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Isospin triplet A=14: search for states with enhanced radii

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Abstract. This article is devoted to study of isobar-analogue states 1^- in triplet A=14: ^{14}C - ^{14}N - ^{14}O . Previously signs of neutron halo in the 1^- , 6.09 MeV state of ^{14}C were obtained by two independent groups. In this article we propose to study neighbouring nuclei ^{14}N and ^{14}O using the Modified diffraction model (MDM) method and the method of Asymptotic normalization coefficients (ANC). Methods were applied to experimental differential cross sections of $^{14}\text{C}(\alpha,\alpha)^{14}\text{C}$ scattering and reactions $^{13}\text{C}({}^3\text{He},d)^{14}\text{N}$ and $^{14}\text{N}({}^3\text{He},t)^{14}\text{O}$. MDM and ANC gave practically similar within errors radii for the studied 1^- states: the 6.09 MeV state in ^{14}C – 2.7 ± 0.1 fm, the 8.06 MeV state in ^{14}N – 2.7 ± 0.1 fm, the 5.17 MeV state in ^{14}O – 2.6 ± 0.2 fm. Moreover, the signs of proton halo in the 1^- state of ^{14}N were obtained for the first time.

1. Introduction

Discovery of the neutron halo in the ground states of some light nuclei [1] was one of the most striking discoveries in nuclear physics made at the end of the last century. The halo is characterized by a presence of a diffuse surface region, surrounding a core with a normal nuclear density, and containing only neutrons. As a result, halo has an increased radius.

According to [2–6] the halo signs are (i) a large probability for finding a cluster component in the total many-body wave function and (ii) a large spatial extension implying that more than half of the probability should be in the classically forbidden region outside the outer classical turning point. These are quite strict requirements, and it is important to answer the question of whether realistic halos satisfy these criteria and how the halo features appear in less-developed halos.

Until recently, it was believed that the halo can be formed only in radioactive nuclei located near stability boundaries, and practically only in the ground states.

Not so far the evidence of the excited states of light nuclei with nonstandard sizes and enlarged radii, located closely and above the particle-emission threshold, was convincingly demonstrated (see, e.g., [7] and references therein). The existence of neutron halos in the short-lived excited states of some stable and radioactive nuclei was revealed, in particular, by the ANC analysis of the neutron-transfer reactions [8,9]. Recently Liu and collaborators [10] observed signs of neutron halo for states 6.09 MeV, 1^- and 6.90 MeV, 0^- in ^{14}C . This result was obtained in ANC analysis of experimental data $^{13}\text{C}(d,p)^{14}\text{C}$ at $E(d) = 17.7$ MeV [11]. They showed that radius for the valence neutron is ~ 2 times larger (4.57 and 5.78 fm correspondingly) than the size of their core (2.48 fm) and the probability of the valence neutron to be outside the nuclear force range (coefficient D_1) and the contribution of the asymptotic part of the wave function to the RMS radius (coefficient D_2) are, respectively, greater than 50% and 90% for both cases. So, strict definition of halo is fulfilled.



Independently, in the paper by Mezhevych [12] the 6.09 MeV, 1^- state was observed and an increased radius for the valence neutron was determined to be 5.16 fm (2 times larger than radius of the core). Observation of neutron halo in the 1^- state of ^{14}C can be used as argument for the possibility of a proton halo in isobar analogue states (IAS) 1^- in ^{14}N and ^{14}O . We can expect the formation of a proton halo in the IAS states in triplet A=14: ^{14}N (8.06 MeV, 1^-) and ^{14}O (5.17 MeV, 1^-) in the vicinity of the proton emission threshold, shown by red in figure 1.

