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The cluster states in light nuclei

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Abstract. The differential cross-sections of the elastic and inelastic α +^{11}B scattering was measured at E(α) = 29 MeV. The analysis of the data by Modified Diffraction Model (MDM) showed that the root-mean-square (RMS) radius of the ^{11}B state 3/2$^-$, E* = 8.56 MeV is ~ 0.5 fm larger than that of the ground state. It is found that the radius of 3/2$^-$ (8.56 MeV) state in the ^{11}B nucleus is close to the radii of the Hoyle state in ^{12}C.

1 Introduction

One of the most significant theoretical predictions was the hypothesis of excited nuclear cluster states with abnormally large radii. The α-particle condensation model is especially popular [1], according to which there could be nuclear states that resemble a Bose condensate in macroscopic objects.

Theoretical and experimental studies of exotic cluster states concentrated on the famous state of the ^{12}C nucleus with the spin–parity $I^\pi = 0^+$ and excitation energy of 7.65 MeV (Hoyle state). This state plays a crucial part in nucleosynthesis, dictating the elemental composition of the Universe.

Recent experiments on resonance scattering from ^{7}Li nuclei [2] a new band of negative parity has been confirmed which include the following excited states of ^{11}B: 3/2$^-$ (8.56 MeV), 5/2$^-$ (10.34 MeV), 7/2$^-$ (11.59 MeV) and 9/2$^-$ (13.03 MeV). Since these states have large widths for alpha-decay then this band may be formed on the basis of the cluster structures. Besides, the analogy of the cluster structure of ^{11}B nucleus with three cluster structure of ^{12}C is a fascinating challenge for the study. In particular, in [3], it was suggested that 3/2$^-$ (8.56 MeV) state may have a structure consisting of three clusters as 2α+t configuration and may be an analog of the excited state of ^{12}C 0^+_2 which has a structure consisting of three alpha particles [4-6]. There are several of works, where analogs of the Hoyle state can also exist in other neighboring nuclei were predicted [3, 7].

Of particular interest is an explore of excited states in ^{11}B nucleus, where both cluster configuration (2α+t), and the shell model structure can co-exist at the same time.

This paper is a part of our extensive study of the cluster structure in the 1p-shell nuclei, where we investigate the interaction of deuterons, ^{3}He and alpha particles with these nuclei at different energies [8-11]. In the present work we continue the investigation of the nature of ^{11}B excited state at low energies.

2 Experiment

Experimental angular distributions of elastic and inelastic scattering of α-particles from nuclei ^{11}B were measured on the extracted beam of isochronous cyclotron U-150M at the Institute of Nuclear Physics (Almaty, Kazakhstan) at E(α)=29 MeV within angular range of 10-120 degrees in laboratory system.

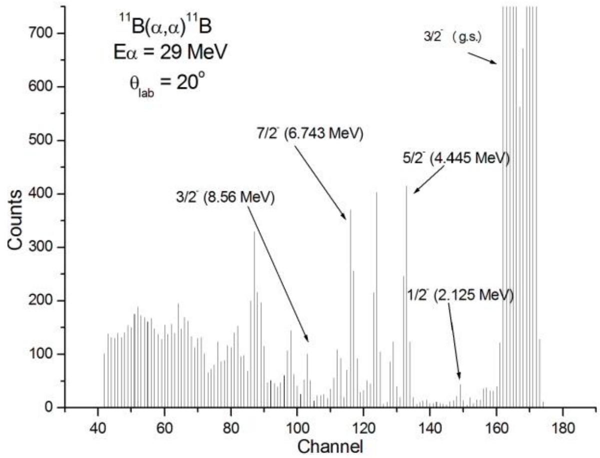

Figure 1. Energy spectra of α-particles scattered from ^{11}B at 20 degrees in laboratory frame, E(α)=29 MeV.

