EFFECT OF CLUSTER POLARIZATION ON THE SPECTRUM OF THE ^{6}Li NUCLEUS*

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The main purpose of this research is to study the nature of resonance states in the ^{6}Li nucleus, and effects of cluster polarization on the spectrum of bound and resonance states. The cluster polarization is associated with changes of the size and shape of clusters (interacting nuclei) as they approach each other. To achieve these goals, a microscopic three-cluster model is used. This model takes into account two three-cluster configurations: ^{4}He+$p+n$ and ^{3}H+$d+p$, which are then projected into four binary channels: ^{4}He+d, ^{5}He+p, ^{5}Li+n, and ^{3}H+^{3}He. These three-cluster configurations made it possible to describe more precisely the internal structure of the d, ^{5}He, ^{5}Li, and ^{3}He clusters, and to take into account their polarizability. It is shown that the used model reproduces well the spectrum of low-lying states of ^{6}Li. It is found that cluster polarization strongly affects the structure of the bound and resonance states, and significantly changes their energy and width.

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1. Introduction

In this work, the ^{6}Li nucleus is considered, which has one bound state and several resonance states, with the positive and negative parity. The existing resonance states of the positive parity are concentrated near the threshold for the breakup of the ^{6}Li nucleus into ^{4}He+d and have low energy of excitation. Resonance states of the negative parity lay above the ^{6}Li breakup threshold through the ^{3}H+^{3}He channel, on the other hand, have a high energy (more than 17 MeV above the ground state). All this

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makes the nature of these resonance states very interesting and challenging. The growing number of recent experimental data [1, 2] also confirms the wide interest of many research groups in the problems of thermonuclear reactions involving the ^{6}Li nucleus. Besides, the ^{6}Li nucleus participates in important for astrophysical applications thermonuclear reactions such as ^{3}H+^{3}He $\rightarrow$ ^{4}He+d and ^{4}He+d $\rightarrow$^{6}Li+γ, which stimulate the study of both the nature of the bound and resonance states manifested in it and the main factors of their formation. As a consequence, various microscopic and semi-microscopic models have been used to study these resonances and effects in the ^{6}Li nucleus. However, in most of the used methods either resonance states with low energy, or only with high energy, have been investigated. This stimulated us to modify the existing microscopic method [3] for studying many-cluster and many-channel systems for the theoretical analysis of resonance states of both types in ^{6}Li. The modified method is a three-cluster version of the resonating group method, which expands the wave functions of the relative motion of clusters in terms of the square-integrable (Gaussian and oscillator) basis functions. The main feature of this method is that two three-cluster configurations are used to study the ^{6}Li nucleus: ^{4}He+$p+n$ and ^{3}H+$d+n$, which allows, on the one hand, to more accurately describe the internal structure of clusters and, on the other hand, take into account cluster polarization. Polarization is a phenomenon in which light nuclei can change their shape and size when interacting with other nuclei. This phenomenon, which manifests itself in the interactions of light nuclei, depends on the binding energy measured from the lowest threshold of its disintegration and can be considered as the elasticity or softness (polarizability) of the nuclei. Since many light nuclei have small binding energies, they can be polarized when interacting with other nuclei. Therefore, it can be expected that polarization effects will be important in reactions involving such light nuclei (clusters) as d, ^{3}He, ^{5}He.

2. Results and discussion

To carry out the necessary calculations and to realize the designed plan, we modified a microscopic three-cluster model which is called Algebraic Model of three-cluster system with the Gaussian and Oscillator Basis (AMGOB) and was formulated in [4, 5]. Previously, this model involved only one three-cluster configuration and thus was able to consider not more than three binary channels. However, to describe the ^{6}Li nucleus under study in a wide energy range, we were forced to use two three-cluster configurations: ^{4}He+$p+n$ and ^{3}H+$d+p$. The first three-cluster configuration ^{4}He+$p+n$ generates three binary channels: ^{4}He+d, ^{5}He+p and ^{5}Li+n. The second three-cluster configuration ^{3}H+$d+p$ also creates three binary chan-

nels: ^{4}He+d, ^{5}He+p, ^{3}H+^{3}He, two of which have already been created by the first three-cluster configuration. Thus, attracting two three-cluster configurations, we have at our disposal four binary channels: ^{4}He+d, ^{5}He+p, ^{5}Li+n, and ^{3}H+^{3}He. These binary channels allow us to study the structure of the ground and excited states, as well as various processes in a wide range of energies. The indicated three-cluster configurations made it possible to more accurately describe the internal structure of clusters: d, ^{5}He, ^{5}Li, and ^{3}He, as well as to take into account their polarizability.

