Vol. 14 (2021) *Acta Physica Polonica B Proceedings Supplement* No 4

OPEN QUESTIONS IN STUDY OF ^{13}C EXOTIC EXCITED STATES*

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(Received November 10, 2021; accepted November 12, 2021)

^{13}C is a good example of a "normal" nucleus that is well described within the shell model. Its level scheme is reliably determined up to excitation energies ~ 10 MeV. However, some questions remain open regarding the structure of low-lying ^{13}C states. This leads to the increased attention to ^{13}C. In 2014, our group announced the discovery of a state of ^{13}C with an abnormally small radius. In the framework of the modified diffraction model (MDM) method, analyzing data on α-scattering on ^{13}C at 65 and 90 MeV, it was shown that this state has a radius reduced by 10%. At the same time, theoretical works predict dilute structure and increased radius for this state, and assumptions were made about its rotational structure. Another important question is the search for possible analogues of the Hoyle state in ^{13}C. Confirmed analog of the Hoyle state is the $1/2^-$ (8.86 MeV) state in ^{13}C. Another possible candidate is the next $1/2^-$ state — 11.08 MeV. Moreover, a hypothesis was put forward about a new type of symmetry in the ^{13}C structure — D'_{3h} symmetry. On the basis of D'_{3h} symmetry, the rotational nature of a whole group of low-lying ^{13}C states was predicted. In the work, 6 rotational bands were proposed, that is, almost

* Presented at III International Scientific Forum "Nuclear Science and Technologies", Almaty, Kazakhstan, September 20–24, 2021.

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all low-lying ^{13}C states were distributed among the rotational bands. Thus, a critical analysis of the available data is required to answer the question about the nature of low-lying excited states in ^{13}C.

DOI:10.5506/APhysPolBSupp.14.781

1. Introduction

The study of exotic states of nuclei has been a priority direction in the development of nuclear physics in recent decades. Properties of such states make it possible to expand the understanding of the properties of nuclear matter in rarefied density, as well as to test existing nuclear models and nucleon–nucleon potentials. Among the most distinctive features of exotic states can be noted abnormally large sizes. Cluster states in light nuclei are one of the types of such states. Particular interest is devoted to the ^{12}C nucleus. Excited states of ^{12}C continue to be intensively investigated theoretically and experimentally. This is especially true for the second excited 0^+, 7.65 MeV state in ^{12}C, the so-called Hoyle state. This state is named after astrophysicist Fred Hoyle who predicted its existence in 1954 [1] before the experimental discovery in 1957 [2]. This state is located 0.287 MeV above 3 α-particles breakup threshold. The proximity of the state to the threshold of dissociation into α-particles indicates the important role of α-clustering of this state. The Hoyle state plays an important astrophysical role in the synthesis of ^{12}C in the Universe. The formation of elements in the Universe heavier than carbon goes through this state. The structure of the Hoyle state is widely discussed. The following possible configurations of this state were proposed: (a) a linear chain of α-particles; (b) dilute gas of α-particles — Bose–Einstein condensate (αBEC); (c) compact structure — 3 α-particles at the vertices of the triangle; (d) dilute structure — 3 α-particles at the vertices of an obtuse triangle (“bent arm”). Most models predict increased dimensions for the Hoyle state. A question appears, such a dilute structure can be saved if we add additional particle–hole or neutron. Or in other words, weather analogues of the Hoyle state can be in the neighboring nuclei ^{11}B and ^{13}C, and what are their sizes. These predictions renewed interest to ^{13}C. A group of diverse scientific theories was applied for the investigation of ^{13}C excited states. A short overview is presented here.

Yamada and Funaki [3] proposed that the coupling of one neutron to ^{12}C* core will lead to possible gas-like states, analog of the Hoyle state, and they predicted that three states: $1/2^-_2$, $1/2^-_3$, and $1/2^-_4$ may have the r.m.s. radii exceeding those of the ground state by 0.6–0.8 fm.

Milin and von Oertzen [4] proposed the existence of two rotational bands built on the $3/2^-_2$, 9.90 MeV state and some $3/2^+$ state which has not been observed yet. These bands were considered as a parity doublet of

^{9}Be (g.s.)+α cluster structure. Furutachi and Kimura [5] suggested two $K^{\pi} = 3/2^{-}$ rotational bands with a large moment of inertia in the vicinity of the $3\alpha + n$ threshold (12.2 MeV). One of them is expected to have a bent 3α linear-chain structure and could be identified with the band based on the 9.90 MeV state. The radii of the member states of this band were predicted [5] to be enhanced ($R_{\rm rms} \sim 3.2$–3.3 fm) relatively that of the ground state of ^{13}C. Our results for the 9.90 MeV state [6] showed that the predicted radius enhancement does not take place.

