Pis'ma v ZhETF, vol. 112, iss. 8, pp. 499 – 500

Search for signs of neutron and proton halos in the isobaric analog excited states of A = 14 nuclei

A. S. Demyanova+1), *A. N. Danilov*+, *A. A. Ogloblin*+, *S. A. Goncharov**, *T. L. Belyaeva*×, *W. H. Trzaska*°, *V. I. Starastsin*+

+*National Research Centre Kurchatov Institute, 123182 Moscow, Russia*

**Lomonosov Moscow State University, 119991 Moscow, Russia*

×*Universidad Autónoma del Estado de México, 50000 Toluca, México*

°*Department of Physics, University of Jyväskylä, FI-40014 Jyväskylä, Finland*

Submitted 4 September 2020
Resubmitted 4 September 2020
Accepted 16 September 2020

DOI: 10.31857/S1234567820200021

One of the most striking discoveries in nuclear physics made at the end of the past century was the finding the neutron halo in the ground states of some light nuclei [1] located near the neutron stability boundary. The halo manifests itself in the presence of a diffuse surface region surrounding a core with a normal nuclear density and containing only neutrons. The result is a long "tail" of their wave function and, correspondingly, an increase in the radius of the entire nucleus in a given state.

Until recently, it was believed that the halo can be formed only in the ground states of radioactive nuclei located near stability boundaries. It turned out that the region of existence of the halo is much wider than previously thought: the halo was found in nuclei not only located near the stability boundaries, but also far from it; not only in the ground states [2], but also in the excited states [3, 4]. Of particular interest is the accumulation of information that states possessing halo properties can be located not only in the discrete spectrum, but also in the continuum [5], and the problem of their unified description is formulated as one of the most important [2]. Besides the neutron halo, the proton halos in ^{8}B [6], ^{17}F [7], and ^{13}N [8] were observed.

The purpose of this article is to search and study nucleonic halo in the isobaric analog states (IASs) of the $A = 14$ nuclei. This allows one to investigate the manifestation of isotopic invariance at new objects and to relate the properties of the neutron and proton halos. The data on the radii can give new information for solving the long-standing problem of a unified description of the halo phenomenon in both parts of the spectrum, discrete and continuous. Our group is one of the first who started works in this area.

The IASs with isospin $T = 1$ in triplet of the $A = 14$ nuclei: ^{14}C, ^{14}N, and ^{14}O, are of particular interest from the point of view of one-nucleon halo formation.

In [9], Liu carried out the ANC analysis of the ^{13}C(d, p)^{14}C data at $E(d) = 17.7$ MeV [10] and revealed that the 6.09-MeV 1^- and 6.90-MeV 0^- states of ^{14}C satisfy the neutron halo criteria. It was shown that the radius of the valence neutron separation is approximately two times larger (4.57 and 5.78 fm, respectively) than the size of the core (2.48 fm). The probability of the valence neutron to be outside the nuclear force range (D_1) and the contribution of the asymptotic part of the wave function to the *rms* radius (D_2) are, respectively, greater than 50 and 90 % for the 6.09-MeV 1^- and 6.90-MeV 0^- states in ^{14}C. So, a strict definition of neutron halo is fulfilled.

The observation of neutron halo in the 1^- state of ^{14}C can be used as an argument in favor of a possibility of a proton halo in the 1^- IASs of ^{14}N and ^{14}O. We can expect the formation of a proton halo in the 8.06-MeV 1^- state of ^{14}N and the 5.17-MeV 1^- state of ^{14}O located in the vicinity of the proton emission threshold.

The proposed approach of determining exotic structure is based on measuring the nuclear radii. In our group, several methods are developed to be used for measuring radii of nuclei in the short-lived excited states: the MDM [11], the ANC method [3, 4], and the nuclear rainbow method (NRM) [12]. The ANC method is the most appropriate to measure halo radii.

Our preliminary MDM analysis of the elastic and inelastic α + ^{14}C scattering data at $E(\alpha) = 35$ MeV [13] shows that the 6.09-MeV 1^- state has an increased ra-

---

[1] e-mail: a.s.demyanova@bk.ru

dius. Extrema positions for the 6.09-MeV 1^- state are shifted towards smaller angles as compared to the curve extracted from the elastic scattering data. This result is a consequence of an increased radius. We have found that the *rms* radius of ^{14}C in the 6.09-MeV 1^- state is equal to 2.7 ± 0.1 fm. We determined the radius of valence neutron to be equal ≈ 6 fm, slightly larger than the result of the ANC calculations [9].

In order to study the 1^-, 8.06-MeV state of ^{14}N, we use the literature data of the $^{13}\mathrm{C}(^3\mathrm{He}, \mathrm{d})^{14}\mathrm{N}$ reaction [13] and analyze them by the coupled-reaction-channels (CRC) method, implying a finite-range one-neutron direct transfer mechanism in the post representation by using the code FRESCO [14].

The 1^-, 8.06-MeV excited states of ^{14}N is localized only 0.51 MeV above the proton emission threshold and belongs to the continuum spectrum. In order to determine the radius of ^{14}N in this state, we carry out the ANC calculation with a small positive proton binding energy ($\varepsilon = -0.1$ MeV). Thus, we can determine the *rms* radius of the last proton by determining the *rms* radius of the *sp* wave function. It is found to be $R_p = 5.9 \pm 0.3$ fm (the channel radius R_N is taken as 5.0 fm). The D_2 coefficient achieves 90 %. The proton transfer reaction to this state is definitely peripheral, though the D_1 coefficient is lower than 50 %.

