DILUTE NUCLEAR STATES in ^{12}C and NEIGHBOR NUCLEI

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A review of recent experiment including those performed by our collaboration is given. The main accent is done to unique information which is extracted from the measurements of the inelastic scattering cross-sections using the Modified diffraction model (MDM). The enhancement of the radii of some highly excited cluster states of ^{12}C, ^{11}B and ^{13}C was definitely observed. The radii values are in general 20 -30% larger than those of the corresponding ground states but much less than those predicted by the model of alpha particle condensation. A rotational band based on the 0^+_2 (Hoyle) state in ^{12}C is identified.

1. Introduction

During the last decade the discussion arose about the possibility of existence of nuclear states with enhanced radii. Different cluster theories like antisimmetrized molecular dynamics (AMD), fermion molecular dynamics (FMD) and some other conjectured the existence of dilute states resembling a “gas” of alpha particles. The most ambitious among them, the model of alpha particle condensation [1] predicted increase of the volumes of some states located near the dissociation thresholds up to the values of 5 – 8 times relatively those of the ground states of the corresponding nuclei.

In this paper a review of some recent experimental studies of diluteness in light nuclei is given. The most popular object of recent research became the famous Hoyle state of ^{12}C (0^+_2, 7.65 MeV) and its possible analogs in the neighbor nuclei.

2. 0^+_2, 765 MeV (Hoyle) state of ^{12}C

The 0^+_2, E* = 7.65 MeV ("Hoyle") state of ^{12}C plays not only extremely important role in stellar nucleosynthesis (the majority of carbon in the universe is produced via the triple α-particle resonance fusion reaction through this state), but also attracts steady attention in nuclear physics researches due to its exotic structure. The proximity of the Hoyle state to the threshold of the ^{12}C dissociation into three α particles naturally lead to a hypothesis of α-cluster structure of the state. Moreover, even the most elaborate shell-model calculations cannot explain the structure the Hoyle state. Nowadays the Hoyle state becomes the main object of testing different cluster theories.

The first cluster model of the Hoyle state considered its structure as a linear chain of alpha particles [2] indirectly implying its enhanced size. However, this model being pure phenomenological was soon rejected. For the first time the position of the Hoyle state was reproduced in Ref. [3]. The microscopic wave function of the Hoyle state proposed by Kamimura [3] up to now is considered to be the most accurate one, and serves a basis of calculating many properties of the state. A strong argument for the alpha condensate model was that its simpler wave function has almost 100% overlap with that by Kamimura. Other modern cluster theories also predict the radius enhancement of the Hoyle state (Table1).

Table 1. Radius of the Hoyle state of ^{12}C

Exp	Theory					
	Micro	Cond1	Cond2	AMD1	AMD2	[FMD]
[4]	[3]	[1]	[5]	[6]	[7]	[8]
2.89 ± 0/04	3.47	3.83	4.31	3.3	2.90	3.38

Recent experiments (e.g.,[8]) have confirmed the dilute structure of the Hoyle state. Its rms radius was determined in Ref. [4] from the inelastic α-particle scattering using the modified diffraction model (MDM). It was found to be ~ 1.2 times larger than that for the ground state. This is less than predicted by most of calculations, especially, by those based on the condensate model. Only the AMD version [7] gives a value in close agreement with the experiment (Table1).

The disagreement in the experimental and the calculated radii shed some doubt on the full adequacy of the wave function [3]. A sensitive test of the structure of the nuclei interior provide nuclear rainbow scattering and such experiment on inelastic ^{12}C + α scattering was recently done at the energies 60 and 65 MeV [11]. The differential cross-sections measured at E(α) = 60 MeV are shown in Fig.1 and demonstrate a deep Airy minimum at 72 degrees. Calculations done with the form factor and folding potential in the exit channel using the wave function [3] do not reproduce either the cross-section in the region of the rainbow minimum. The obtained result indicates to not full adequacy of the wave function [3] for the description of the Hoyle state.

