Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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IOP Conf. Series: Journal of Physics: Conf. Series **1023** (2018) 012025 doi:10.1088/1742-6596/1023/1/012025

Exotic states of ^{13}C nuclei

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Abstract. The new study of differential cross sections of ^{13}C$(\alpha, \alpha')^{13}$C inelastic scattering at E_α=29 MeV with the excitation of the 9.90 MeV state of the initial nucleus has been carried out. Modified diffraction model analysis showed that the root-mean-square (RMS) radius of the nucleus at this level might be approximately 20% less than the one of the ground state. We have showed the possibility of the existence of various states in the structure of the ^{13}C nucleus.

1. Introduction

Recently, data on the existence of excited states of light nuclei with anomalously large radius has been obtained. Firstly, these excited states have α-cluster structure, such as the famous Hoyle state (0^+, E=7.65 MeV) of the ^{12}C nucleus, which plays a significant role in stellar nucleosynthesis, and their analogs in ^{11}B and ^{13}C [1-4]. Secondly, these excited states have a neutron halo as those in ^{13}C ($1/2^+$, 3.09 MeV) [5,6] and in ^{9}Be ($1/2^+$, 1.68 MeV)[7].

Anomalously large radii of nuclei in excited states were predicted in various theoretical works, especially after the appearance of a hypothesis about the possible existence of an α-particle condensate [8]. The specific radii were obtained as a result of the experiments and enabled us to make a choice between different theoretical models. At the same time, the fact of observing dilute states agrees with existing concepts about the nucleus. But, is it possible for the existence of other, exotic states in stable nuclei?

In current work we continue the investigation of the nature of ^{13}C excited states at low energies.

2. Experimental Details

The experimental angular distributions of α-particles scattering by ^{13}C nuclei at energies E_α=29 MeV has been measured on the extracted beam of the U-150M isochronous cyclotron of the INP (Almaty, Kazakhstan). In the experiment we used sets of ΔE-E telescopes with silicon semiconductor detectors. Three telescopes of ΔE (with a thickness of 100 μm) and E (with a thickness of 2 mm) detectors were used for registration of scattered α-particles. The target was a self-sustaining film made of ^{13}C isotope (86% enrichment) with a thickness of $\sim$0.35 mg/cm^2. Targets contained some admixtures of the ^{12}C and ^{16}O nuclei. Figure 1 shows a typical spectrum of ^{13}C nucleus.

