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Possible existence of neutron-proton halo in ^{6}Li

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Abstract

One of the most recent results was the determination of the proton halo in the first excited state of the ^{13}N nucleus using of an analog of the MDM method for the charge exchange reactions (^{3}He, t). It turned out that this state has the same radius as the mirror state 1/2^{+}, 3.09 MeV in ^{13}C.This observation allows us to take the next step and try to apply this approach to measure the radii of states. The increased radii in the isobar - analogue states of the ^{6}He-^{6}Li-^{6}Be triplet, which may also have a halo structure, are not excluded. As a first step, we analyzed the published differential cross sections for inelastic scattering of ^{3}He + ^{6}Li with the excitation of the 2.19 MeV, 3^{+} state at energies 34 and 72 MeV and 3.56 MeV, 0^{+} state at energies 24.6 and 27 MeV. Probably the state 0^{+}, 3.56 MeV has the same radius as its ”Borromian” isobar analogue ^{6}He and is neutron-proton halo. The predicted enlarged radius because of the more extended wave function p - n, apparently, does not take place. We recall that the spatial structure of the ^{6}He nucleus was predicted to be quite complex, in which correlations of two types appeared: ”cigar” and ”dineutron”. The question arises: does the structure of the state change so much when passing from ^{6}He to the isobar-analogue in ^{6}Li, which requires the introduction of a special kind of “tango-halo”.

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1. Introduction

The first studies of the neutron halo led to the discovery of completely new nuclear configurations. In particular, this statement applies to three-particle systems near the neutron stability boundary. The most popular structure here was the so-called the Borromian scheme in which each pair of particles does not form a bound cluster (for example, in the nucleus ^{11}Li, considered as^{9}Li + n + n, ^{10}Li and the dineutron are not connected), and together they form a nucleus stable with respect to neutron emission. A large number of papers have been devoted to the study of the Borromian structures (see, for example, reviews [1]). Along with the Borromian structures were

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also discussed those in which one of the three pairs turned out to be loosely related. To emphasize the difference between the latter and other three-particle halos, it was suggested to call such configurations, including similar objects in atomic and molecular physics, "tango-halo" [2].

There were few candidates for belonging to the "tango-halo" in the nuclear physics (see review [3]). For example, they referred to the nucleus ^8B [3], considered as a ^7Be cluster (the binding energy of ^3He + ^4He is 1.59 MeV), plus the proton forming a halo, whose binding energy is only 137 keV. The question to what extent the correlated motion of ^3He and ^4He in composition ^8B determines the halo properties and whether it is impossible to consider this problem simply as a two-body remained open. Nevertheless, the term "tango - halo" has been preserved in some recent articles [4].

One of the most interesting and accessible to research is the ^6Li nucleus. Its three lower states have the configuration α + p + n. In the ground state, 1^+ nucleons are combined into a deuteron, and ^6Li has a well-defined quasimolecular structure "alpha particle" plus deuteron. The review [3] formally refers this state to tango-halo, referring to the correlated motion of the proton and neutron in the deuteron and the absence of bound states of α + p and α + n. True, it is stipulated that in this case it is not entirely correct to speak of any halo, since the deuteron itself is quite compact (the binding energy of ^2H = p + n is 2.2 MeV), and the distance to the decay threshold $^6Li \rightarrow {}^4He$ + p + n is large (3.7 MeV).

The first excited state of 2.19 MeV, 3^+ lies above the threshold $^6Li \rightarrow \alpha + d$ (1.474 MeV) and under the threshold $^6Li \rightarrow {}^4He$ + p + n. Most likely the conservation of the structure of the ground state with the difference that the deuteron now has an orbital momentum L = 2.

As far as we know, the question of a halo (deuteron or proton-neutron) in this state has not been discussed.

The second excited state is 3.56 MeV, $0^+$is only 14 keV under the decay threshold $^6Li \rightarrow {}^4He$ + p + n, and it is quite natural to expect a proton-neutron halo in it. Obviously, in the "singlet" deuteron in the alpha-particle field, the p-n correlation is significant, and according to the classification [3], this halo refers to the "tango" type. The latter was predicted [5] on the basis that the calculated distributions of the nucleon densities in it and in the isobar-analog ground state ^6He, which already knew the presence of a two-neutron halo, are very close.

