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Search for exotic states in ^{13}C

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^{13}C is usually recognized a good example of a "normal" nucleus well described by the shell model. Its level scheme is reliably determined up to the excitation energies ~ 10 MeV. However, some new ideas and results renewed interest in ^{13}C. The most ambitious among them is hypothesis [1] about possible existence of α-particle Bose–Einstein condensation (αBEC). Some features of the condensate structure were predicted [1] and observed [2, 3] in the second 0^+, 7.65 MeV state of ^{12}C (so called Hoyle state). It was also suggested [4, 5] that the structures analogous to the Hoyle state may exist in some neighbor nuclei, e.g., ^{13}C. In [6] existence of two rotational bands built on the $3/2_2^-$, 9.90 MeV state and some yet not seen $3/2^+$ state was proposed. The radii of the members of the first band were predicted [7] to be enhanced (more than 3 fm). Our results for the 9.90 MeV state [8] showed that the predicted radius enhancement doesn't take place. Recently a hypothesis was put forward about a new type of symmetry in the ^{13}C – D'_{3h} symmetry [9]. 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 about the ^{13}C structure will radically change. Thus, a critical analysis of the available data is required to answer the question about the nature of low-lying excited ^{13}C states.

Recently another approach was proposed for measuring the radii of nuclei in the excited states, the modified diffraction model (MDM) [3]. Its application [10] to the analysis of existing quite scarce literature data demonstrated that the radii of some states in ^{13}C really are enhanced. However, this result should be taken with some reservation because the used data were obtained at 1-2 energies. Later our group made two experiments on scattering of α-particles on ^{13}C at 65 and 90 MeV [8, 11, 12]. Previous results for the increased radii of the 3.09 and 8.86 MeV states were confirmed. Some amazing result was obtained for the 9.90 MeV state – decreased radius [11, 12]. So in ^{13}C coexistence of different structures is seen: neutron halo (3.09 MeV), cluster state (8.86 MeV, analog of the Hoyle state), compact cluster state (9.90 MeV) [11, 12]. Moreover, our team has successfully applied MDM to study of isobar-analog states (IAS) [13, 14]. Study of isobar-analog states in ^{13}N can be additional check of obtained results for ^{13}C states.

First aim of this work was search for possible analogs of the Hoyle state in excited states of ^{13}C. As mentioned in [5], possible candidate can be the $1/2_3^-$, 11.08 MeV state. Previously increased radius for this state was determined using MDM in [10] but this result was obtained only based on data at single energy 388 MeV [4]. This is upper energy limit for MDM application. So new experimental data were very desirable. The 11.08 MeV state was observed in both experiments at 65 and 90 MeV [8, 11, 12]. We applied MDM to this new experimental data. Averaged on two energies rms 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 [5]. It can be an argument to possible close structure of these states.

Second aim is question about the 9.90 MeV state. Our previous MDM analysis has shown that the 9.90 MeV state $3/2^-$ is compact [11, 12]. While some theoretical works [7] contradict this result and predict radius enhancement for the 9.90 MeV state. Moreover, it was

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proposed in [9] that the 9.90 MeV state is member of rotational band $K^{\pi} = 1/2^-$ based on the 8.86 MeV state. As the 8.86 MeV state has increased radius, quite natural that other members of the band should also have increased radius.

To check these results we study the isobar-analog state of the 9.90 MeV state in ^{13}N – the 9.48 MeV state using MDM [14]. Several works have been found in the literature on the reaction $^{13}\mathrm{C}(^3\mathrm{He,t})^{13}\mathrm{N}$ at 43.6 MeV [15] and 450 MeV [16] with the excitation of the 9.48 MeV state. We applied MDM to these data. There are two variants of determining radius [14] using MDM based on charge-exchange reactions. We obtained following results for the 9.48 MeV state: 2.5 ± 0.3 fm for the first variant and 2.3 ± 0.3 fm for the second. So, both variants gave practically the same result: we obtained normal, non-increased radius for the 9.48 MeV state, which within errors coincides with the radius of the ground state. But the data at 450 MeV is on the upper limit of the MDM applicability and, therefore, additional verification is required. So a new experiment with ^{3}He beam at middle energies is highly desireable.

Also we have clarified radius of the 9.90 MeV state based on existing experimental data. Averaged on 65 and 90 MeV rms radius is 2.0 ± 0.3 fm. Obtained value of the radius practically coincided with value from [8] but value of error is a bit larger. 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 rather large value of errors, values are similar.

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 [17] while the 8.86 MeV state is not. This means that α-cluster structures of the 8.86 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. So, 8.86 and 9.90 MeV states can't be members of one band due to different structures and rms radii and proposed in [9] band $K^{\pi} = 1/2^-$ most likely doesn't exist. At the same time, proposed in [6] band $K^{\pi} = 3/2^-$ can exist and members of this band should have normal rms radius. Anyhow, question regarding rotational states and bands in ^{13}C is still open and deeper analysis is needed.

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