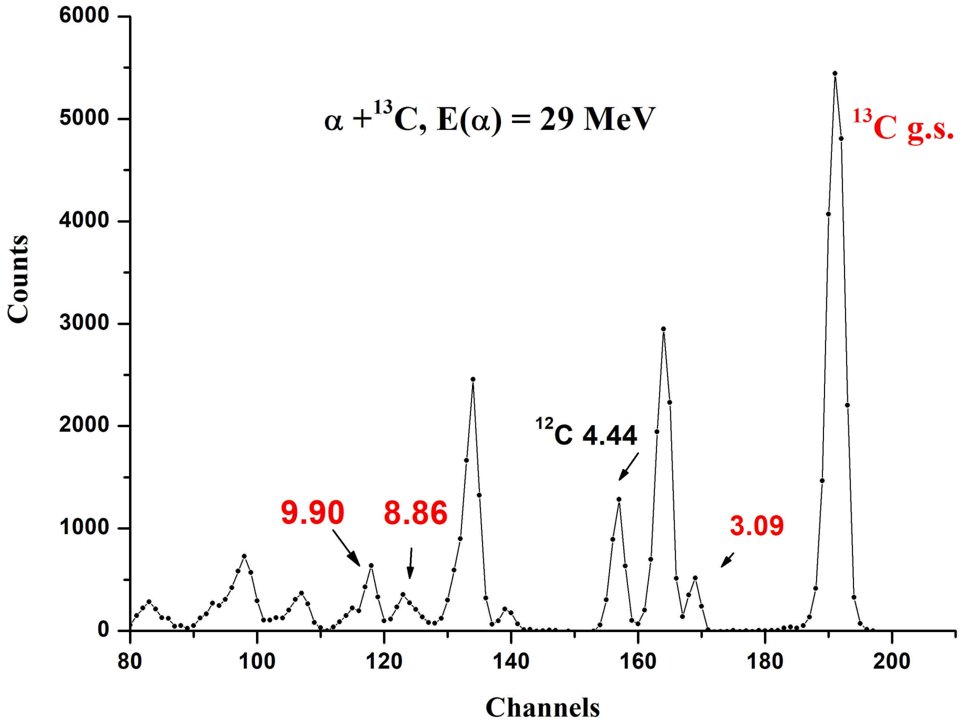

Figure 1. Typical spectrum of ^{13}C$(\alpha,\alpha)^{13}$C at 32 degree, E_α=29 MeV. Red color - exotic excited states of ^{13}C nucleus.

3. Results and discussion

The analysis of the experimental data was made in several stages. At the first stage, the data on elastic scattering were analyzed within the framework of the standard optical model of the nucleus and the double folding (DF) model. Optical potential (OP) parameters have been chosen for achieving the best agreement between the theoretical and experimental angular distributions. This is described in detail in our previous papers [5,9]. The obtained values of the optical potential for a wide range of energies [5,9] are given in Table 1.

Table 1. Parameters of optical and folding potentials for the α+^{13}C system.

E, MeV	Set	V, MeV	r, fm	a, fm	N_r	W_V, MeV	r_V, fm	a_V, fm	r_C, fm
29	OM	147.22	1.112	0.736		12.844	1.6	0.731	1.28
29	DF				0.98	12.844	1.6	0.731	1.28
65	OM	123.07	1.112	0.8		14.97	1.6	0.76	1.28
65	DF				0.98	14.97	1.6	0.76	1.28
90	OM	115.5	1.112	0.645		20.21	1.6	0.6	1.28
90	DF				0.96	20.21	1.6	0.6	1.28

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The task of determining the parameters of the OP from the analysis of elastic scattering can not be solved uniquely. At the second stage, in order to verify the adequacy of the set of potential parameters for a "true", OP were tested with corresponding data on inelastic scattering of α-particles by ^{13}C nuclei, within the framework of CC (couple channels) and DF methods [9].

All our calculations for determining radii of the nuclei in the excited states were carried out within the framework of the modified diffraction model (MDM), which is described in detail in [2].

The ^{13}C nucleus seems to be unique, because several different structures coexist in its spectrum. In addition to the usual levels of the shell model, there are two "dilute" states of various types: one of them has a neutron halo (3.09 MeV ($1/2^+$)), and the other one is an analogue of the Hoyle state (8.86 MeV ($1/2^-$)). In our several earlier works [3,5,10,11], we provided calculations made within the framework of the MDM, which confirm that these states actually exist in the structure of the ^{13}C nucleus.

We can not exclude existence of structures (compact states), for example, even more "exotic" with the reduced radii [12]. It is interesting to note that the 9.90 MeV state and other parts of its rotational band are strongly excited in the α-cluster transfer nuclear reactions: (^{6}Li,d) and (^{7}Li,t)^{9}Be nucleus [13]. This means that the α-cluster structure of the 9.90 MeV state has a strong $\alpha+^9$Be component, which can eventually lead to an enhancement of the radius of this state. Indeed, in [14], authors assume that the RMS radius of a given state might be large.