Thus, all three lower ^6Li states are associated with the halo problem, in particular, with its "tango" variety. The presence of a halo in the 0^+ state does not raise any doubts. However, up to now there have been no experimental data on the most important characteristic, which makes it possible to identify the halo radii of the excited states under discussion.

The purpose of this paper was to determine the radii of these states using the Modified diffraction model [6], analyzing data on inelastic and elastic scattering. To determine the radius of the 3.56-MeV state, only the data [7] on elastic and inelastic scattering of ^{3}He + ^{6}Li at the energies of 24.6 and 27.0 MeV satisfied the necessary requirements. To determine the radius of the state 3^{+}, 2.19 MeV, the data of [8] were used. The cross sections for elastic scattering were taken from [9].

2. Methods of analysis

Calculations of the cross sections for elastic scattering were carried out using a semi-microscopic dispersion optical model of SMDOM [10]. For monitoring, we compared the calculations made by the coupled channel method [8] and obtained additional confirmation that the minima/maxima of the angular distributions used in the MDM analysis are indeed diffraction.

Calculations of the inelastic scattering cross sections were performed by the distorted wave method using the DWUCK4 [11] code. In the case of inelastic scattering, the phenomenological approach was used in the state 0^{+}, (3.56 MeV), in which the inelastic form factor is represented by the derivative of the optical potential of the input channel with arbitrary normalization for each transferred moment L. For the target nucleus, the density obtained in the three-particle model was used [12].

The radii of the excited states were determined from the position of the diffraction minima/maxima of inelastic and elastic scattering. According to MDM [6], for RMS radius of the excited state $<R^{*}>$, we get:

$$< R* > = < R_0 > + [R^{*}(dif) - R_{0.0}(dif)], \qquad (1)$$

where $<R_0>$ is the root-mean-square radius of the ground state, and the terms in square brackets are the diffraction radii of inelastic and elastic scattering cross sections correspondingly.

3. Results and its discussion

One of the most recent results was the development of an MDM analog for the charge exchange reactions (^{3}He, t), the use of which made it possible to determine the proton halo in the first excited state of the ^{13}N nucleus [13]. It turned out that this state has the same radius as the mirror state $1/2^{+}$, 3.09 MeV in ^{13}C, in spite of the fact that one of them lies under the neutron emission threshold, and the second one is above the proton emission threshold. This observation allows us to take the next step and try to apply this approach to measure the radii of isobar - analogue states.

The study of triplets and mirror states in doublets makes it possible to significantly expand knowledge of the halo. In many cases, the left-handed triplet members have a neutron halo in the ground or excited states. Therefore, there is every reason to believe that right-handed members can also have a proton halo. However, the wave function of the valence proton due to the presence of the Coulomb barrier can differ greatly from the wave function of the neutron analog, and the appearance of a proton halo is not obvious. Moreover, the right-hand members of triplets and doublets are often unstable. Until now, the theory has not considered a halo in the continuum or, at least, it was thought to be of a different type. Comparing the right and left terms, one can obtain an inaccessible wound material about the halo in a discrete and continuous spectrum (there is already an example of A = 13). A special place is occupied by the average members of triplets with the same number of neutrons and protons. In them, a new type of halo (pn) is possible, which makes it possible to study the transition from the Borromian halo to tango (A = 6), see Figure 1.