Recently, a hypothesis was put forward about a new type of symmetry in the ^{13}C structure — D'_{3h} symmetry [7]. Earlier the same team of authors proposed a similar type of D_{3h} symmetry for the ^{12}C nucleus [8]. On the basis of D'_{3h} symmetry, the rotational nature of a whole group of low-lying ^{13}C states was predicted. If this hypothesis is confirmed, our understanding of the ^{13}C structure will radically change. In [7], 6 rotational bands are proposed, that is, almost all low-lying ^{13}C states are distributed among the rotational bands.

In [9], the antisymmetrized molecular dynamics (AMD) analysis was done to search for analog of the Hoyle state in ^{13}C. In contrast to [3], it was shown that the $1/2^{-}_{3}$, $1/2^{-}_{4}$, and $1/2^{-}_{5}$ states are $3\alpha + n$ cluster states in which the ^{12}C$(0^{+}_{2})\otimes 0p_{1/2}$ and ^{12}C$(2^{+}_{2})\otimes 0p_{3/2}$ configurations are mixed but cannot be regarded as the Hoyle-analog state because the S factors in the ^{12}C$(0^{+}_{2})\otimes p_{1/2}$ channel are small. It was proposed that the $1/2^{+}_{2}$ state located at 15.4 MeV is a Hoyle-analog state dominated by the ^{12}C$(0^{+}_{2})\otimes 1s_{1/2}$ configuration with $S = 0.64$.

Our results [10] has shown the coexistence of different structures in ^{13}C: 3.09 MeV (neutron halo), 8.86 MeV (dilute α-cluster state) and 9.90 MeV (compact state) states co-exist together with a number of states with normal radii.

Thus, a critical analysis of the available data is required to answer the question about the nature of low-lying excited ^{13}C states. In this work, three questions will be discussed: first, the possible analog of the Hoyle, $1/2^{-}_{3}$ and its radius; second, the question on the existence of compact state $3/2^{-}_{2}$, 9.90 MeV state; third, the possible rotational bands in ^{13}C.

Our group is developing methods of determining radii. In this work, the modified diffraction model method [11] is used. For MDM analysis, we used our experimental data [6, 10] on α+^{13}C scattering at 65 and 90 MeV and also existing literature data. Not so far MDM was developed for charge-exchange reactions [12] and it gave a possibility to compare results on radii of isobar-analog states (IAS). The question about compact state $3/2^{-}_{2}$, 9.90 MeV will be investigated on its IAS in ^{13}N — the 9.48 MeV state. IAS states should have similar features and radii.

2. $1/2_3^-$ 11.08 MeV state

The 11.08 MeV state was observed in both experiments at 65 and 90 MeV [6, 10]. As expected, angular distributions correspond to the angular momentum transfer $L = 0$. We applied MDM to experimental data at 65 and 90 MeV. In both cases, diffraction radii of the 11.08 MeV state are increased, so r.m.s. radius of this state is also increased. Taking into account the radius of the g.s. 2.28 ± 0.04 fm [13], average r.m.s. radius is 2.8 ± 0.2 fm. This value within errors coincides with the radius of the 8.86 MeV state in ^{13}C and the Hoyle state in ^{12}C, and is smaller than predictions [3]. Moreover, if we compare the energy dependence of diffraction radius of the 11.08 MeV state, based on new experimental data together with existing literature data, it practically coincides with the energy dependence of the 8.86 MeV state and the Hoyle state. Obtained increased radius close to the radius of the Hoyle state can be an argument to possible close structure of these states.

3. $3/2_2^-$ 9.90 MeV state

Our previous MDM analysis has shown that the 9.90 MeV state $3/2^-$ is compact [6, 10], while as was mentioned in the introduction a number of theoretical works contradict this result and predict radius enhancement for the 9.90 MeV state. Moreover, it was proposed in [7] that the 9.90 MeV state is a member of the rotational band based on the 8.86 MeV state. Members of this band are: 8.86 MeV $1/2^-$, 9.90 MeV $3/2^-$, 10.82 MeV $5/2^-$. As the 8.86 MeV state has increased radius, it is quite natural that other members of the band should also have increased radius. Thus, rather contradictive results are present for the 9.90 MeV state.

