STUDY OF DIFFRACTION CLUSTER PROCESSES IN THE $d+{}^{11}$B REACTION WITH AN ENERGY OF 14.5 MeV*

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To study the ^{11}B cluster states, in this work, experiments were carried out on the elastic scattering of 14.5 MeV deuterons by ^{11}B at the U-150M cyclotron (INP, Almaty, Republic of Kazakhstan) phase analysis (PFA). Using the PFA from oscillations of Fraunhofer-type diffractions of experimental angular distributions of differential cross sections of elastically scattered ions on target nuclei, the parameters of the S-matrix were determined by the method of fitting using the unique minimum Pearson values for ten pairs of free parameters of the theory. The paper presents experimental data on the elastic scattering of deuterons with $E_d = 14.5$ MeV on the ^{11}B target for the ground state in comparison with experimental world data. From the performed analysis, the values of the interaction radii and the blurring of the edge of the ^{11}B nucleus were obtained.

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1. Introduction

At present, cluster models are widely studied to describe the structure of the lungs [1–3], medium, and exotic nuclei [4]. Such models make it possible to explain the nonuniform radial distribution of the nuclear matter density, which can manifest itself in the form of anomalously large radii. It is confirmed by the presence of a halo of exotic nuclei [5] or "looseness"

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of the nucleus from the point of view of the dynamic formation of nucleon associations inside the nucleus. Historically, the foundation for the creation of such a microscopic theory of cluster systems was laid in [6]. A description of the differential cross section of the cluster structure of atomic nuclei in the framework of the Born approximation was proposed in [7], and the role of cluster configurations in atomic nuclei was studied, in particular, in [8].

In this work, we performed experimental studies on the interaction of a deuteron beam with an ^{11}B target, accelerated to an energy of 14.5 MeV at the U-150M cyclotron. Measurements of the cross sections of scattering processes were carried out on the extracted deuteron beams in a scattering chamber, the geometry of which and its spectrometric characteristics are given in [9].

2. Theoretical analyses

The possibility of the existence of a cluster structure of boron isotopes was first shown in [10], where, based on the molecular-orbital model, these nuclei were described as consisting of a core including two alpha particles, a proton and neutrons around them. In [11], when studying the ^{11}B nucleus, a model was used in which the nucleus was represented in the form of $^7\mathrm{Li}(t+a)+a$.

One of the methods for the experimental detection of a multicluster structure is described in [12–16]. The authors presented the decomposition of the experimental angular distributions of differential cross sections for the elastic diffraction scattering into multicluster components (amplitudes), on which, with appropriate statistical weights, incident particles are quasi-elastically scattered. In [17], the analysis of the contributions of channels with large angular momenta was carried out in the framework of the DWBA model, taking into account the cluster approximation to describe the transfer process, as a result of which quasi-molecular states were shown at resonance energies. In [18], indications were obtained of the possible existence of a compact excited state of the ^{13}C nucleus with a radius smaller than the radius of the ground state, within the framework of a modified diffraction model, which indicates further studies of the formation of cluster states. In [19], an empirical relationship was found between the alpha-cluster effect manifested in the form of light $4n$ nuclei as a parameter of the nuclear quadrupole deformation and its sign. The modulus of nuclear quadrupole deformation was extracted from the nuclear matrix element by the method of complex angular momenta [19] from the following relation:

$$|\beta_2| = \frac{2.24|C_1(2)|}{l_0/k - 2.6}\,, \tag{1}$$

where all designations are generally accepted and are defined in [19].

The matrix element is extracted from fitting the free parameters of the theory to the experimental cross sections for the elastic scattering and inelastic scattering (with excitation of collective states) of incident particles on the nucleus under study

$$|C_n(I)|^2 = \frac{4\pi(n!)^2}{k^{2n}(2I+1)\left(\theta^2-\theta_C^2\right)^n}\frac{\left[\sigma_I^{(n)}(\theta)\right]_{\max}}{\left[\sigma_0^{(0)}(\theta)\right]_{\max}}\,, \tag{2}$$

where all designations are generally accepted and are defined in [19].