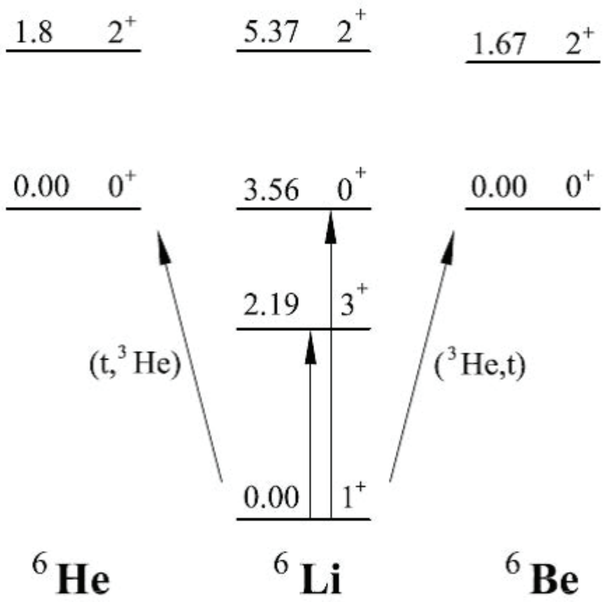

Figure 1: The states of the triplet ^{6}He - ^{6}Li - ^{6}Be are presented. 0$^+$, g.s. of ^{6}He, 0$^+$, 3.56 MeV of ^{6}Li and 0$^+$, g.s. of ^{6}Be are isobar-analogues.

Among these triplet states, the neutron halo in^{6}He is well known. A proton-neutron halo is predicted in the excited state of 0$^+$, 3.56 MeV in ^{6}Li, which lies only 137 keV below the ^{6}Li → ^{4}He + p + n threshold. Its radius is not known, but it is predicted by about 0.25 Fm larger than the radius of ^{6}He [5]. We can expect the appearance of a two-proton halo in the ground state of ^{6}Be. The table shows the known radii of states shown in Figure 1.

Table 1: The RMS radii of states ^{6}Li and ^{6}He (g.s.).

Nucleus	E^* (MeV)	I^π	R_{rms} (fm)	Ref.
^{6}Li	0.00	1^+	2.36 ± 0.03	[1]
^{6}Li	3.56	0^+	2.73 **(predicted)**	[5]
^{6}He	0.00	0^+	2.50 ± 0.05	[1]

Figure 2 shows examples of cross sections for elastic and inelastic scattering (with 3^+, 2.19 MeV excited state) as a function of the momentum transfer q.

In the case of a one-step diffraction mechanism, the cross sections of a particular process, measured at different energies, must coincide. In the experiment, there is some difference, both between the data itself and with the theoretical calculations, which indicates an admixture of other reaction mechanisms. Nevertheless, on the whole, a good description of the angular distributions of elastic scattering of ^{3}He + ^{6}Li in the range of angles is obtained, where the role of elastic transmission is unimportant.

In the case of equality of the diffraction radii, the minima/maxima in the elastic and inelastic scattering cross sections must be in antiphase, since the $1^+ \rightarrow 3^+$ transition requires the momentum transfer L = 2. As can be seen from Fig.2, a shift of the extremes in inelastic scattering toward the smaller q indicates an increased diffraction radius of this process in comparison with elastic scattering. The calculated radius for 2.19 MeV is increased by ∼ 0.46 Fm in comparison with the ground state radius ^{6}Li. The effect is most likely associated with the addition of centrifugal energy (L = 2) to the ground state. The known width of the state is in good agreement with the estimate of the penetrability of a centrifugal barrier.

Figure 3 shows the differential cross sections for elastic and inelastic scattering of ^{6}Li + ^{3}He with excitation of the 0^+, 3.56 MeV state at energies of ^{3}He 24.6 and 27 MeV [7]. The nature of the inelastic scattering cross section is determined by two allowed moments L = 0 and L = 2. The positions of the minima/maxima of both components are close (except for the first extreme) and should be in antiphase with the elastic scattering cross section, which is observed experimentally. Thus, DWBA approach satisfactorily reproduces the positions of the minima/maxima, and this in principle is sufficient for the application of MDM in order to obtain diffraction radii and, respectively, the RMS radii.

The resulting radius for the state 0^+, 3.56 MeV in ^{6}Li practically equals to the radius of the ground state of its "Borromian" isobar analogue ^{6}He. It is equal 2.49 ± 0.16 Fm.