In the "E - ΔE" telescope of detectors, ΔE - detector is a surface-barrier silicon detector with an active layer of thickness of 30 to 200 μm and thin inlet (~ 40 μg/cm^2 Au) and outlet (~ 40 μg/cm^2 Al) windows. The complete absorption E detector is used as a stop detector-

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company ORTEC high-purity silicon; thickness of 2 mm. Targets were thin metal foils made of 90% enriched boron-11 isotope with thickness of ~ 320 μg/cm^2. The detailed description of targets preparation and measuring the thicknesses of the targets is given in [12]. Typical energy spectrum of 29 MeV α-particles scattered by ^{11}B is given in Fig. 1.

3 Results and discussions

For checking these predictions differential cross sections of the inelastic scattering α + ^{11}B at E(α) = 29 MeV were measured and analyzed together with the data obtained at different energies. The analysis was done within the Modified Diffraction Model (MDM) [13]. This method allows determining the radii R^*_{rms} of the excited states via the difference of the diffraction radii of the excited and the ground states using the following expression:

$$R^* = R_0 + [R^*_{dif} - R_{dif}(0)] \qquad (1)$$

Here R_0 is the RMS of the ground state of the nucleus under discussion, R^*_{dif} and $R_{dif}(0)$ are the diffraction radii determined from the positions of the minima and maxima of the experimental angular distributions of the inelastic and elastic scattering, correspondingly. More information about MDM can be found in the work [13].

The theoretical calculations of the angular distributions for the different excited states were performed using the coupled-channel (CC) method implemented in code FRESCO [14] using different potential sets. Parameters of optical and folding potentials that were used in the calculation of elastic and inelastic scattering can be found in our previous work [15].

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 neighbouring nuclei, for example in ^{11}B and ^{13}C. As noted above, it was suggested that the states 8.56 MeV (3/2$^-$) of ^{11}B and 8.86 MeV (1/2$^-$) of ^{13}C [3, 7]. There are several works [8, 16] dedicated to the investigation of cluster structure of excited state 8.56 MeV (3/2$^-$) of ^{11}B using MDM, but all the experimental data used in these works lay in the higher energy region (65 and 388 MeV). The method of extracting the radii within the MDM used in [17] is probably not quite adequate, since at high energies (≥ 100 MeV), the nucleus becomes too transparent. Consequently, new measurements, especially at lower energies, are highly desirable.

In order to finally confirm the first calculations made within the framework of MDM [8, 16], which were of particular importance for the method as a whole, 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 differential cross sections of 3/2$^-$ (8.56 MeV) state at E(α) = 29 MeV compared with the calculations within CC (with Woods-Saxon (WS) potential) method. Fairly good agreement is achieved. The disagreements may due to the non-potential mechanisms contribution as this state has cluster structure.

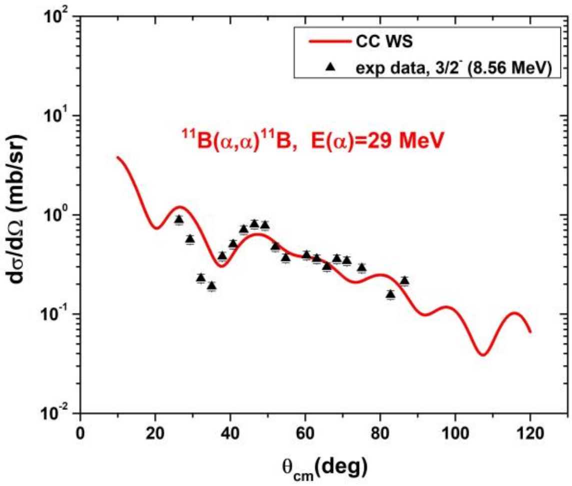

Figure 2. Angular distributions of inelastic scattering of alpha particles from ^{11}B nuclei at E(α) = 29 MeV with experiment of 3/2$^-$ (8.56 MeV) state in comparison with calculated differential cross sections using WS potential in CC method.