In this work, to detect clustering, a parametrized phase analysis was used, which has the uniqueness of the fitted parameters in the scattering matrix to determine the nuclear phases of partial waves. The theoretical approach for identifying multicluster structures in ^{11}B with the elastic scattering of deuterons was applied within the framework of the diffraction theory, in the form of expansion in partial waves, which is a rigorous mathematical formalism with respect to the elastic scattering

$$A(\theta) = \frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)(\mathrm{e}^{2i\eta_l}-1)P_l(\cos(\theta))\,, \tag{3}$$

where the phase η_l in the case of scattering of charged particles has two components — the Coulomb σ_l and nuclear δ_l phases, the rest of the notation is generally accepted (4)

$$\eta_l = \sigma_l+\delta_l\,, \tag{4}$$

$$A(\theta) = \frac{1}{2ik}\sum_{l=0}^{\infty}(2l+1)S_l\mathrm{e}^{2i\sigma_l}P_l(\cos(\theta))\,, \tag{5}$$

where the S_l-matrix is defined as follows [20]:

$$S_l = \frac{1}{1+\mathrm{e}^{\frac{l_1-l}{\lambda_1}}} + i\frac{b}{ch^2\left(\frac{l-l_2}{\lambda_2}\right)}\,, \tag{6}$$

and $b, l_1, l_2, \lambda_1, \lambda_2$ — free parameters that reflect the contribution of the corresponding nuclear mechanisms. The real part of the matrix describes nuclear scattering, and the imaginary part describes nuclear absorption. Thus, the free parameters of the real part of the matrix are sensitive to the diffraction scattering, both on the nucleus itself and its substructures.

In this work, a graphical view of the real and imaginary parts of the S-matrix (6) is shown in figure 1.

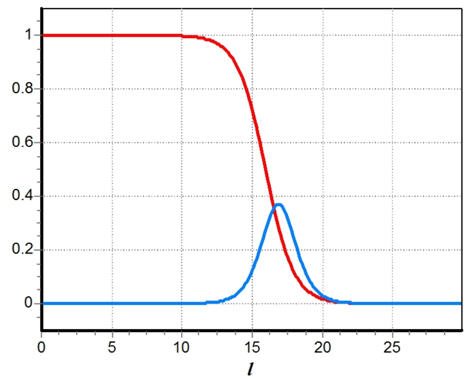

Fig. 1. S-matrix of the form of (6).

Using the method of fitting according to the unambiguous minimum values of the χ^2-maps for ten pairs of free parameters of the theory, the values were obtained according to the equation

$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{(\sigma_i)_{\mathrm{T}} - (\sigma_i)_{\mathrm{Exp}}}{\Delta(\sigma_i)_{\mathrm{Exp}}}\right]^2, \tag{7}$$

where $(\sigma_i)_{\mathrm{T}}$ and $(\sigma_i)_{\mathrm{Exp}}$ — calculated and experimental values of differential cross sections for a given angle θ, N is the number of measured points. The fitting results are shown in Fig. 2.

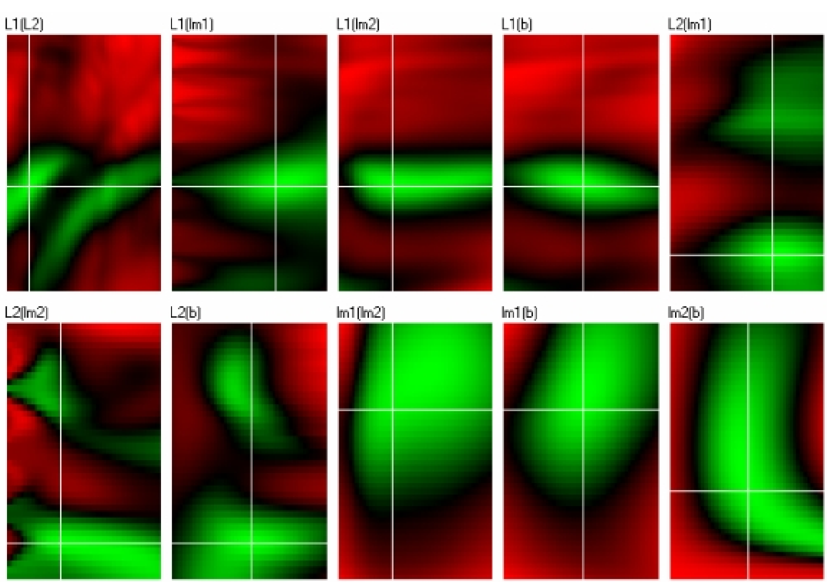

Fig. 2. χ^2-maps for ten pairs of free theory parameters.

