NEW CASES OF HALO IN ISOBAR-ANALOG STATES*

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The purpose of this research is to search and study halo in isobar-analog states of light nuclei. The study of states with a halo in isobar analogs allows one to investigate the manifestation of isotopic invariance at new objects and to relate the properties of the neutron and proton halo. The question of the existence of halo in isobar-analog states has so far not been practically raised in the experimental plan. The proposed approach is based on measuring the radii of states in which the halo exists or can exist. The data on the radii can give new information for solving the long-standing problem of a single description of the halo in both parts of the spectrum — discrete and continuous. We propose to solve problem: experimentally determine the radii of a number of states in which there can be a halo in nuclei, forming isobar-analog doublets and triplets. We have discovered new possible candidates for a halo in the isobar-analog multiplets $A = 12$ and $A = 14$. First, most of the states lie in the continuous spectrum. Second, the results were obtained within the framework of two independent methods: ANC and MDM. A great achievement was the development of the ANC method for studying resonance states, which made it possible to identify new cases of a proton halo in isobaric analog states.

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1. Introduction

One of the most striking discoveries in nuclear physics made at the end of the last century was the discovery of a neutron halo in the ground states of

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some light nuclei [1] located near the neutron stability boundary. The halo manifests itself in the presence of a diffuse surface region surrounding the core with normal nuclear density and containing only neutrons. The result of this is a long "tail" of their wave functions and, accordingly, an increase in the radius of the entire nucleus in a given state. Until recently, it was believed that a halo can be formed only in radioactive nuclei located near the boundaries of stability, and practically only in ground states. However, back in the late 1950s, long before the discovery of the halo, Baz [2] actually predicted the possibility of its appearance even in the stable nuclei near the thresholds of neutron emission. The first indication of the presence of a neutron halo in a stable ^{13}C nucleus in its first excited state of 3.09 MeV, $\frac{1}{2}^{+}$ was obtained in [3] and confirmed by us in [4]. It turned out that the area the existence of a halo is much wider than previously thought: the halo was found in nuclei not only located at the boundaries of stability, but also far from it; not only in ground states [5], but also in excited states [3, 4]. Of particular interest is the accumulating information that states with halo properties can be found not only in the discrete spectrum, but also in the continuum [6, 7], and the problem of their unified description was formulated as one of the most important [5].

The discovery of the halo led to a revision of many established concepts and the emergence of a new direction of research in nuclear physics. The very name "exotic nuclei" arose in connection with the neutron halo. At present, many dozens of experimental and theoretical works are devoted to the halo problem, which continues to be studied intensively. The most recent reviews on this topic are published in [5, 8]. Moreover, it is obvious that unusual neutron correlations can take place in the halo, for example, of the "dineutron condensate" type proposed in [9]. By the type of valence nucleon, the halo can be proton or neutron. The proton halo is quite a rare phenomenon. We recently discovered a proton halo in an unbound ^{13}N state with an energy of 2.37 MeV, $\frac{1}{2}^{+}$ [10] which is a mirror state with respect to the ^{13}C state with an energy of 3.09 MeV with a confirmed neutron halo. This was the third case of identification of a one-proton halo, previously reported on the detection of a proton halo in ^{8}B [11] and ^{17}F [12].

The purpose of this research is to search and study the halo in isobar-analog states of light nuclei. Our group is one of the first who started works in this area. Isobaric invariance leads to the fact that the states of two neighboring nuclei obtained by replacing a neutron with a proton and having the same quantum numbers, including isospin, are analogous, *i.e.* they have in the first approximation the same structure and radii. In the case of isobaric analogs having a halo, the situation is more complicated: replacing the neutron in the halo state with a proton does not necessarily lead to the appearance of a similar proton structure. The fact is that the appearance of a halo is determined by the proximity of the valence nucleon to the emission threshold, and it can be very different for a neutron and a proton.