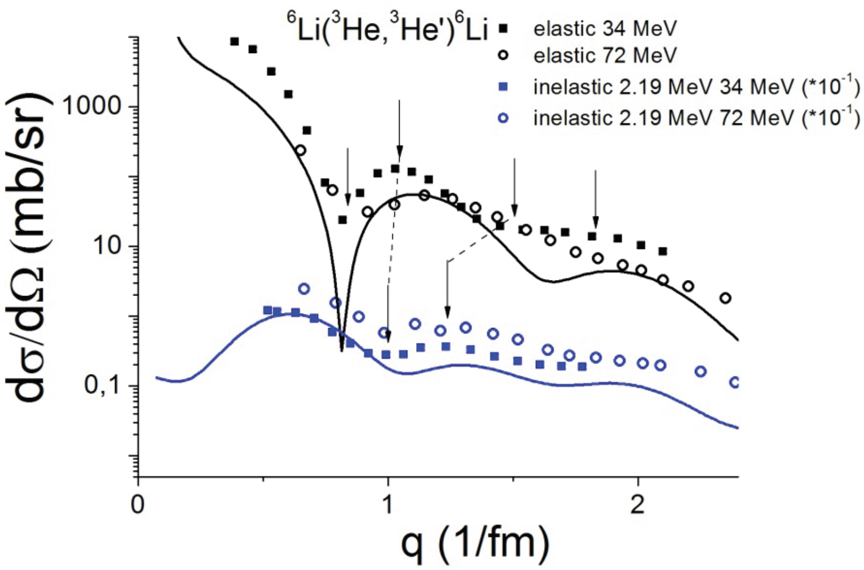

Figure 2: Differential cross sections for elastic and inelastic (with 2.19 MeV, 3^+ excited state) scattering of ^{6}Li + ^{3}He at energies of ^{3}He 34 and 72 MeV [9], depending on the momentum transfer. The curves were obtained as a result of calculations based on the optical model and the distorted wave method for energy 34 MeV. The arrows denote the minima/maxima of the angular distributions over which the diffraction radii were determined. The dashed lines connect corresponding extremes in elastic and inelastic scattering.

It can be said preliminary that 0^+, 3.56 MeV state in ^{6}Li is "Borromian" also and is neutron-proton halo.

We can not yet confirm the increase in the radius predicted in [5]. Enlarged radius for the 3.56 MeV state was obtained due to more spatially extended proton distribution. It is reasonable because of the Coulomb repulsion. Thus, the transition from the Borromian to the “tango” structure does not change the radius of the state. We recall that the spatial structure of the ^{6}He nucleus was predicted to be quite complex [12], in which correlations of two types appeared: "cigar" and, "dineutron. In this connection, the question arises: does the structure of the state change so strongly when passing from ^{6}He to the isobar - analogue in^{6}Li that requires the introduction of a special type of “tango – halo”. The similar stability of the radius to the change in the wave function was also observed in the other case in mirror states in ^{13}C-^{13}N having halo [13]: the first of them (1/2 $^+$, 3.09 MeV) is bound, and the second (1/2 $^+$, 2.37 MeV) is located in the continuum.

On Figure 4 the diffraction radii of elastic scattering are ^{3}He + ^{6}Li and inelastic with the excitation of 2.19 and 3.56 MeV states in the ^{6}Li nucleus are presented as a function of energy. For comparison, the energy dependence of the diffraction radii of elastic scattering ^{6}Li + ^{12}C are also shown.

The energy dependence of the diffraction radii for lithium data has the following peculiarity: in the low-energy region the diffraction radii decrease rather steeply, but in the medium-energy region they already reach the plateau. Moreover, experimental data for 3.56 MeV state exist only at two close low energies of 24.6 and 27 MeV. Therefore, it is advisable to carry out an experiment at medium energies in the plateau region.

