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Rotational band in ^{12}C based on the Hoyle state

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Abstract. α + ^{12}C inelastic differential cross-sections were measured at the energies 65 and 110 MeV. A new broad state at 13.75 MeV was observed. Its spin-parity has been determined as 4^+ and the diffraction radius of the corresponding L = 4 transition is ~ 0.8 fm larger than that of the excitation of the 4+, 14.8 MeV level. The 13.75 MeV state was considered to be the third member of the rotational band based on the Hoyle state.

1 Introduction

The structure of the 0^+_2, 7.65 MeV “Hoyle” state of ^{12}C permanently attracts attention due to its importance for understanding many features of clustering phenomena in nuclei. During last decade there appeared several new theoretical approaches which predicted some unusual features of this state. The most ambitious among them was the model of alpha particle condensation (APC) [1] according to which the Hoyle state was expected to have enhanced dimensions resembling a gas of almost non-interacting alpha particles. Most of the other cluster models like the antisymmetrized molecular dynamics (AMD) also predicted the enhancement of the radius of the Hoyle state, though in a less extent. The experimental data on the inelastic scattering [2] supported these suggestions (the collection of the theoretical radii values together with the experimental one is given in Table.1).

Table 1. RMS radii of the Hoyle state in ^{12}C from different models and experiment.

1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10 EXP***
3.83	3.27	4.31	3.47	3.38	3.22	3.53	2.90	2.4	2.89±0.04

1. Y. Funaki et al., Phys. Rev. C **80,** 064326 (2009); ***2.*** Y. Kanada-En'yo, Phys.Rev. C **75**, 024302 (2007); ***3.*** T. Yamada, P. Schuck, Eur. Phys. J. A **26**, 185 (2005); ***4.*** M. Kamimura, Nucl. Phys. A **351**, 456 (1981); ***5.*** M. Chernykh et al., Phys. Rev. Lett. **98,** 032501 (2007); ***6.*** M. Gai, EPJ Web of Conf. **38**, 15001 (2012); ***7.*** N. Furutachi, M. Kimura, Phys. Rev. C **83**, 021303 (2011); ***8.*** T.Suhara and Y.Kanada-En’yo, PTP, **123,** 303 (2010); ***9.*** E. Epelbaum, Phys. Rev. Lett. **106**, 192501 (2011); ***10.*** A.N. Danilov et al., Phys. Rev. C **80**, 054603 (2009)

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Moreover, another prediction of the APC that all three alpha particles in ^{12}C should predominantly occupy the lowest *s*-orbit also was confirmed by experiment giving for the occupation probability $W_s(\alpha)$ = 0.6 [3] (to be compared with the theoretical value 0.7 - 0.8 [4]). Thus, the experiment definitely demonstrated the exotic features of the Hoyle state including those which could be interpreted as the manifestation of rudimentary APC ("ghost" of condensation). However, some new open questions appeared, and they were connected with possible existence in ^{12}C of the excited states genetically connected with the Hoyle one.

The idea that the Hoyle state might be the head of a rotational band became quite natural after appearance of the Morinaga's model [5] describing this level as a chain-like configuration of three alpha particles. However, the extremely large moment of inertia required the location of the corresponding 2^+ state at a too low excitation energy (no more than ~ 0.8 MeV). Recent experiments [6, 7] identified the 2^+_2 level in ^{12}C at E* = 9.6 – 9.8 MeV. On the other hand, according to the APC model the 2^+_2 state is formed by lifting one of the α's to the next *d*-orbit from the *s* one and has an extremely large *RMS* radius ~ 6 fm [8]. Consequently, in the frame of APC the 2^+_2 state should be almost spherical and cannot belong to a rotational band.

Recently, the radius of the 2^+_2 state was determined [9] to be ~ 3.1 fm. i.e. practically the same as that of the Hoyle state. As the *RMS* rigid rotator radius estimated from the moment of inertia is quite close to this value (2.7 fm) these findings provide some arguments in favor of the suggestion that the states 0^+_2 - 2^+_2 really are the members of the second rotational band in ^{12}C. Of course, the decisive conclusion could be done only after identification of the corresponding 4^+ state. Some indication to existence of such a state was obtained in Ref. [10] claiming to the observation of a 4^+ broad state at E* = 13.3 MeV. In any case this finding should be confirmed.