Another test confirming the pronounced α-cluster structure of the Hoyle state has been performed in Ref. [12], where the coupled-channels model calculations of the angular distributions of α + ^{12}C elastic and inelastic scattering at 110 MeV [10,13] revealed a mechanism of the direct transfer of ^{8}Be cluster at large angles. These calculations showed that the cluster configuration [α - $^{8}Be(I=0)$] with the relative angular momentum L = 0 dominates in the 0^+_2 state, being more than three times larger than that in the g.s. of ^{12}C. The occupation probability W(L=0) which may be considered as a condensate fraction of the lowest 0s α-particle orbit in the 0^+_2 state was found to be ≈ 60% in comparison with W(L=0) 70 - 80% predicted by condensate model [11] (Fig.2).

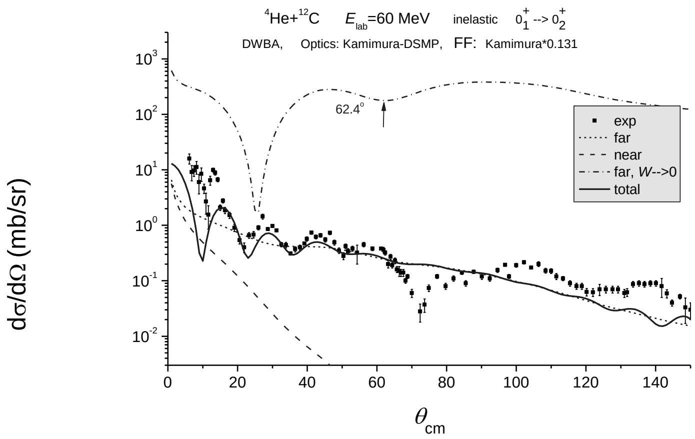

Fig.1. Differential inelastic ^{12}C + α cros1s-section at E(α) = 60 MeV leading to the excitation of the Hoyle state. Calculations using the wave functions [3] are shown by a solid curve. The dashed curves correspond to the far and near components of the cross-section. The dash-dotted curve represents the far component without absorption (W = 0).

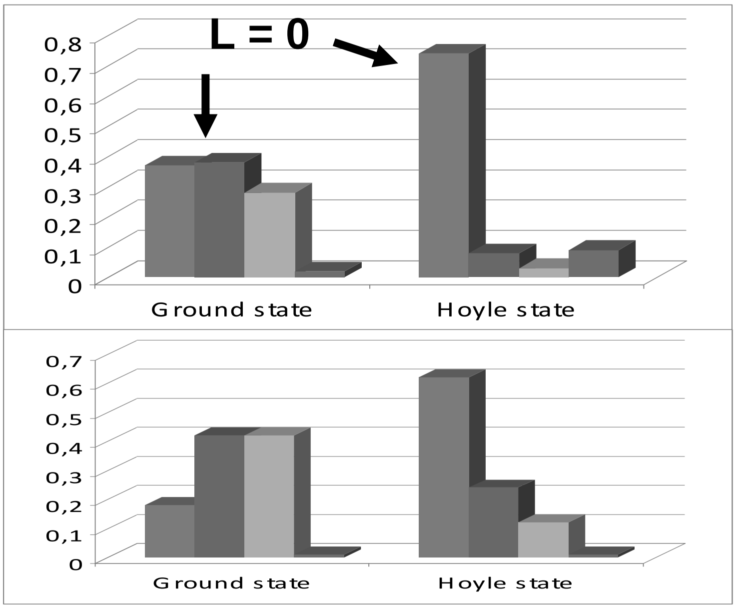

Fig.2. Occupation of the single alpha particle orbitals of the ground and Hoyle states of 12C. The upper part relates to the predictions [11], the lower part represents the experimental data [9]. The component with L = 0 may be considered as the condensateion fraction.

The measured value of the condensate fraction differs from the theoretical predictions in much less extent than the corresponding values of the radii. The reason is that the values of the radius and the condensation fraction are interdependent [12]. A well developed condensation requires nucleon densities $\rho \sim 0.025$ n/fm^3 which lead to W(L = 0) ~ 80%, while the measured values for the Hoyle state: $\rho \sim 0.9$ ($R_{RMS} \approx 2.9$ fm) and W(L = 0) ~ 60%, are consistent as well. To summarize these findings, one may say that the main features of alpha condensation really were observed in the Hoyle state but in a non-developed, rudimentary form. The situation may be described as existence of a "ghost" of condensation.