The proposed approach of determining exotic structure is based on measuring the nuclear radii. Our group has several methods that can be used for radius determination of short-lived excited states: Modified Diffraction Model (MDM) [13], Asymptotic Normalization Coefficients (ANC) method [8,9], and Nuclear Rainbow Method (NRM) [14]. The ANC method is the most adequate method to measure a halo radius. Unfortunately, the ANC method is applicable only to bound states. In case of unbound states, we propose to use MDM. The use of the MDM method requires differential cross section data from inelastic scattering measurements. However, not all excited states can be populated through scattering or would require implementation of radioactive beams. In any case, it is highly desirable to find a more universal method for measuring radii of proton rich states and for performing proton-halo searches. We propose to use charge-exchange reactions for that purpose. Its first usage was rather successful [15].

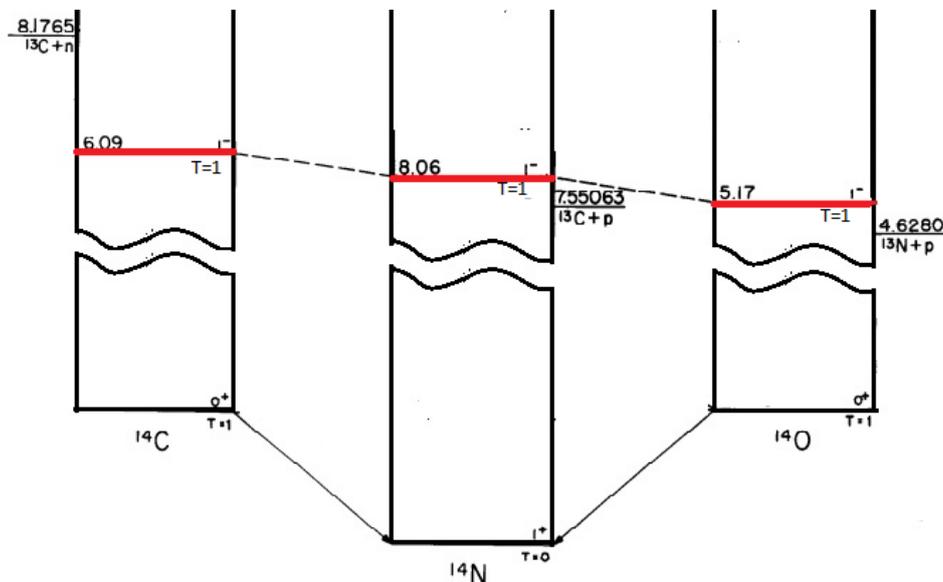


Figure 1. Triplet A=14. The red thick lines indicate possible halo states.

2. Methods of radius determination

2.1. MDM application to charge-exchange reactions

In order to measure nuclear radii in unbound states, we propose to use the MDM [13] for the analysis of inelastic differential cross sections. However, not all excited states can be populated through inelastic scattering. It has been known for a long time that charge-exchange reactions have much in common with inelastic scattering [16]. We therefore propose to extend MDM approach to $(^3\text{He},t)$ reactions. In case of charge-exchange reactions, in the plane wave approximation, the cross sections are described by spherical (rather than by cylindrical in case of scattering) Bessel function, so:

$$\frac{d\sigma}{d\Omega} \sim [j_L(qR)]^2 \quad (1)$$

where q is the linear transferred momentum and R is the radial parameter. In accordance with (1), extrema of experimental angular distributions are associated with squared extrema of a Bessel function of the corresponding order depending on the transferred linear momentum. On base of this, diffraction radius is determined, which is the only parameter of the model.