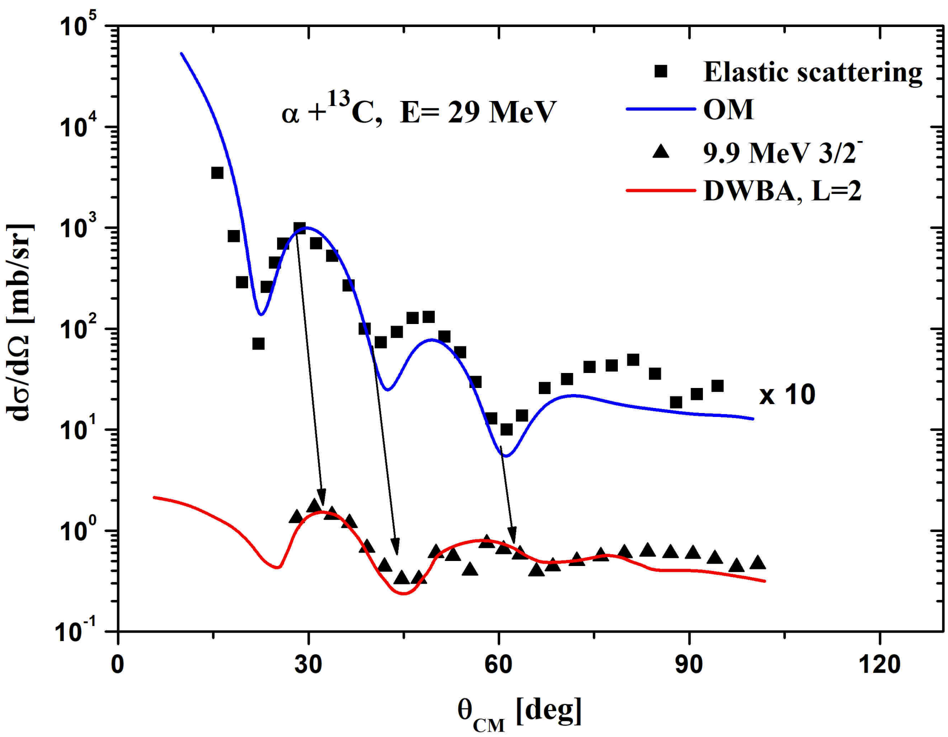

Figure 2. Differential cross sections of elastic $\alpha+^{13}$C and inelastic scattering for the 9.90 MeV state of ^{13}C nucleus at energies of α-particles 29 MeV. Solid curves are calculations within the OM and the distorted-wave Born approximation (DWBA), respectively. Straight lines connect extrema, which, when the diffraction radii are equal, must be in antiphase.

According to Blair's rules [15], the angular distributions of the elastic and inelastic scattering must coincide in phase. The shift of the minima and maxima of the inelastic scattering cross sections toward smaller or larger angles in comparison with the elastic scattering curve, is an indicator, of increase or decrease, respectively, of the diffraction radius of a certain excited state. In our case, as Figure 2 shows, we observed a clear systematic shift of the minima and maxima of the inelastic scattering cross section toward large angles in comparison with the elastic scattering curve. This character of the shift, as we noted above, is an indicator of a decrease in diffraction radius of the 9.90 MeV excited state.

Indeed, analysis of the differential cross section of the 9.90 MeV state within MDM showed that the RMS radius of this state is smaller by 20% than the ground state Table 2. For comparison, Table 2 also shows the results for other incident particles and energies [5,12]. Within the limits of error, the obtained results are similar.

Table 2. Diffraction and RMS radii for the state of the ^{13}C nucleus at different energies

E*,MeV, I^π	R_{dif},fm	R_{rms},fm	E_α, MeV
$0.00, 1/2^-$	5.31 ± 0.07	2.33	65
$9.90, 3/2^-$	4.99 ± 0.07	1.97 ± 0.07	29
$9.90, 3/2^-$	5.00 ± 0.12	2.02 ± 0.14	65
$9.90, 3/2^-$	4.80 ± 0.20	1.76 ± 0.23	90

In this paper, we considered a wider range of experimental data [5,9,12]. From this analysis, we can conclude that the predicted enhancement of the radius [14] of the 9.90 MeV state of the ^{13}C nucleus is not observed, but, on the contrary, the ^{13}C nucleus has a more compact size in this excited state.

4. Conclusion

In this paper we have obtained data indicating the possible existence of nuclear states with anomalously small dimensions. Joint analysis of the results of experiments within the study of inelastic scattering of α particles by ^{13}C at the energies of 29, 65 [5] and 90 MeV [12] with excitation of the $3/2^-$, E=9.90 MeV state showed that another phenomenon was discovered in the structure of the ^{13}C nucleus a "supercompact" size. The 9.9 MeV ($3/2^-$) excited state has a smaller radius than the ground state of the ^{13}C nucleus. So far, such "condensed" excited states of nuclei have not yet been observed.

5. Acknowledgements

The work was supported by grants AP05133606 and AP05131597 of Ministry of Education of Republic of Kazakhstan.

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