The corresponding *rms* matter radii of ^{14}N in the state is found equal to R_{rms} (1^-, 8.06 MeV) $= 2.67 \pm \pm 0.07$ fm and is increased relatively to the radius of ^{14}N in its ground state (g.s.), R_{rms} (g.s.) $= 2.47$ fm [15]. The great values of D_1 and D_2 coefficients and the increased *rms* radius indicate the presence of proton halo in the 8.06-MeV 1^- state of ^{14}N. This result is obtained for the first time. It should be also mentioned that the *rms* radius of the 8.06-MeV 1^- state of ^{14}N is very close to the value obtained by the MDM for the 6.09-MeV 1^- state of ^{14}C.

We carry out the MDM analysis of the differential cross sections of the $^{14}\mathrm{N}(^3\mathrm{He}, \mathrm{t})^{14}\mathrm{O}$ reaction leading to the 0^+ g.s. and the excited 5.17-MeV 1^- states of ^{14}O at $E_{\mathrm{lab}} = 44.6$ [16] and 420 MeV [17] and estimated its value as 2.6 ± 0.2 fm.

Two independent methods, the ANC and the MDM, were used for analysis of the isobaric analog states with isospin $T = 1$ in triplet of the $A = 14$ nuclei: ^{14}C, ^{14}N, and ^{14}O. All calculations gave the similar enhanced *rms* matter radii (within the error bars) for all three nuclei in these 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 the signs of a proton halo in the 8.06-MeV 1^- state of ^{14}N. This result was obtained for the first time. Previously neutron halo was confirmed for the 6.09-MeV 1^- state of ^{14}C. In order to answer the question whether a proton halo exists in the corresponding state of ^{14}O, one requires a more complete theoretical analysis, which is still in progress.

This work was supported by Russian Science Foundation 18-12-00312.

Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364020200011

---

1. I. Tanihata, H. Hamagaki, O. Hashimoto, S. Nagamiya, Y. Shida, N. Yoshikawa, O. Yamakawa, K. Sugimoto, T. Kobayashi, D. E. Greiner, N. Takahashi, and Y. Nojiri, Phys. Lett. B **160**, 380 (1985).
2. I. Tanihata, H. Savajols, and R. Kanungo, Prog. Part. Nucl. Phys. **68**, 215 (2013).
3. Z. H. Liu, C. J. Lin, H. Q. Zhang, Z. C. Li, J. S. Zhang, Y. W. Wu, F. Yang, M. Ruan, J. C. Liu, S. Y. Li, and Z. H. Peng, Phys. Rev. C **64**, 034312 (2001).
4. T. L. Belyaeva, R. Perez-Torres, A. A. Ogloblin, A. S. Demyanova, S. N. Ershov, and S. A. Goncharov, Phys. Rev. C **90**, 064610 (2014).
5. A. A. Ogloblin, A. N. Danilov, A. S. Demyanova, S. A. Goncharov, T. L. Belyaeva, and W. Trzaska, in *Nuclear Particle Correlations and Cluster Physics*, World Scientific, Singapore (2017), p. 311.
6. R. E. Warner, J. H. Kelley, P. Zecher, F. D. Becchetti, J. A. Brown, C. L. Carpenter, A. Galonsky, J. Kruse, A. Muthukrishnan, A. Nadasen, R. M. Ronningen, P. Schwandt, B. M. Sherrill, J. Wang, and J. S. Winfield, Phys. Rev. C **52**, R1166 (1995).
7. Zh. Dongmei, Zh. Yongnan, Yu. Daqing, Zh. Xizhen, Z. Yi, T. Minamisono, M. Matsuta, M. Fukuda, M. Mihara, Zh. Chunlei, W. Zhiqiang, Du. Enpeng, L. Hailong, X. Guoji, and Zh. Shengyun, J. Phys. G: Nucl. Part. Phys. **34**, 523 (2007).
8. A. S. Demyanova, A. A. Ogloblin, S. A. Goncharov, A. N. Danilov, T. L. Belyaeva, and W. Trzaska, Phys. Atom. Nucl. **80**, 831 (2017).
9. Z. H. Liu, Chin. Phys. Lett. **19**, 1071 (2002).
10. R. J. Peterson, H. C. Bhang, J. J. Hamill, and T. G. Masterson, Nucl. Phys. A **425**, 469 (1984).
11. A. N. Danilov, T. L. Belyaeva, A. S. Demyanova, S. A. Goncharov, and A. A. Ogloblin, Phys. Rev. C **80**, 054603 (2009).
12. A. S. Demyanova, A. A. Ogloblin, S. A. Goncharov, and T. L. Belyaeva, Int. J. Mod. Phys. E **17**, 2118 (2008).
13. R. J. Peterson and J. J. Hamill, Nucl. Phys. A **362**, 163 (1981).
14. FRESCO user's manual and code, available from the author.
15. A. Ozawa, T. Suzuki, and I. Tanihata, Nucl. Phys. A **693**, 32 (2001).
16. G. C. Ball and J. Cerny, Phys. Rev. **155**, 1170 (1967).
17. A. Negret, T. Adachi, B. R. Barrett et al. (Collaboration), Phys. Rev. Lett. **97**, 062502 (2006).