Direct application of the MDM would involve a comparison of the inelastic and elastic scattering. In analogy with the scattering, in case of charge-exchange reactions, the RMS radius of the excited state is estimated using practically the same formula

$$\langle R^* \rangle = \langle R_0 \rangle + [R_{dif}^* - R_{dif}(0)] \quad (2)$$

where $\langle R_0 \rangle$ is the presumably known root-mean square radius of the nucleus in the ground state, R_{dif}^* is the diffraction radius determined from the positions of the minima and maxima of experimental angular distributions of (${}^3\text{He}, t$) reaction with excitation of corresponding state. As for the ground-state diffraction radius, $R_{dif}(0)$, it should be determined in accordance with the MDM procedure, in the case of the ${}^{14}\text{N}({}^3\text{He}, t){}^{14}\text{O}$ reaction, from elastic scattering of ${}^3\text{He}$ or ${}^3\text{H}$ on ${}^{14}\text{O}$, but, as mentioned above, this is almost impossible. Therefore, it is proposed to use elastic ${}^3\text{He} + {}^{14}\text{N}$ scattering. Since the radii of the ground states of ${}^{14}\text{N}$ and ${}^{14}\text{O}$ have close values, their diffraction radii should only differ by a correction, which takes into account the fact that the Coulomb interaction in the exit channels is different for the triton and ${}^3\text{He}$ nucleus.

There are convincing arguments to apply MDM to charge-exchange reactions for the study of isobar analog states. We have first applied this approach to determine the proton halo in an unbound state of ${}^{13}\text{N}$ [15], more detailed description is present in [17].

2.2. ANC method

ANC method [18] is developed especially for peripheral reactions and can be adequately applied for describing the properties of the short-lived excited states. In particular, the ANC theory was used for determining the radii of the nuclei in the excited states produced in the nucleon transfer reactions, in which the neutron halos are formed.

It is well known that many transfer reactions with light nuclei are actually sensitive only to a tail of the overlap function, i.e., they are peripheral. In accordance with a general definition, the ANC's represent the asymptotic behavior of the radial part of the overlap function for the virtual cluster vertex $B \rightarrow A + \nu$. Numerous studies have shown that for the peripheral direct nuclear reactions, the experimental ANC

$$C_{Av,lj}^{\text{exp}t} = [S_{lj}^{\text{exp}t}(B \rightarrow A + \nu)]^{\frac{1}{2}} b_{Av,lj} \quad (3)$$

is almost constant or only weakly depends on the model parameters, contrary to the empirical values of spectroscopic factors (SF) $S_{lj}^{\text{exp}t}(B \rightarrow A + \nu)$ and the single-particle (sp) ANC $b_{Av,lj}$ separately.

The persistence of $C_{Av,lj}^{\text{exp}t}$ in a number of cross-section calculations with different sp wave functions is considered as a criterion of peripherality of this reaction.

The aim of an ANC analysis of the reaction is to answer the question of whether there exist nuclear states that are formed due to the peripheral nucleon-transfer reactions, that is, the reaction where the valence nucleon is distant from the core approximately by the channel radius R_N or a larger distance. Thus, analyzing the differential cross section of the peripheral reaction, one can determine parameters of the state "core plus nucleon", the radius of the "orbit" of the transferred nucleon in the final state and the weight of the asymptotic part of the wave function in the sp approximation.

3. Results and analysis

3.1. ${}^{14}\text{C}$ nucleus

Our MDM analysis of the experimental data of the ${}^{14}\text{C}(\alpha, \alpha){}^{14}\text{C}$ reaction at $E(\alpha)=35$ MeV [19] showed that the 6.09 MeV, 1^- state has an increased radius. Figure 2 shows the shift of extrema positions for the 6.09 MeV, 1^- state towards smaller angles as compared to the curve from the elastic scattering data. This result is a consequence of the increased radius. Our MDM analysis yielded (2.7 ± 0.1) fm as the RMS radius for the 6.09 MeV, 1^- state. Corresponding radius of the valence neutron is 6.0 ± 0.6 fm, a bit larger than the result of ANC calculations [10].