The study of states with a halo in isobar analogs allows one to investigate the manifestation of isotopic invariance at new objects and to relate the properties of the neutron and proton halo. The question of the existence of halo in isobar-analog states has so far not been practically raised in the experimental plan. The proposed approach is based on measuring the radii of states in which the halo exists or can exist. The data on the radii can give new information for solving the long-standing problem of a single description of the halo in both parts of the spectrum — discrete and continuous. We propose to solve the problem: experimentally determine the radii of a number of states in which there can be a halo in nuclei, forming isobar-analog doublets and triplets.

The study of halo in isobaric-analog (IAS) states led to very interesting results. Until now, such studies have hardly been carried out. Nucleon transfer reactions and charge-exchange reactions appear to be optimal reactions for searching for halos in IAS. Nucleon transfer reactions are traditionally used to obtain information on single-particle (sp) states, spectroscopic factors (SF), asymptotic normalization factors (ANC), and nucleus–nucleus optical potentials. In addition, these reactions are widely used to find states with increased radii. Charge-exchange reactions, in particular the $(^3\mathrm{He}, t)$ reaction [13], can also be used to obtain information on the radii of states. Their advantage lies in the possibility of studying unbound states in a continuous spectrum. It should be noted that the interpretation of the halo in excited states located above the particle emission threshold remains an open question. Since there is no possibility of a quantitative calculation of the weight of the asymptotic part of the nucleon wave function, when describing an unbound state, difficulties arise when comparing its asymptotic and internal parts.

The radii of short-lived particle-unstable states cannot be measured in traditional ways. Only non-direct methods (electron scattering form factors, CC, DWBA) existed until recently. Our group has developed methods for studying halos in isobar-analog states. They include two main methods: the Asymptotic Normalization Coefficient (ANC) method [4] and the Modified Diffraction Model (MDM) method [14]. The first method works with peripheral transfer reactions and has previously been used only for bound states. The second method was originally used for unbound states, but was developed for the elastic and inelastic scattering data. During the consideration of specific isobar-analog multiplets, both methods were refined, which made it possible to obtain a whole group of new results on the halo.

The ANC method was developed for application to resonance states located near the nucleon emission threshold. Unlike MDM, which gives only the radius of the state under consideration, the ANC method allows one to obtain information about the structure of the state: the probability of finding a valence nucleon outside the range of the potential (D1), as well as the weight of the asymptotic part in the root-mean-square radius (D2).

The ANC calculations of the cross sections for unbound states are performed with scattering wave functions corresponding to resonant nucleon scattering. The asymptotic parts of the resonance wave function are described in terms of their S-matrix elements. To calculate the form factor of the resonant state, a resonant wave function with averaged energy is used, the so-called "bin" wave function [15].

2. Triplet ^{12}B–^{12}C–^{12}N

The first object of the study was the IAS 2^- and 1^- states with isospin $T = 1$ in triplet of ^{12}B, ^{12}C, and ^{12}N nuclei. All these states are located near the nucleon emission thresholds.

In [16], the discovery of neutron halo was announced for the 1.67 MeV, 2^- and 2.62 MeV, 1^- states in ^{12}B. To determine the radii of the excited states of ^{12}B, the ANC method was used [16]. However, the result was obtained only at one energy, which is not very reliable. Therefore, to verify this result and expand the existing information on low-lying excited states of ^{12}B, our group carried out an experiment to study the ^{11}B(d, p)^{12}B reaction at $E(d) =$ 21.5 MeV. The experiment was done at the K130 cyclotron of the University of Jyväskyla, Finland. The aim of the experiment was to obtain angular distributions for low-lying excited states of ^{12}B with $E^* < 4$ MeV. One of the difficulties of the experiment was the need to separate two neighboring states: 2.62 MeV, (1^-) and 2.72 MeV, (0^+). Therefore, prior to the experiment, the beam was monochromatized [17], which made it possible to reduce the energy spread in the beam by several times. Observation of halos in 2^- and 1^- states in ^{12}B was confirmed. The ANC method was used for halo radius extraction $R_{\mathrm{h}} = 4.01 \pm 0.61$ and 5.64 ± 0.90 fm, respectively. The results of our analysis are present in [18].