3. Excited Hoyle states

One of the long-standing problems is if ^{12}C has excited states of the same structure as the Hoyle state. The 2^+_2 state predicted by Morinaga [2] recently was discovered at the excitation energy 9.84±0.06 MeV [14] (alternative values 9.6±0.1 MeV [15] and ~ 10 MeV [16] were also announced). The

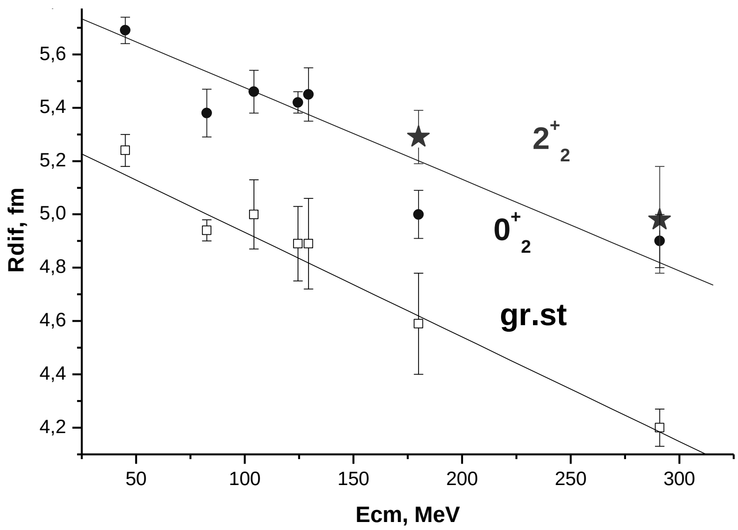

Fig.3. Diffraction radii of 2+2, 9.6/9.84 MeV state from 12C + α scattering [] marked by stars. Diffraction radii of the Hoyle and ground states of 12C are given for comparison

calculations [3] are consistent both with rotational or vibration nature of the Hoyle state. The condensate model predicts a different structure for the 2^+_2 state. According to it [18] the 2^+_2 excited Hoyle state is formed by lifting one of the α clusters from the 0s-orbit to the next 0d-orbit. Its rms radius is predicted to be extremely large, Rrms = 6.12 fm [14] (see Table1 for comparison). Evidently, within the condensate model both states cannot form a rotational band, because all the members of the latter should have similar radii.

The radius of the 2^+_2, 9.6/9.84 MeV state was determined in Ref. [19] by MDM, The diffraction radii obtained [19] from the analysis of experimental data at two alpha particle energies 240 MeV [20] and 386 MeV [15] are shown in Fig. 3 in comparison with those for the Hoyle and ground states of ^{12}C [4]. The obtained values of the 2^+_2 state diffraction radii are close to of the diffraction radii of the 0^+_2, 7.65 MeV (Hoyle) state and fit very well the energy dependence of the latter. The averaged value $R_{RMS}(2^+_2)$ = 3.07 ± 0.13 fm practically coincide with the *RMS* radius of the Hoyle state (Table 1).

The similarity of the radii of the 2^+_2 level and that of the Hoyle state indicates to the nearness of the structures of these states and make reasonable suggestion that they both are the first members of a new rotational band. Extrapolation of the line connecting the 0^+_2 and 2^+_2 states shows that the next 4^+ band memeber should have the excitation energy close to 14 MeV (Fig.4).