The radius of "exotic" 3/2$^-$ (8.56 MeV) state was determined at E(α) = 29 MeV. The radius of 3/2$^-$ (8.56 MeV) state obtained in the present work is equal to 2.88 ± 0.16 fm. This value is ~ 1.20 times larger than that for the ground state. Also, in Table 1 the radius for the excited state of 8.86 MeV of the ^{13}C nucleus is showed, which is also an analog of the Hoyle state (7.65 MeV) in ^{12}C [9, 11]. The comparison of rms radii of excited states of ^{11}B, ^{12}C and ^{13}C nuclei is given in Table 1. The obtained radii are in fair agreement with the results obtained in other works within MDM [8, 16] and other approaches for determining the radii of excited states, such as antisymmetrized molecular dynamics (AMD) [18] and orthogonality condition model (OCM) [19].

Table 1. Comparison of rms radii of excited states of ^{11}B, ^{12}C and ^{13}C nuclei.

System	rms radii of excited states, fm	Model	Energy MeV
α+^{11}B	2.4 ± 0.03 (ground state)		[20]
α+^{11}B	2.88 ± 0.16 (8.56 MeV)	MDM	29
α+^{11}B	2.87 ± 0.13 (8.56 MeV)	MDM	65 [16]
α+^{11}B	2.99 ± 0.18 (8.56 MeV)	MDM	388 [8]
α+^{11}B	3.1 (8.56 MeV)	AMD	theor.work
α+^{11}B	3.0 (8.56 MeV)	OCM	theor.work
α+^{12}C	2.89± 0.16 (7.5 MeV)	MDM	65 [13]
α+^{13}C	2.52± 0.3 (8.86 MeV)	MDM	29 [11]
α+^{13}C	2.68± 0.1 (8.86 MeV)	MDM	65 [9]

The values of the extracted diffraction radii for α+^{12}C and α+^{11}B systems are shown in Fig. 3 [16]. The visible enhancement of the diffraction radii of the excited states 3/2$^-$ (8.56 MeV) is observed. The data excellently fit the systematics obtained in [13] for the formation the Hoyle and ground states of ^{12}C. As is seen in Fig. 3 [16], with decreasing energy the diffraction radius increases and, therefore, the rms radius of this excited state increases as well. This we can see from the data of our calculations.

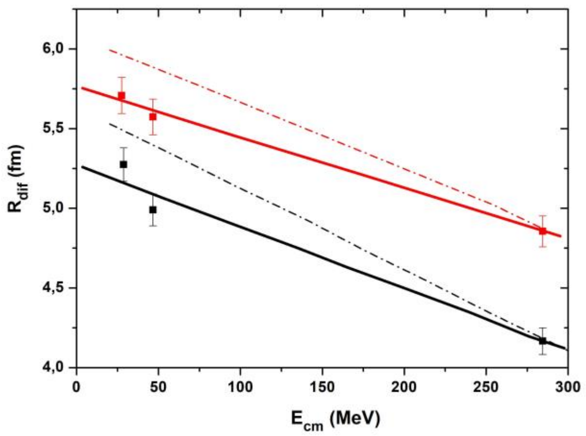

Figure 3. Energy dependence of diffraction radii: black dash-dotted line – diffraction radii for elastic scattering α + ^{12}C, red dash-dotted line – for 7.65 Hoyle state, black squares with bars – for elastic α + ^{11}B, black solid line – linear fit for the black squares, red squares with bars – for 8.56 MeV state, red solid line – linear fit for the red squares [16].

Indeed, the results obtained in some earlier works at higher energies [8, 16] and obtained in this paper (Table 1) turned out to be close and are in reasonable agreement with the predictions of cluster theories.

Thus, the obtained result together with our previous results at higher energy clearly indicate to the similarity of the structures of the 8.56 MeV state of ^{11}B and the Hoyle state of ^{12}C and we could assert that this excited state is an analog of the Hoyle state.

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