэB, I^π	R_{dif}, fm	R_{rms}, fm	E_α, MeV
7.65, 0^+ (^{12}C)	5.71±0.04	**2.89±0.04**	
8.86, $1/2^-$	5.64±0.09	**2.67±0.06**	29
8.86, $1/2^-$	5.66±0.10	**2.68±0.12**	65

Danilov A.N. et. al. PRC 80, 054603 (2009).

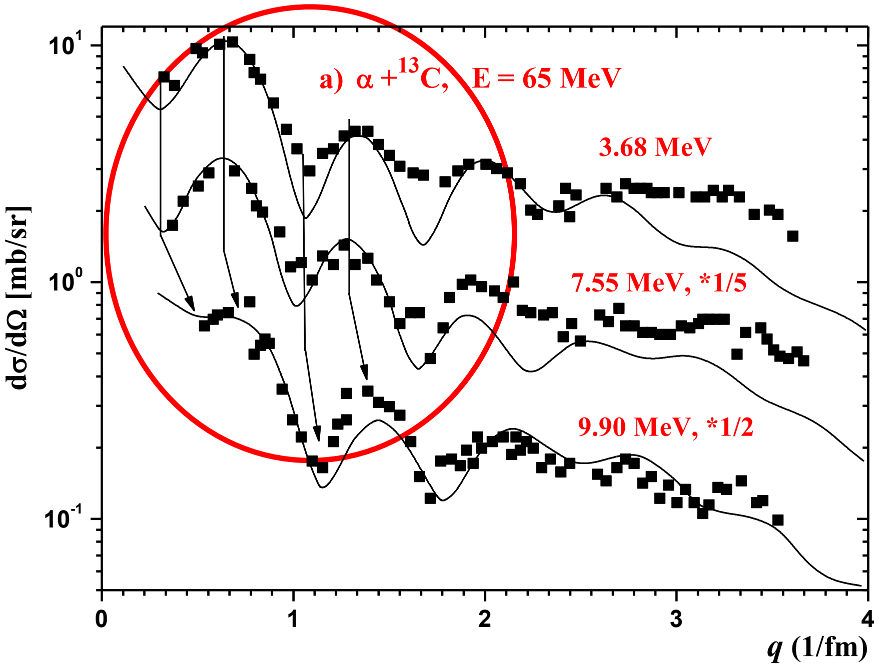
"Supercompact" state

The ^{13}C nucleus seems to be unique in the sense that several different structures coexist in its spectrum. In addition to the usual levels of the shell model, there are two "diluted" states of various types: one of them contains **a neutron halo** (3.09 MeV), and the other is an **analog of the Hoyle state** (8.86 MeV).





It can not be ruled out that there may exist structures, even more exotic, "supercompact". For example, the rms radius of the excited state is **3/2⁻ (9.90 MeV)**, obtained from an inelastic scattering analysis within the MDM framework is less than the ground-state radius (2.0 fm and 2.3 fm, respectively).



E^*, MэB, I^π	R_{dif} fm	R_{rms}, fm	E_α, MeV
0.00, 1/2⁻	5.31±0.07	**2.31**	65
9.9, 3/2⁻	4.99±0.07	**1.97±0.07**	29
9.9, 3/2⁻	5.00±0.12	**2.02±0.14**	65

COMPARISON OF RECEIVED RESULTS WITH MDM, WITH OTHER METHODS OF DETERMINATION OF RADIUS OF EXCITED STATES OF NUCLEI

E^*, MeV, J^π	MDM, 65 MeV	INRS, 65 MeV	ANC, 65 MeV
0.00, $1/2^-$			
3.09, $1/2^+$	2.92±0.09	≥2.7	2.62±0.10, 2.68 theory
8.86, $1/2^-$	2.68±0.12	≥2.5	
9.90, $3/2^-$	2.02±0.14		

Ohkubo S. and Nirabayashi. PRC 70, 041602(R) (2004).

Liu Z.H. et al. PRC 64, 034312(2001).

Conclusion

- The radii of the **"exotic"** excited levels ($1/2^+$, 3.09 MeV and $1/2^-$, 8.86 MeV) of the ^{13}C nucleus at 29 and 65 MeV are calculated.

- A "supercompact" excited state is found at ^{13}C nuclei

Thus, the uniqueness of the $\mathbf{^{13}C}$ nucleus is shown. The several different structures coexist in its spectrum.

Thank you for attention!