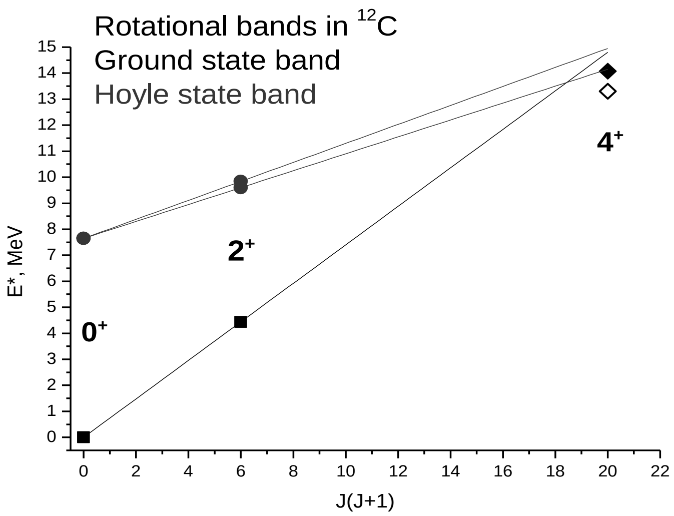

Fig.4. Rotational bands of ^{12}C. Filled squares and a filled rhomb denote the states belonging to the ground state band. Filled circles denote the states probably forming the rotational band based on the excited 0^+_2,7.65 MeV Hoyle state. Two alternative 2^+_2 states, 9.84 and 9.6 MeV are shown. The lines connecting 0^+_2 and 2^+_2 states are extrapolated to larger J(J = 1) values. The open rhomb denotes possible 4^+, 13.3 MeV [21] state

The existence of a 4^+ state at the excitation energy 13.3 MeV was claimed recently [21]. Very preliminary results of another experiment on $^{12}C(\alpha,\alpha')$ at $E(\alpha) = 65$ [22] are shown in Fig.5.

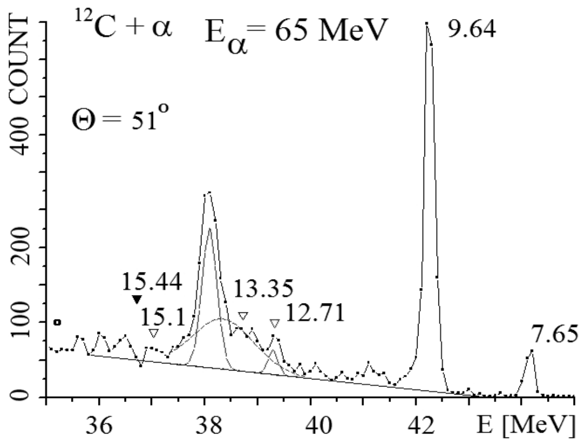

Fig.5. A sample spectrum of α-particles from the inelastic $^{12}C + \alpha$ scattering at 65 MeV

A group corresponding to a broad level with the excitation energy 13.75 MeV serving a pedestal to a well known 4+, 14.08 MeV state is clearly seen. The differential cross-sections of the inelastic scattering leading to the excitation of both states are quite similar proving that a 13.75 MeV level is also 4^+.

4. Analogs of the Hoyle states in the neighbor nuclei

There are predictions and some indications [6,23] that the analogs of the Hoyle state can exist in ^{13}C and ^{11}B. They are expected to have the structure 0^+_2 + n or 0^+_2 - p correspondingly. The analysis of the diffraction scattering done by MDM [24] confirmed that the states $1/2^-$, 8.86 MeV in ^{13}C and $3/2^-$, 8.56 MeV in ^{11}B have enhanced radii approximately of the same value as the Hoyle state (Table 2).

Table 2. Radii of excited cluster states of 13C and ^{11}B

Experiment			Theory			
[24]	[28]*	[30]	[31]	[6]	[29]	
^{13}C, 8.86, $1/2^-_2$	2.91±0.12	2.71±0.12	3.36	2.9		
^{11}B, 8.56, $3/2^-_3$	2.99±0.18	2.68 ± 0.15			3.1	2.65

* preliminary

Different theoretical predictions are closer to experimental data in comparison with the Hoyle state. However, it was suggested in Ref. [25] that the real Hoyle state analog in ^{11}B is located at the excitation energy 12.56 MeV, has $I^{\pi} = 1/2^{+}$ and its *RMS* radius reaches a giant value ~ 6 fm, i.e. like in Uranium nucleus. Note, that the same authors suggested a similar radius for the 2^{+}_{2} state in ^{12}C.