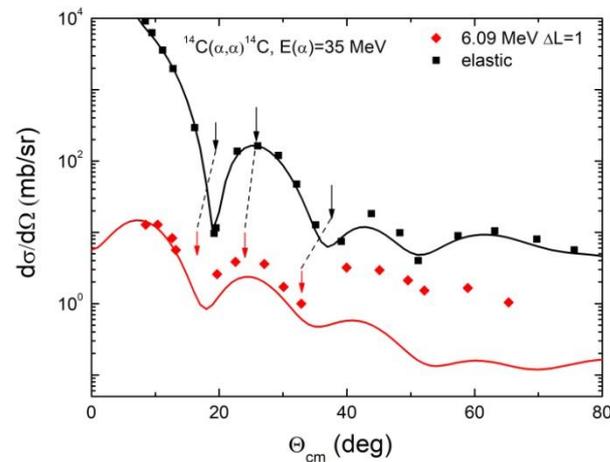


Figure 2. Angular distributions for the $^{14}\text{C}(\alpha,\alpha)^{14}\text{C}$ scattering at $E(\alpha)=35$ MeV [19]: black points correspond to elastic scattering; red points – to inelastic with excitation of the 6.09 MeV, 1^- state. Solid lines correspond to optical model and DWBA calculations, correspondingly.

Similar results were obtained independently by ANC method. Our calculations showed that the rms radii of the last neutron for the 6.09 MeV, 1^- state of ^{14}C within errors is close to result of [10].

3.2. ^{14}N nucleus

In order to study the 1^- , 8.06 MeV state of ^{14}N we propose to use ANC for analysis of the $^{13}\text{C}({}^3\text{He},d)^{14}\text{N}$ reaction at $E({}^3\text{He})=43.6$ MeV [19]. The only difficulty is that this state is a resonance state and is located 0.5 MeV above proton emission threshold. To determine the radius of ^{14}N in the 1^- , 8.06 MeV state, we carry out the calculation with a small positive proton binding energy ($\varepsilon = -0.1$ MeV). Our ANC calculations showed that the rms radii of the last neutron for the 8.06 MeV, 1^- state of ^{14}N is $R_p = 5.9 \pm 0.3$ fm. Corresponding rms radius is 2.67 ± 0.07 fm. It is increased relatively to the radius of the g.s. 2.47 fm [20]. Values of D_1 and D_2 were obtained 42% and 90% correspondingly. While D_1 is a bit less than 50% but D_2 is rather large and rms radius is increased, so together all these facts 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 rms radius of the 8.06 MeV, 1^- state of ^{14}N is close to value obtained by MDM for the 1^- state of ^{14}C .

3.3. ^{14}O nucleus

To study 1^- state in ^{14}O we analyze literature data on $^{14}\text{N}({}^3\text{He},t)^{14}\text{O}$ reaction using MDM. The difficulty of the MDM analysis in this case is that 1^- , 5.17 MeV of ^{14}O is excited by transfer of two angular momenta $L=1$ and $L=3$. To solve it, at first, we have made DWBA analysis of angular distributions from [21] for this state. Angular distributions together with DWBA calculations are shown in figure 3. As can be seen from figure 3, for the 5.17 MeV state transferred angular momentum $L=1$ is more preferable. This result simplifies usage of the MDM analysis.

Angular distributions of the $^{14}\text{N}({}^3\text{He},t)^{14}\text{O}$ reaction with excitation of the 5.17-MeV, 1^- state of ^{14}O exists only at incident energies 44.6 [21] and 420 MeV [22]. These data are presented in figure 3 as function of linear transferred momentum. Arrows correspond to the positions of the extrema used for the MDM analysis.

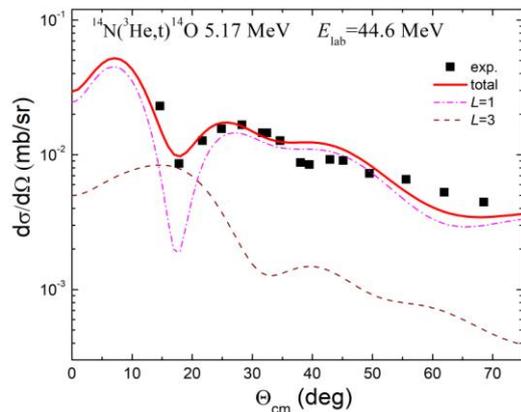


Figure 3. Triton angular distribution for the $^{14}\text{N}(^3\text{He},t)^{14}\text{O}$ reaction with excitation of the 5.17 MeV state at $E(^3\text{He}) = 44.6$ MeV [21] together with DWBA analysis.