2 Results and discussion

We measured the differential cross-sections of the inelastic α + ^{12}C scattering at the alpha particles energy 65 MeV leading to the states of ^{12}C at the excitation energies up to E* ≈ 20 MeV. The experiment was performed at the JYFL cyclotron at the alpha particles energy 65 MeV. The sets of ΔE – E telescopes installed in the scattering chamber LSC were used. The overall energy resolution was about 200 keV due to use of a beam monochromatization system. Besides, we reconstructed the cross-section of the inelastic scattering cross-section to the state 4^+, 14.08 MeV from the data measured at 110 MeV previously [11] but unpublished at that time.

Sample spectra at both energies are shown in Fig.1. They were decomposed into separate groups.

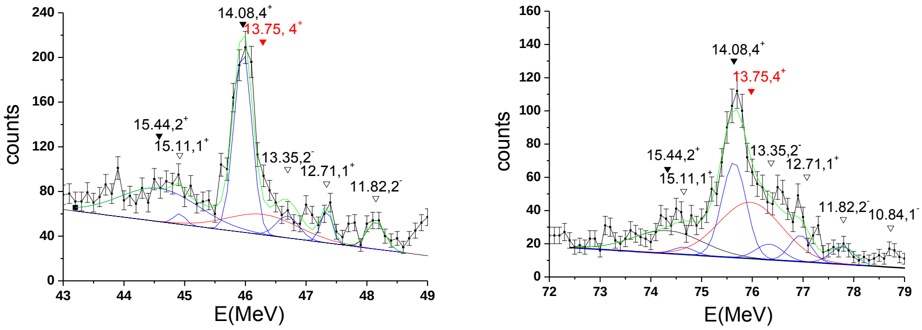

Figure 1. Sample α-particles spectra at E (α) = 65 MeV, Θ_{lab} = 30.8° (left) and E (α) = 110 MeV, Θ_{lab} = 43.6° (right). The results of the decomposition into the groups corresponding to the known levels of ^{12}C and the new one at 13.75 MeV are shown.

The decomposition procedure contained a few steps. First, the background approximated by the straight lines (Fig.1) was subtracted. Secondly, we chose several spectra at E (α) = 65 MeV measured at the backward angles where the background was practically negligible and tried to decompose them into the groups corresponding to the known levels of ^{12}C in the excitation energy region of interest: 15.44 (2^+), 14.08 (4^+), 15.11 (1^+, T=1), 13.35 (2^-), 12.71 (1^+) and 11.83 (2^-). In principle, the spectra could be reproduced, however, the χ^2 value was significantly larger than in the other attempts and the intensity of the group corresponding to the state 2^-, 13.35 MeV was several times larger than that related to the state 2^-,11.83 MeV in all the spectra decomposed in this way. As the four last levels have abnormally parity (and one of them even T = 1) they could be excited only via some multi-step mechanisms. Consequently, we suggested that the cross-sections of the formation of both closely lying 2^- levels should be equal, and made the decomposition of the spectra under such condition. The result was that the inelastic scattering cross-section in the excitation energy region 13 – 14 MeV was not exhausted by the known ^{12}C states. For this reason we have done two other types of decomposition assuming either the existence of a level with the parameters taken from Ref. [10] (E* = 13.3 MeV, Γ = 1.7 MeV) or a new state whose excitation energy and width were adjusted. The second variant of decomposition led to a broad group corresponding to the new state E* = 13.75 ± 0.12 MeV, Γ = 1.4 ± 0.15 MeV and gave better description of the data at both initial energies and practically at all the measured angles.

The differential cross-sections of the inelastic scattering leading to the excitation 14.08 and 13.75 MeV states are shown in Fig.2 (E_α = 110 MeV) and Fig.3 (E_α = 65 MeV).

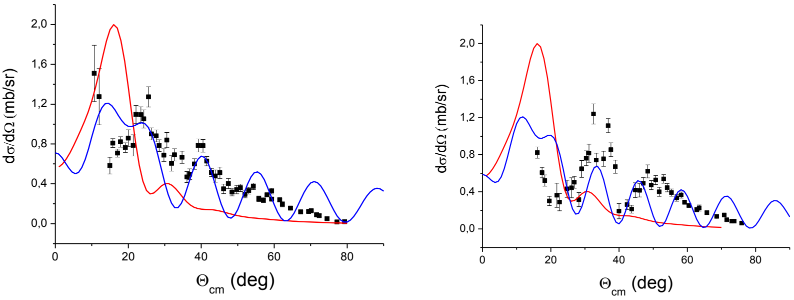

Figure 2. Differential cross-sections of the ^{12}C + α inelastic scattering at E (α) = 110 MeV with excitation of the 14.08 MeV, 4^+ (left) and 13.75 MeV (right) states. The red curves are calculated by DWBA with L = 4 and the similar parameters of OM potential and form factor obtained from the scattering data to the 2^+_1 (4.44 MeV) state (with necessary corrections to the difference of the initial energy). The blue curves are calculated using the diffraction scattering model with L = 4 and the diffraction radii R = 4.2 fm (left) and 5.0 fm (right).

