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Investigation of exotic states of ^{13}C at low energy

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The differential cross-sections of the elastic and inelastic α+^{13}C scattering have been measured at E(α) = 29 MeV. The radii of the exited states: 3.09 ($1/2^+$) and 8.86 ($1/2^-$) MeV were determined using the Modified Diffraction Model. The radii of these excited states are larger than that of the ground state of ^{13}C, confirming the suggestion that the 8.86 ($1/2^-$) MeV state could be an analog of the Hoyle state in ^{12}C and the 3.09 ($1/2^+$) MeV state has a neutron halo. The possibility of coexistence of various exotic states in the structure of the ^{13}C nucleus is shown.

Keywords: Exotic states; radii of nuclei; modified diffraction model; neutron halo; cluster states.

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1. Introduction

Since the middle of the last century, particle scattering has been one of the standard methods for studying the structure of the target nucleus. The study of elastic and inelastic interaction processes of α-particles with nuclei is one of the important sources of information on the ground and excited states of atomic nuclei. These processes, which occur in collisions of α-particles with energies of several tens of MeV, make it possible to obtain important information on the structure of specific nuclear states.

The problem of measuring the radii of nuclei in unbound states has attracted much attention in the last decade in connection with the hypothesis of the possible existence of α-particle condensate in alpha finite nuclei.[1] Until now, it was thought that the most probable candidate with the α-particle condensate structure is the 7.65 MeV (0_2^+) Hoyle state in the ^{12}C nucleus, which plays a key role in stellar nucleosynthesis. In Ref. 2, it is assumed that analogs of the Hoyle state can be found in some neighboring nuclei, for example, in the 8.86 MeV ($1/2^-$) excited state of the ^{13}C nucleus.

In addition to the analog of Hoyle state, the ^{13}C nucleus is also interesting for the reason that various structures can coexist in its spectrum such as, for example, the halo structure. The discovery of the neutron halo has become one of the most exciting discoveries in nuclear physics made at the end of the last century. Until now, the neutron halo has been observed almost exclusively in the ground states of some radioactive nuclei. But such a halo phenomenon also can be observed in stable nuclei. In particular, in Ref. 3, it was assumed that the first excited state 3.09 MeV($1/2^+$) of the ^{13}C nucleus may have a halo structure with an increased radius.

Indeed, the dimensions of the nuclei, its charge or nucleon distributions are one of the important parameters that determine the basic properties of nuclei and are a consequence of the fundamental features of strong interaction.

Recently, several direct methods for determining the radii of nuclei in excited states have been proposed and developed: modified diffraction model (MDM),[4] inelastic rainbow-scattering (IRS) model[5,6] and method of asymptotic normalization coefficients (ANC).[7] All these methods are model-dependent, because they are based on certain features of the differential cross-sections of nuclear reactions and have different and limited fields of application.

In this work, new results are obtained for the root-mean-square (rms) radii of the "exotic" excited states of the ^{13}C nucleus at an energy of incident alpha particles $E(\alpha) = 29$ MeV, calculated within the framework of MDM.

2. Results and Discussion

The experiment was carried out at the Institute of Nuclear Physics U-150 cyclotron, (Almaty, Kazakhstan). A set of the ΔE–E telescopes was used for detection of the