To study the ^{12}N levels, the ^{12}C(^{3}He, t)^{12}N experiment was carried out by us at $E(^3\mathrm{He}) = 40$ MeV. The experiment was also done at the K130 cyclotron of the University of Jyväskyla, Finland. The obtained experimental data were analyzed together with the available literature data [19, 20] using the MDM method [13]. It was shown that the root-mean-square radii for the 2^-, 1.19 MeV and 1^-, 1.80 MeV ($T = 1$) states in ^{12}N are increased: for the 2^-, 1.19 MeV state — 2.8 ± 0.2 fm, for the 1^-, 1.80 MeV state — 3.3 ± 0.2 fm. The obtained radii, within the limits of errors, coincided with the data on the radii for the IAS states at ^{12}B. This result was obtained for the first time and is presented in [21]. The last studied objects of the multiplet $A = 12$ were the 2^- and 1^- states in ^{12}C. To study them, new experimental data were obtained on the reaction $^{11}\mathrm{B}(^3\mathrm{He}, d)^{12}\mathrm{C}$, $E(^3\mathrm{He}) = 25$ MeV with the excitation of high-lying ^{12}C states 15.11 MeV 1^+, 16.57 MeV 2^- and 17.23 MeV 1^-. The obtained angular distributions of the differential reaction cross sections were analyzed within the coupled channel method for direct proton transfer into bound and unbound states.

The radii of the valence proton were determined using ANC for all states under study: for the 16.57 MeV, 2^- state, 6.76 ± 0.35 fm, and 17.23 MeV, 1^- state, 7.05 ± 0.35 fm, while the radius of the valence proton in the ground state was 2.9 ± 0.1 fm. Thus, for the considered states, the radius of the valence proton is more than twice times larger than the radius of the valence proton in the ground state. Moreover, the coefficient D1, which determines the probability of finding a valence nucleon outside the range of the potential, is 52% for the 1^- state and 47% for the 2^- state. The formal condition for a halo is the excess of the D1 coefficient over 50%. Thus, the proton halo was confirmed for the 17.23 MeV, 1^- state. For the 16.57 MeV, 2^-– state, we assume the presence of a halo-like state. The r.m.s. for these states were also determined: 16.57 MeV, 2^- 2.88 ± 0.13 fm and 17.23 MeV, 1^- 2.94 ± 0.13 fm. Within the limits of errors, the obtained radii coincide with the radii of the IAS of the 2^- and 1^- states in ^{12}B and ^{12}N. The results are published in [15] and [21].

Thus, we revealed that ^{12}B, ^{12}N, and ^{12}C in the IAS with $T = 1$ and spin-parities 2^- and 1^- have increased radii and exhibit properties of neutron and proton halo states.

3. Triplet ^{14}C–^{14}N–^{14}O

Two independent methods, ANC and MDM, were used to analyze the IAS states with isospin $T = 1$ in the triplet ^{14}C, ^{14}N, and ^{14}O. All calculations gave the same increased root-mean-square radii (coinciding within the error limits) for all three nuclei in these 1^- states: (2.7 ± 0.1) fm for ^{14}C, (2.67 ± 0.07) fm for ^{14}N, and (2.6 ± 0.2) fm for ^{14}O. Moreover, the ANC analysis showed signs of a proton halo in the 8.06 MeV state 1^- at ^{14}N. This result was obtained for the first time. Previously, the neutron halo was confirmed for the 6.09 MeV 1^- state in ^{14}C. As for the 1^- state in ^{14}O, so far the only argument in favor of the halo is the obtained increased radius. Our prospective future experiment will allow us to check this result and draw a final conclusion about the possibility of a halo in this state. The analysis results are presented in [22].

4. Conclusion

Our results confirm that the halo phenomenon is universal and manifests itself not only in the ground states of exotic nuclei, but also in the excited states of ordinary light nuclei. This statement is based on the increased radii obtained in our works by different methods, as well as the obtained large values of the probability of finding a valence nucleon, neutron or proton outside the range of the interaction radius. A great achievement was the development of the ANC method for studying resonance states, which made it possible to identify new cases of a proton halo in isobaric analog states.

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