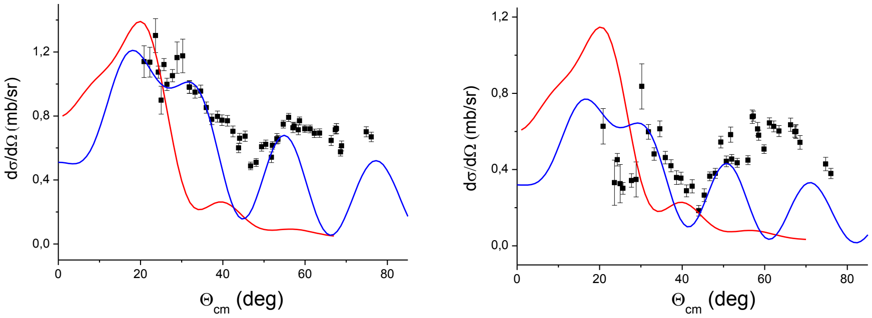

Figure 3. The same as in Fig.2 at E (α) = 65 MeV

One can see from Figs.2, 3 that the shapes of the angular distributions corresponding to the excitation of the 14.08 MeV, 4^+ state and the 13.75 MeV one are quite similar in their main features (note two prominent maxima and minima at the angles larger than ~ 15^o). The diffraction model calculations with the angular moment transfer L = 4 reproduce rather satisfactory their positions. In the case of the 14.08 MeV state the diffraction origin of these maxima and minima is well demonstrated by the observed shift of the main extremes with the energy to the smaller angles which is approximately proportional, as expected, to $1/E^{1/2}$. In the case of the 13.75 MeV state such shift manifests itself in much less extent and is observed only at the large angles. Probably, this is connected with some uncertainties in the spectra decomposition procedure. Nevertheless, it is reasonable to suggest the $I^{\pi} = 4^{+}$ value for the 13.75 MeV level.

For preliminary DWBA analysis we deliberately used the parameters of the optical model (OM) potentials and the form factors which had been obtained by fitting the calculations to the inelastic scattering cross-sections to the 2^{+}_{1} (4.44 MeV) state with necessary corrections to the differences in the energy. The agreement occurred to be rather poor even in the case of the 14.08 state where one might expect more similarity in the excitation the 2^{+} and 4^{+} states belonging to the same rotational band. It is interesting to note that the cross-section of the excitation of the 4^{+}, 10.36 MeV state (being also a member of the rotational band) in the ^{16}O (α, α') reaction measured in Ref. [12] at the same center-of-mass energy (E_{lab} = 104 MeV) practically coincides with our $^{12}C + \alpha$ data in the overlapping regions of the linear momentum transfers. The DWBA calculations [12] also did not reproduce the prominent maximum at ~ 25°. This result indicates the necessity of more detailed study of the dynamics of the reactions under discussion.

The Modified diffraction model (MDM) [2] was used for estimating the radii of the 14.08 and 13.75 MeV states. The best fit was obtained with the diffraction radius of the transition to the 14.08 MeV state R_{dif} = 4.2 fm (left parts of Fig.2, 3), which is almost 1 fm less than that for the elastic scattering. A probable origin of this effect lies in large centrifugal barrier and will be discussed elsewhere. In spite of this the diffraction radius corresponding to the formation of the 13.75 MeV state can be estimated relatively to that of the 14.08 MeV level. It occurred to be R_{dif} = 5.0 fm, i.e. 0.8 fm larger than that of the 14.08 state. This value agrees well with the differences between the ground and the excited 0^{+}_{2} and 2^{+}_{2} states (0.6 fm and 0.8 fm correspondingly according to [9]) providing another evidence of belonging of the 13.75 MeV level to the rotation band based on the Hoyle state (Fig.4).

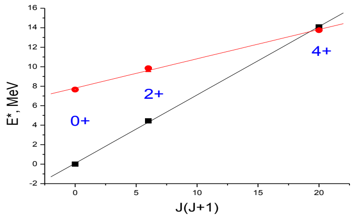

Figure 4. Rotational bands of ^{12}C

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