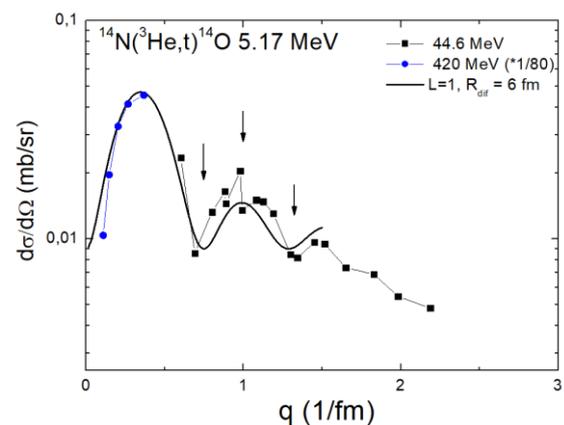


Figure 4. Triton angular distribution for the $^{14}\text{N}(^3\text{He},t)^{14}\text{O}$ reaction as a function of linear transferred momentum. Black points correspond to data at $E(^3\text{He})=44.6$ MeV [21], blue points – at $E(^3\text{He})=420$ MeV [22]. Solid curve corresponds to the spherical Bessel functions $J_L(x)$ of corresponding order $L=1$.

As can be seen from this figure 4, data at two energies complement each other, so full curve is obtained.

In accordance with equation (2) the diffraction radius of the elastic $^3\text{He} + ^{14}\text{N}$ scattering was taken, as the starting point. Using existing literature data, following diffraction radius is obtained ~ 5.5 fm. Then the “corrected” ground-state diffraction radius for ^{14}N is estimated as: $R'_{\text{dif}} = 5.8 \pm 0.2$ fm.

The diffraction radius for the 5.17 MeV state is determined using (1). As mentioned previously dominated angular transferred momentum is $L=1$. Corresponding diffraction radii is found to be 6.0 ± 0.1 fm. This value is larger than R'_{dif} , so the rms radius in this state is increased. Obtained preliminary rms radius is 2.6 ± 0.2 fm.

Overview of results on radii of 1^- states in triplet $A=14$ obtained by different methods can be seen in the Table.

Table. Halo and rms radii of the ^{14}C , ^{14}N and ^{14}O nuclei in the $T=1$ IAS 1^- states determined by different methods

1^- state	Method	R_h (fm)	R_{rms} (fm)	D_1 (%)	D_2 (%)
6.09 MeV ^{14}C	ANC [10]	4.57 ± 0.30	2.49	55.7	91.4
6.09 MeV ^{14}C	[12]	5.16	2.57		
6.09 MeV ^{14}C	MDM, this work	6.0 ± 0.6	2.7 ± 0.1		
8.06 MeV ^{14}N	ANC, this work	5.9 ± 0.3	2.67 ± 0.07	42	90
5.17 MeV ^{14}O	MDM, this work	5.2 ± 1.0	2.6 ± 0.2		

4. Conclusions

Two independent methods ANC and MDM were used for analysis of the IAS 1^- states in members of isobaric triplet $A=14$. These methods gave similar within errors enhanced rms radii for all three states: ^{14}C - 2.7 ± 0.1 fm, ^{14}N - 2.67 ± 0.07 fm, ^{14}O - 2.6 ± 0.2 fm. Moreover, the ANC analysis showed presence 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 . So a reasonable question appears regarding possible proton halo in ^{14}O . The analysis is still in progress.

Acknowledgments

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