To check these points, we study the isobar-analog state (IAS) of the 9.90 MeV state in ^{13}N — the 9.48 MeV state using MDM [12]. Several works have been found in the literature on the ^{13}C(^{3}He, t)^{13}N reaction at 43.6 MeV [14] and 450 MeV [15] with the excitation of the 9.48 MeV state. r.m.s. radius of the 9.48-MeV $3/2^-$ state was determined to be 2.5 ± 0.3 fm. So, we obtained a normal, non-increased radius for the 9.48 MeV $3/2^-$ state, which within errors coincides with the radius of the ground state. But there are two facts that should be bear in mind. The first one is that the data at 450 MeV is on the upper limit of the MDM applicability and, therefore, additional verification is required. The second fact is that angular distributions for the ^{13}C(^{3}He, t)^{13}N reaction with excitation of the 9.48 MeV state and inelastic scattering ^{13}C(^{3}He,^{3}He)^{13}C with the excitation of the 9.90 MeV state are out of phase while these states are isobar-analog states. Probably this can be explained by the fact that the target in [14] contained impurities of ^{12}C and 9.64 MeV state of ^{12}C could give a contribution to cross section. Therefore, a new experiment with ^{3}He beam at middle energies with simultaneous measurements of scattering and (^{3}He, t) reaction is highly desirable. We suppose to do it in near future.

We have clarified the radius of the 9.90 MeV state based on existing experimental data. Averaged on 65 and 90 MeV r.m.s. radius is 2.0 ± 0.3 fm. The obtained value of the radius practically coincided with the value from [6] but the value of error is a bit larger. This is due to the necessity to take into account the errors in determining a position of the extrema. In principle, within the error limits, the value of the radius obtained for the 9.90 MeV in ^{13}C coincides with the radius of the 9.48 MeV state in ^{13}N state and radius of the g.s. in ^{13}C; perhaps, due to a rather large value of errors, these values are similar.

4. Possible rotational bands in ^{13}C

Theoretical works [4, 5, 7] predict rotational nature for a number of excited state in ^{13}C. In this work, we will discuss the possibility of these bands existence based on MDM analysis. For clarity, these bands are shown in Fig. 1.

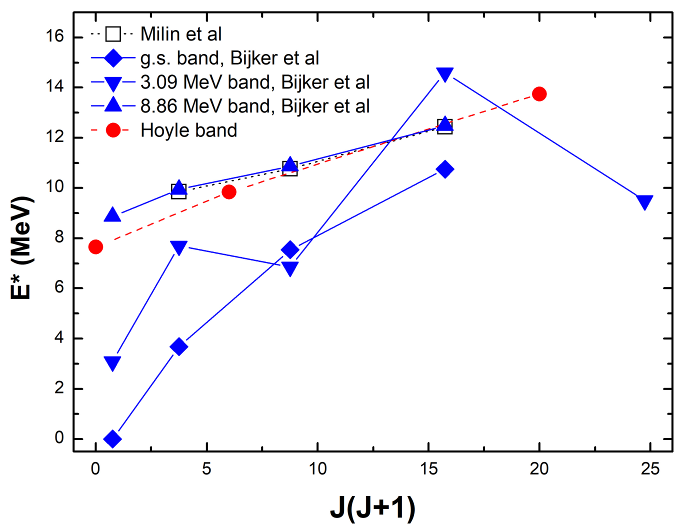

Fig. 1. Predicted rotational bands in ^{13}C. For comparison, the proposed band in ^{12}C based on the Hoyle state is presented.

The band based on the g.s. [7] can exist as MDM analysis has shown that all states of this band have normal non-increased radii.

The band based on the 3.09 MeV state is very interesting and perspective as its first state is halo. And the question is what about the other states of this band? It is quite natural that states of one band should have similar features. Should the halo structure be saved for them? Also, it should be mentioned that all other members of this band are in continuum despite the 3.09 MeV state which is bound.

The both proposed bands in [4] and [7], which contain 9.90 MeV state, also include the 10.82 MeV $5/2^-$ state. We found angular distributions with excitation of this state in [14] in both ^{3}He and ^{4}He scattering. MDM analysis has shown that this state has a normal non-increased radius. Also, these bands are practically parallel to the Hoyle-state band.

It is interesting to note that the 9.90 MeV state is strongly excited in the α-cluster transfer reactions $(^6\mathrm{Li}, d)$ and $(^7\mathrm{Li}, t)$ on ^{9}Be [16], while the 8.86 MeV state is not. This means that α-cluster structures of the 8.86 MeV and 9.90 MeV states are probably different: the latter has a strong $^9\mathrm{Be}+\alpha$ component which is absent in the 8.86 MeV. Thus, 8.86 MeV and 9.90 MeV states cannot be members of one band due to different structures and r.m.s. radii, and proposed in [7] $K^\pi = 1/2^-$ band: 8.86 MeV $1/2^-$ — 9.90 MeV $3/2^-$ — 10.82 MeV $5/2^-$ most likely does not exist. At the same time, $K^\pi = 3/2^-$ band proposed in [4] can exist and members of this band should have a normal r.m.s. radius.

The question regarding rotational states and bands in ^{13}C is still open and deeper analysis is needed. We suppose that a future experiment will help to solve it.

The reported study was funded by RFBR, project number 20-32-70115.

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