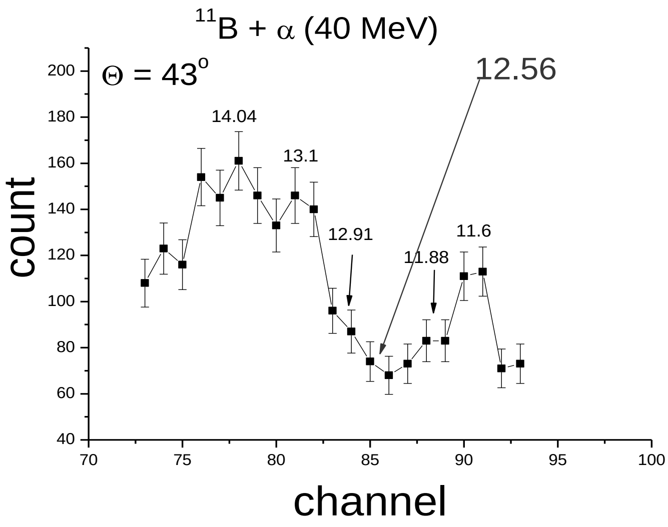

Fig.6. A sample spectrum of the $^{11}B(\alpha,\alpha')$ inelastic scattering. Long arrow denote the expected position of the group corresponding to the 12.56 MeV level.
The states 13.1 MeV and 11.6 MeV may belong to a new proposed rotational band [29].

Two experimental responses followed. The 12.56 MeV state was not observed either in the $^{7}Li + \alpha$ fusion reaction [26] or $^{11}B(\alpha,\alpha')$ inelastic scattering measured at 40 [27] and very recent experiment of our collaboration [28]. A spectrum obtained in [27] is shown in Fig.6.

An interesting moment is that the states 13.1 MeV ($9/2^{-}$) and 11.6 MeV ($7/2^{-}$) may belong to the rotational band based on the $3/2^{-}$, 8.56 MeV [29]. If so, there are all grounds to expect that they also have enhanced radii. The MDM analysis of the corresponding angular distributions is in progress [28].

5. Summary

The main result of the discussed experiments is a quantitative confirmation of the existence of dilute nuclear excited states. Due to use of the Modified diffraction model (MDM) it became possible to extract the radii of unstable states from the inelastic scattering differential cross-sections. The observed dilute states in ^{12}C (7.65 MeV, 0^+, Hoyle state), ^{11}B (8.56 MeV, $3/2^-$) and ^{13}C (8.86 MeV, $1/2^-$) have a developed alpha cluster structure and are located close to the α-particle emission thresholds. All three abovementioned states have similar radii (20 – 30% larger than those of the ground states) what indicates to their possible genetic relations (3α, 3α – p, 3α + n correspondingly). The radius of the second 2^+_2 level (9.6/9.84 MeV) in ^{12}C occurred to be similar to that of the Hoyle state. The existence of a new 4^+ level in the vicinity of the excitation energy ~ 14 MeV was proved. So the evidence of the second rotational band 0^+ - 2^+ - 4^+ in ^{12}C and, consequently, the similar structure of these states was obtained. This finding seems to contradict to the condensate model which interpreted the formation of the excited Hoyle states as a result of changing the orbit by one of the alpha cluster.

Practically all modern cluster theories predicted the radii enhancement for these particular states but the quantitative agreement was observed only with some of them. The best agreement with the experiment demonstrated the version [7, 29] of the antisymmetrized molecular dynamics (AMD). The alpha condensate model systematically overestimates the radii values. Especially large disagreement was observed for the 2^+_2 level in ^{12}C. Similarly, the predicted "giant" $1/2^+$ state in ^{11}B was not observed at all. Still, some signatures of the condensation effects like relatively large probability of the occupation by alpha clusters of the L = 0 orbit in the Hoyle state (together with only the moderate radius enhancement) were identified. These findings allow speaking about the manifestation of a "ghost' of condensate.

6. Acknowledgments

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