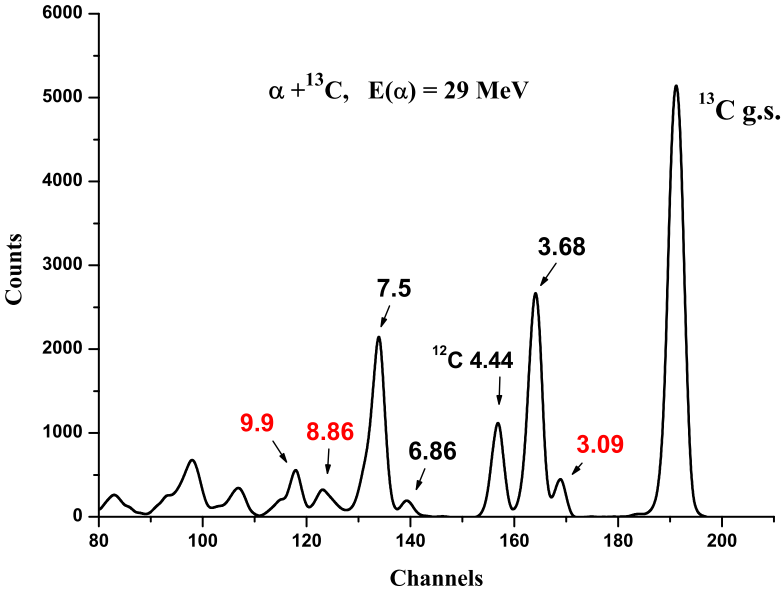

Fig. 1. (Color online) Typical spectrum for ^{13}C$(\alpha,\alpha)^{13}$C at angle 32°, E(α) = 29 MeV. The "exotic" excited states of the ^{13}C nucleus are marked with red color.

α-particles. A self-supporting ^{13}C target (40 μg/cm^2) with the 90% enrichment was used. It contained some impurities of ^{12}C and ^{16}O. A sample spectrum is shown in Fig. 1. More details about the experiment and the technology of the production of the target, determination of its thickness are described in our previous work.[8]

The MDM was proposed in Ref. 4 and the results of its application were published in a number of articles. The model employs inelastic scattering of, for example, α-particles with energies about several tens of MeV. In this case, the differential cross-section at small angles reveals a clear-cut oscillatory structure. One assumes that this structure is diffractive, which implies that the minima and maxima of the angular distributions correspond to extrema of the squares of Bessel functions of various order that depend on the argument $qR_{\rm dif}$, where q is the momentum transfer and $R_{\rm dif}$ is a parameter (diffraction radius) that has dimensions of length. If necessary, the diffractive nature of oscillations should be confirmed by modern methods for the analysis of nuclear reactions, such as the coupled channel method or the Distorted-wave Born approximation (DWBA).

The diffraction radius depends both on the structure of the nucleus involved and on interaction dynamics. According to the modified diffraction model, the true $R_{\rm rms}$ radius of an excited state can be determined by adding the difference of the respective diffraction radii to the ground state radius $R^{\rm g.s.}_{\rm rms}$; that is,

$$R^*_{\rm rms} = R^{\rm g.s.} + [R^*_{\rm dif} - R^{\rm g.s.}_{\rm dif}].$$

It follows that, from the experiment, one in fact determines the difference of the radii of the excited and ground states. The accuracy of knowledge of the ground state radius also affects the final result. More details on the applicability of this method, its advantages and disadvantages are given in our previous work.[4]

2.1. *Exotic states*

A vivid example of the fact that nuclei with increased radii can indeed have completely new properties is the discovery of a neutron halo in some light nuclei lying on the stability boundary.[9] In this case, the valence neutron forming the halo occupies the *s*-orbit, since the absence of a centrifugal barrier can lead to a significant increase in the radius. As mentioned above, the state 3.09 MeV ($1/2^+$) of the ^{13}C nucleus should have an increased radius. In our case, the first excited state of ^{13}C (3.09 MeV ($1/2^+$)) is located 1.86 MeV below the $^{13}C \longrightarrow ^{12}C + n$ threshold.

Nevertheless, the method of extracting the radii within the MDM used in Ref. 10 is probably not quite adequate, since at high energies ($\geq$ 100 MeV), the nucleus becomes too transparent. Consequently, new measurements, especially at lower energies, are highly desirable.