Calculations of the ^{6}Li spectrum are performed with the semi-realistic Minnesota nucleon–nucleon potential [6, 7], which contains the central and spin-orbit components. This potential is often used in many-cluster calculations, which will allow us to substantively compare the results of our model with the results of other alternative models.

After choosing the nucleon–nucleon potential, we have to determine the only parameter of the model — the oscillator radius b. This parameter is the same for all clusters and determines the distribution density of nucleons in each cluster consisting of two or more nucleons. In our calculations, the oscillator radius was chosen $b = 1.285$ fm, this value of b gives the minimum energy of an alpha particle with the Minnesota potential. Two parameters — the intensity of the exchange forces u and the intensity of the spin-orbit interaction f_{LS} of this potential are often used as fitting parameters. In our calculations, we use the following values of these parameters: $u = 0.863$ and $f_{LS} = 1.123$. They make it possible to describe with good accuracy the bound state of the ^{6}Li nucleus: $E_0 = -1.474$ MeV.

All calculations are carried out taking into account the cluster polarization (P) and without taking it into account (N). As a result, two sets of numerical data are obtained describing the bound and excited states of the ^{6}Li nucleus. These two data sets, together with the available experimental data (Exp.) [8], are presented in Table I. They clearly demonstrate the ef-

TABLE I

Influence of cluster polarization on the bound and resonance states in ^{6}Li. Energies E and widths Γ are in MeV.

	P		N		Exp. [8]	
J^π	E	Γ	E	Γ	E	Γ
1^+	-1.474		-0.249		-1.4743	
3^+	0.711	0.0204	1.741	0.284	0.712 ± 0.002	0.024 ± 0.002
2^+	3.259	1.612	3.913	2.237	2.838 ± 0.022	1.3 ± 1.00
	4.962	0.812	5.262	1.41	3.892 ± 0.015	0.541 ± 0.020
1^+	3.974	2.812	4.108	3.919	4.176 ± 0.050	1.5 ± 0.2

fects of cluster polarization in the spectrum of the ^{6}Li nucleus. As we can see, cluster polarization plays an important role in the formation of bound and low-energy resonance states in ^{6}Li. Allowance for cluster polarization leads to a significant energy shift (more than 1 MeV) of the ground state and the 3^+ resonance state. Due to cluster polarization, the energy of the 3^+ resonance state is decreased by about 2.6 times and the total width is diminished by almost 10 times. For the broad resonance 1^+ and 2^+ states, the effect of cluster polarization is not so significant. The quality of the calculation of the wave function of the ^{6}Li ground state and the merits of the model can be checked by calculating the root-mean-square radius. The results of calculations of the proton R_p, neutron R_n, and mass R_m root-mean-square radii are shown in Table II. It also shows the results of calculations in other microscopic models and available experimental data. As we can see, the AMGOB model quite satisfactorily describes the experimental data for the root-mean-square radii of the ^{6}Li nucleus. In addition, the results of the AMGOB model are compatible with those of other models. The relationship between the values: R_p, R_n, R_m, obtained in the AMGOB model, indicates that the state with isospin $T = 1$ has a significant weight in the wave function of the ^{6}Li ground state.

TABLE II

Proton, neutron, and mass root-mean-square radii of the ^{6}Li ground state, determined by different methods.