The number of partial waves over which the summation took place in (5) was selected for each reaction optimal. On average, this value did not exceed 20–25.

From the free parameters, the interaction radius was determined as [19]

$$R_{\rm int} = \frac{1}{k}\left(n + \sqrt{n^2 + l_1(l_1+1)}\right) , \tag{8}$$

where k — wavenumber; n is the Coulomb parameter, and the diffuseness of the nucleus edge is defined as

$$\Delta R = \frac{2.2(2l_1+1)\lambda_1}{k\left(n + \sqrt{n^2 + l_1(l_1+1)}\right)} . \tag{9}$$

3. Results and discussion

As a result of the fittings, the optimal free parameters of the S-matrix were obtained, as well as the interaction radii and the blurring of the core edge (Table I). The obtained optimal parameters were used to calculate the differential cross sections of the angular distributions of elastic scattering of 14.5 MeV deuterons at ^{11}B. Such calculations were carried out and systematized for other energies according to the experimental data of the world literature. Figure 3 shows these taxonomies.

TABLE I

Optimal free parameters and radii of interaction and blurring of the edge of the ^{11}B nucleus in the elastic scattering of deuterons with different energies.

E [MeV]	l_1	l_2	λ_1	λ_2	b	χ	$R_{\rm int}$ [fm]	$\Delta R_{\rm int}$ [fm]
11.8	3.559	3.432	1.106	1.305	0.495	0.695	4.824	5.064
13.6	3.529	3.432	1.166	1.465	0.449	0.466	4.543	5.003
14.5	3.755	3.569	1.205	1.405	0.419	0.667	4.518	5.214
18.0	3.785	3.655	1.545	1.872	0.306	0.913	4.051	5.823
21.5	4.169	3.905	1.696	1.990	0.325	0.888	4.011	5.896
27.7	4.119	4.355	1.996	1.765	0.331	1.073	3.477	6.146

Figure 4 shows the radii of interaction and blurring of the edge of the ^{11}B nucleus for the elastic scattering of deuterons with different energies. It can be seen that the blurring of the edge of the nucleus increases with the energy of the incident deuterons. Thus, for example, the ^{9}Be nucleus has an anomalously large value of the diffuseness of the nucleus edge. Considering

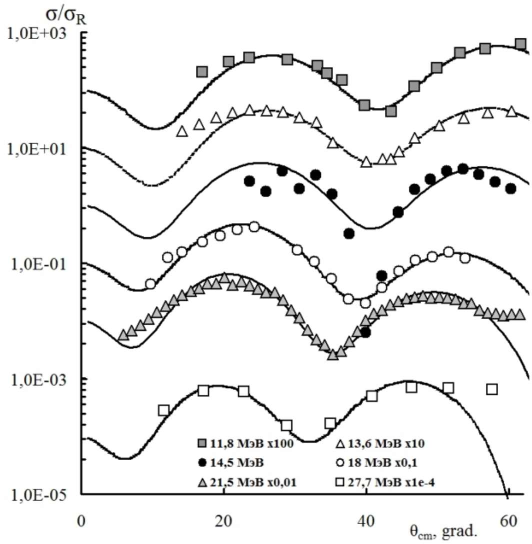

Fig. 3. Experimental data (points) and theoretical curves (curves) of differential cross sections of the angular distributions of elastic scattering of deuterons at ^{11}B.

the ^{9}Be nucleus as $\alpha + \alpha + n$, the binding neutron has an orbit much larger than the radius of the nucleus. This, in turn, is reflected in the optimal parameter λ_1, which is associated with the diffuseness of the core edge (9). This conclusion is indirectly confirmed by the ambiguity of Jung's schemes. In addition, the probe particle itself is a "loose" deuteron with a binding energy of only 2.2 MeV. The "looseness" of the probe particle, apparently, contributes to the value of the diffuseness of the edge of the nucleus.