At the first stage, in several early works of Ogloblin *et al.*,[11] to calculate the radius of 3.09 MeV ($1/2^+$) state, we used literature data at energy E(α) = 388 MeV.[12] At the second stage of our study, the results of experiments that were carried out on the JYFL accelerator (Finland) at 65 and 90 MeV were presented.[13–15]

In order to finally confirm the first calculations made within the framework of MDM,[13–15] which were of particular importance for the method as a whole, since it allowed us to compare the results obtained with the results of other independent approaches such as IRS and ANC, and also to show the applicability and adequacy of MDM for the calculation of rms radii, it was decided to make calculations in the region of lower energy within the framework of this model.

Figure 2 shows the measurements of the differential cross-sections of the excited state 3.09 MeV ($1/2^+$) at E(α) = 29 MeV with calculations within DWBA (L = 1).

Table 1 shows the calculations of the diffraction and rms radii of the 3.09 MeV ($1/2^+$) state of the ^{13}C nucleus in comparison with the ground-state radius (adopted value) at E(α) = 29 MeV.

As can be seen from this table, the calculations made within the framework of MDM indeed confirm the assumptions about the increased radius of this state. Within the limits of the error, the results obtained at different energies coincides with the results of our previous studies at higher energies,[13–15] so we can say that the excited state 3.09 MeV ($1/2^+$) of the ^{13}C nucleus has a neutron halo.

The discovery of unusual properties, especially of anomalously large sizes, in the Hoyle state initiated the question of the possible existence of analogs of this α-cluster state in neighboring nuclei ^{13}C and ^{11}B, which differ from the ^{12}C nucleus, by the addition of a neutron or the removal of a proton, respectively. As noted above, it was suggested that the states 8.86 MeV ($1/2^-$) of ^{13}C and 8.56 MeV ($3/2^-$) of

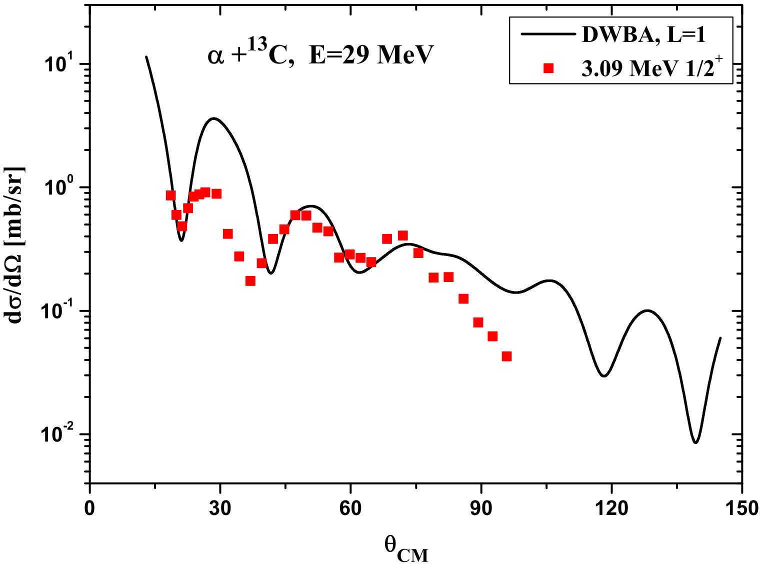

Fig. 2. Differential cross-sections of inelastic α+^{13}C scattering for the 3.09 MeV ($1/2^+$) excited state at energy E(α) = 29 MeV. The calculation within DWBA is shown by a solid line at the transferred angular momentum L = 1.

Table 1. Diffraction and rms radii of the 3.09 MeV ($1/2^+$) excited state of the ^{13}C nucleus determined within MDM.

$\mathbf{E}^*$, MeV, I^π	$\mathbf{R}_{\rm dif}$, fm	$\mathbf{R}_{\rm rms}$, fm	$\mathbf{E}(\alpha)$, MeV
0.00, $1/2^-$	5.6 ± 0.1	2.33 ± 0.03	29
3.09, $1/2^+$	6.0 ± 0.4	2.7 ± 0.4	29

^{11}B nuclei,[12,16] which are not reproducible by the shell model, may turn out to be such analogs.