Method	R_p [fm]	R_m [fm]	R_n [fm]
AMGOB	2.522	2.480	2.501
Csótó, Lovas [9, 10]	2.643		
Horiuchi, Suzuki [11]	2.41		2.27
Arai *et al.* [12]	2.44	2.44	2.44
Exp. [13]	2.32 ± 0.03	2.32 ± 0.03	2.32 ± 0.03
Exp. [14]	2.54 ± 0.03	2.54 ± 0.03	2.54 ± 0.03

Figure 1 compares the phase shifts of elastic ^{4}He+d scattering for the 2^+ and 3^+ states obtained within the framework of this three-cluster model and within the two-cluster model realized in Ref. [5]. In both cases, the parameters of the Minnesota potential were tuned to reproduce the energy of the ^{6}Li ground state. Figure 1 shows that the phase shifts of the 3^+ states practically coincide, while the phase shifts for the 2^+ state are noticeably different. Further, the phase shifts of elastic ^{3}H+^{3}He scattering were considered. Figures 2 and 3 show the phase shifts for 2^- and 3^- states, which were obtained in the single-channel approximation (1C), in the two-channel

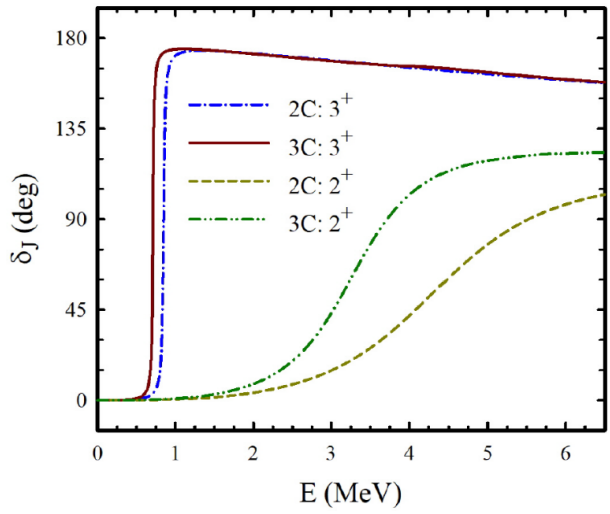

Fig. 1. Phase shifts of elastic ^{4}He+d scattering obtained in two-cluster (2C) and three-cluster (3C) models for 2^+ and 3^+ states.

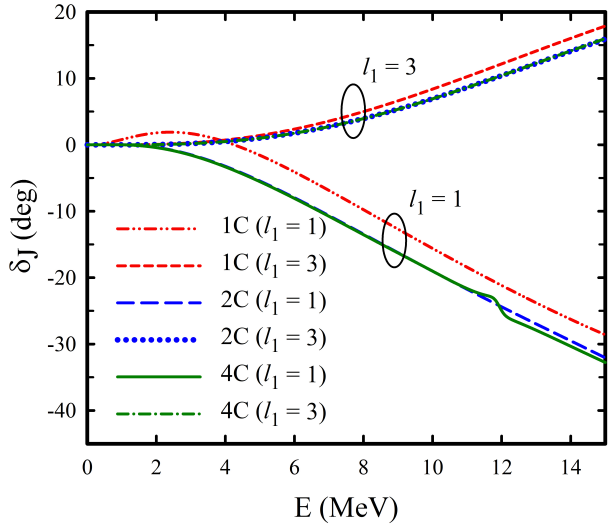

Fig. 2. Phase shifts of elastic ^{3}H+^{3}He scattering in the 2^- state, in the single-channel (1C), two-channel (2C), and four-channel (4C) approximations.

approximation (2C) with coupled ^{3}H+^{3}He and ^{4}He+d channels, as well as in the four-cluster approximation (4C). The partial orbital momentum l_1 is the relative orbital momentum of ^{3}He around ^{3}H. The results presented in figures 2 and 3 were obtained without taking into account cluster polarization. As can be seen from figures 2 and 3, there is a weak coupling

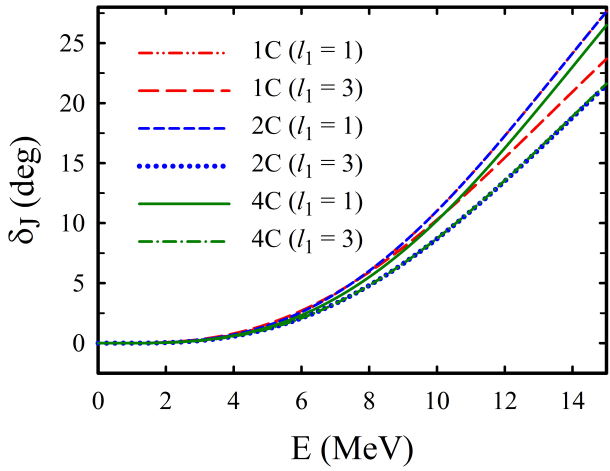

Fig. 3. Phase shifts of elastic ^{3}H+^{3}He scattering in 3^- states, calculated in single-channel (1C), two-channel (2C), and four-channel (4C) approximations.