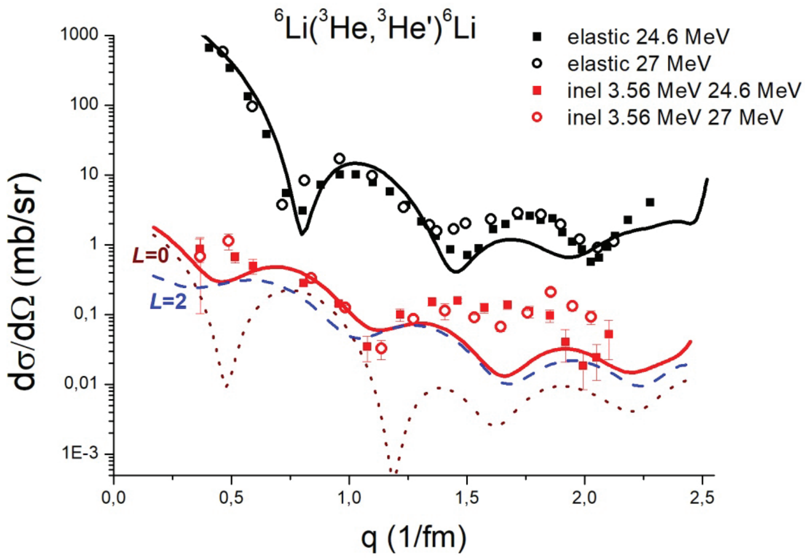

Figure 3: Differential cross sections for inelastic scattering with excitation of the 3.56 MeV state (red squares at ^{3}He 24.6 MeV and red open circles at ^{3}He 27 MeV) and elastic scattering (black squares at ^{3}He 24.6 MeV and open circles at ^{3}He 27 MeV). The curves correspond to DWBA calculations with *L* = 0 (dotted curve) and *L* = 2 (dashed line) and incoherent sum of their (solid red curve) for energy ^{3}He 24.6 MeV. Solid black curve corresponds to optical model calculations for elastic scattering at ^{3}He 24.6 MeV.

In perspective it is important a measurements of the cross sections for the reaction ^{6}Li (^{3}He, ^{3} He ′) ^{6}Li at other large energies of ^{3}He ions in the plateau region(Fig.4), which would allow us to determine the radius of the 3.56 MeV state in ^{6}Li more exactly and with a smaller error.

As a next step it is possible to study the first excited states of the ^{6}He, ^{6}Be and third exited state in ^{6}Li, which may also have a halo structure (see fig.1). The increased radii for them are not excluded. A new method with the aid of the reaction (^{3}He, t) is necessary to use for determination the radius ^{6}Be. It is also necessary to show the universality of this method. Consideration of other isobar-analog triplets can lead to unexpected results.

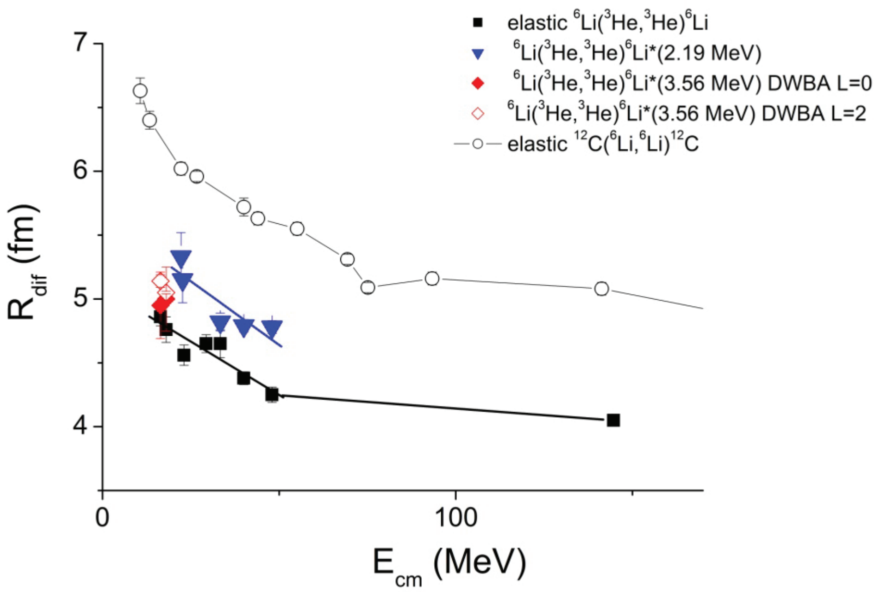

Figure 4: The diffraction radii of elastic scattering (black squares) ^{3}He + ^{6}Li and inelastic with the excitation of 2.19 MeV (blue triangle and 3.56 MeV (closed, L=2 and open, L=0 red rhombus) states as a function of energy. For comparison, the energy dependence of the diffraction radii of elastic scattering ^{6}Li + ^{12}C are also shown.

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