Figure 3 shows the measurements of the differential cross-sections of the 8.86 MeV ($1/2^-$) excited state at energy 29 MeV, with calculations within DWBA. Such a diffraction pattern corresponds to the momentum transfer with an angular momentum L = 0.

Indeed, the results obtained in several of the earlier works at higher energies[13–15] and obtained in this paper (Table 2) turned out to be close to the value and are in reasonable agreement with the predictions of cluster theories.[17,18]

Summing up, the obtained diffraction radii for two states, the ground state and the 8.86 MeV ($1/2^-$), are accounted for by the errors in the energy dependences of the radii that were presented earlier in the work.[11]

For a state of 3.09 MeV ($1/2^+$), the value of the diffraction radius at 29 MeV was obtained with a large error. Perhaps this is due to some limitations of the use

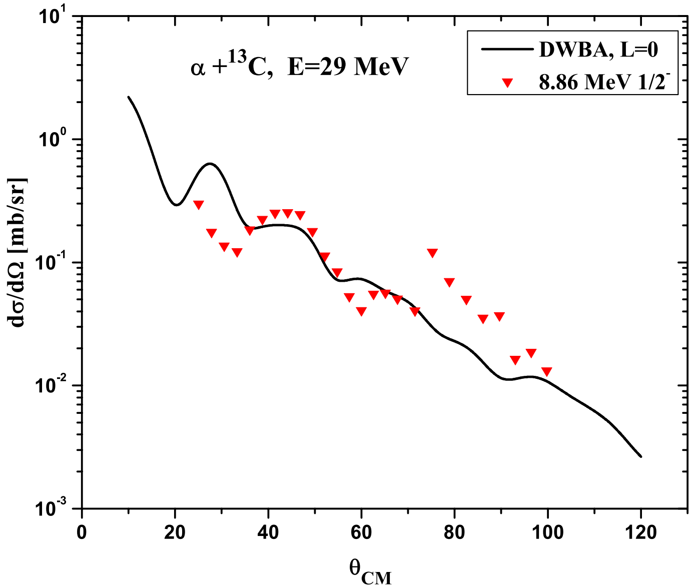

Fig. 3. The differential cross-sections for inelastic $\alpha+^{13}$C scattering for the 8.86 MeV $(1/2^-)$ excited state at energy $E(\alpha) = 29$ MeV with the calculations within DWBA (solid line).

Table 2. The rms radii of the 8.86 MeV $(1/2^-)$ excited state of the ^{13}C nucleus obtained in the framework of MDM.

$\mathbf{E}^*$, MeV, I^π	$\mathbf{R}_{\text{dif}}$, fm	$\mathbf{R}_{\text{rms}}$, fm	$\mathbf{E}(\alpha)$, MeV
0.00, $1/2^-$	5.6 ± 0.1	2.33 ± 0.03	29
8.86, $1/2^-$	5.8 ± 0.31	2.5 ± 0.32	29

of MDM at such energies. Nevertheless, this radius is close to the course of the energy dependence.

Thus, based on the radii obtained for the states of 3.09 MeV $(1/2^+)$ and 8.86 MeV $(1/2^-)$, it is said that the first state belongs to a halo, in the case of the second, it is an analog of the Hoyle state.

3. Summary

In this work, we considered a wider range of experimental data.[5,9,10] Within the framework of MDM, the diffraction and rms radii of excited "exotic" states 3.09 MeV $(1/2^+)$ and 8.86 MeV $(1/2^-)$ MeV at energy $E(\alpha) = 29$ MeV were determined for the first time. Analysis of the experimental data made within MDM made it possible to discover, in addition to the usual states of the shell model, two "dilute" states of various types: one of them contains a neutron halo (3.09 MeV $(1/2^+)$) and the other is an analog of the Hoyle state (8.86 MeV $(1/2^-)$).

The obtained results demonstrate a coexistence of different structures in ^{13}C, thereby showing the uniqueness of this nucleus.

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