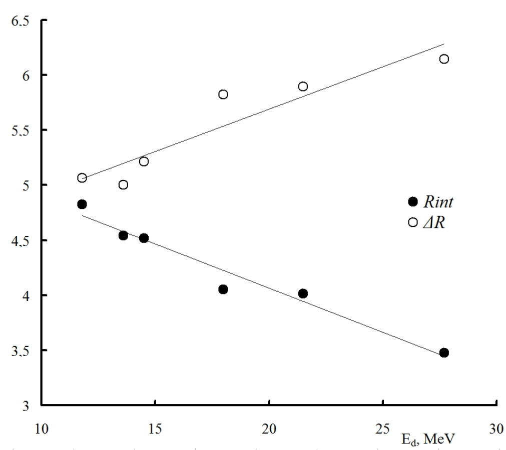

Fig. 4. Interaction radii and blurring of the edge of the ^{11}B nucleus in the elastic scattering of deuterons with different energies.

Figure 5 shows the dependence of some light nuclei, for which the diffuseness values of the nucleus edge were calculated in this work, on the modulus of quadrupole nuclear deformation known for these nuclei, taken from the CDFE base (Center for Photonuclear Experiments Data). According to [19], it can be assumed that in some cases there should be a direct dependence of the diffuseness of the nuclear edge on the modulus of nuclear quadrupole deformation, taking into account, of course, the fact that the contribution of the wave functions of noncluster components is very large [21].

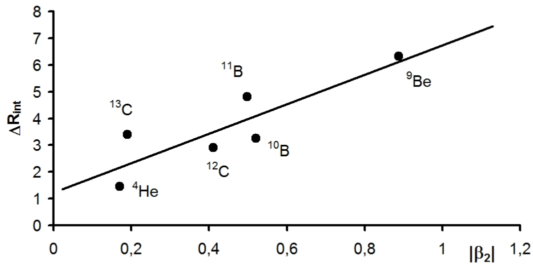

Fig. 5. Dependence of diffuseness of the nuclear edge on the modulus of nuclear quadrupole deformation.

Figure 6 shows the dependences of some optimal free parameters of matrix (6) on the energy of incident deuterons on ^{11}B. It can be seen that at a deuteron energy of 18 MeV, the nuclear mechanism changes, after which the blurring of the nuclear edge sharply increases, and the contribution of

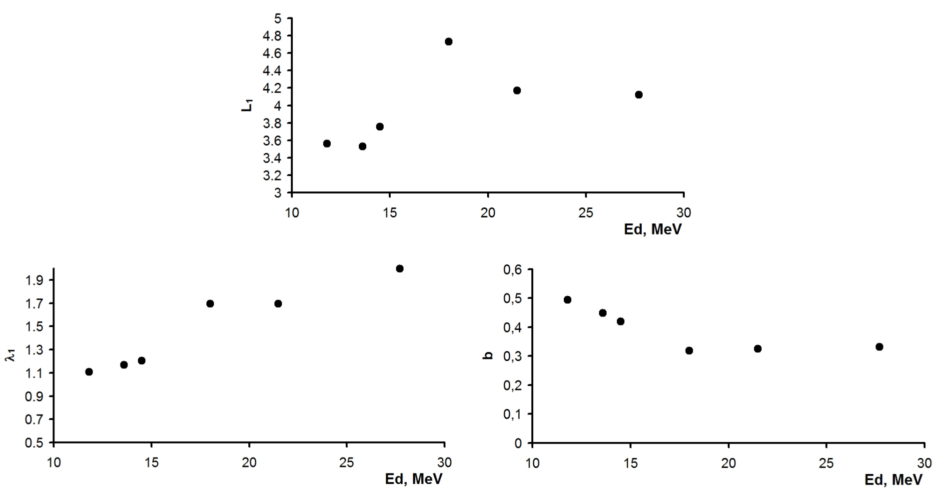

Fig. 6. Dependence of the free parameter l_1 (top), λ_1 (bottom left), and b (bottom right) on the energy of incident deuterons at ^{11}B.

nuclear absorption decreases. Most likely, this is due to the fact that the contribution of the partial scattering waves on the $\alpha + \alpha + t$ system begins to increase with respect to the scattering on the ^{11}B nucleus as a whole.

4. Conclusions

From the analysis performed, the optimal values of the free parameters of the theory, the values of the interaction radii and the blurring of the edge of the ^{11}B nucleus were obtained. Figure 4 shows that with an increase in the energy of the incident deuterons, the blurring of the "looseness" of the nucleus increases. It is shown that at a deuteron energy of 18 MeV, the nuclear mechanism changes, after which the blurring of the nuclear edge sharply increases, and the contribution of nuclear absorption decreases. The points falling out of the main linear trend (Fig. 4), most likely, can be explained by resonance scattering on nuclear clusters.

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