between the channels in the energy region above the ^{3}H+^{3}He thresholds. Indeed, the phase shifts of ^{3}H+^{3}He elastic scattering obtained in the 1C approximation differ somewhat from the phase shifts obtained in the 2C and 4C approximations. New channels (^{4}He+d, ^{5}He+p, ^{5}Li+n) added to the ^{3}H+^{3}He channel slightly decrease the phase shifts determined in the 1C approximation. This situation is completely different from what we observed above for elastic scattering of ^{4}He+d at low energies. The slow growth of phase shifts indicates the presence of very wide 2^- and 3^- resonance states.

3. Conclusions

In this work, we have investigated the structure of the bound and low-lying resonance states of the ^{6}Li nucleus. The study has been carried out within the framework of a microscopic three-cluster model. This model took into account two main three-cluster configurations ^{4}He+$p+n$ and $t+d+p$. With their help, four binary channels were involved in the calculations: ^{4}He+d, ^{5}He+p, ^{5}Li+n ^{3}H+^{3}He. Besides, this model made it possible to more accurately describe the internal structure of the deuteron and nuclei ^{5}He, ^{5}Li, ^{3}He, which were presented as two-cluster systems $p+n$, ^{4}He+n, ^{4}He+p, $d+p$, respectively. It also allows to take into account the polarizability of nuclei: d, ^{5}He, ^{5}Li, ^{3}He. It is shown that cluster polarization plays a huge role in the formation of the ground state, as well as 3^+, 2^+, and 1^+ resonance states. For example, it decreases the ground state and narrows 3^+ resonance by more than 1 MeV. In addition, cluster polarization reduces the total width of the 3^+ resonance state by almost 14 times. It is also shown

that the used model reproduces quite well many observable quantities, such as the energies of bound and resonance states, resonance widths, and also the charge and mass root-mean-square radii of the ^{6}Li ground state.

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REFERENCES

[1] N. Burtebayev *et al.*, *Acta Phys. Pol. B* **50**, 703 (2019).

[2] S.B. Sakuta *et al.*, *Acta Phys. Pol. B* **45**, 1853 (2014).

[3] V.S. Vasilevsky, F. Arickx, J. Broeckhove, T.P. Kovalenko, *Nucl. Phys. A* **824**, 37 (2009).

[4] A.V. Nesterov, V.S. Vasilevsky, T.P. Kovalenko, *Phys. Atom. Nuclei* **72**, 1450 (2009).

[5] V.S. Vasilevsky, A.V. Nesterov, T.P. Kovalenko, *Phys. Atom. Nuclei* **75**, 818 (2012).

[6] D.R. Thompson, M. LeMere, Y.C. Tang, *Nucl. Phys. A* **286**, 53 (1977).

[7] I. Reichstein, Y.C. Tang, *Nucl. Phys. A* **158**, 529 (1970).

[8] D.R. Tilley *et al.*, *Nucl. Phys. A* **708**, 3 (2002).

[9] A. Csótó, R.G. Lovas, *Phys. Rev. C.* **46**, 576 (1992).

[10] A. Csótó, R.G. Lovas, *Phys. Rev. C.* **49**, 3035 (1994).

[11] W. Horiuchi, Y. Suzuki, *Phys. Rev. C.* **76**, 024311 (2007).

[12] K. Arai, Y. Suzuki, K. Varga, *Phys. Rev. C.* **51**, 2488 (1995).

[13] I. Tanihata *et al.*, *Phys. Lett. B* **289**, 261 (1992).

[14] I. Tanihata *et al.*, *Phys. Rev. Lett.* **55**, 2676 (1985).