Eurasian Journal of Physics and Functional Materials
2017, **1**(1), 35-40

The first identification of the proton halo in the excited state of ^{13}N

A. S. Demyanova [*,1], A.A. Ogloblin [1], A.N. Danilov [1], T.L. Belyaeva [2], S.A.Goncharov [3], W.Trzaska [4]

[1] *National Research Center "Kurchatov Institute", Moscow, 123182, Russia*
[2] *Universidad Autonoma del Estado de Mexico, Toluca, 50000, Mexico*
[3] *Lomonosov Moscow State University, Moscow, 119991, Russia*
[4] *JYFL, Department of Physics, University of Jyvaskyla, Finland*
[*] *e-mail: a.s.demyanova@bk.ru*

Received 25.10.2017

We demonstrate that the radii of excited nuclear states can be estimated using the (^{3}He, t) charge-exchange reaction and relying on the modified diffraction model.The radius of the ^{13}N excited state with an excitation energy of E*=2.37 MeV,which lies in a continuous spectrum, is determined. The radius of this state proves to be close to that of the mirror 3.09-MeV state of the ^{13}C nucleus, which possesses a neutron halo but lies in a discrete spectrum. Thereby, we demonstrate that the 2.37-MeV state of the ^{13}N nucleus has a proton halo. The analysis is based on published measurements of differential cross sections for relevant reactions.

Keywords: inelastic scattering, dilute excited states, MDM model; radii of excited states.

Introduction

The discovery of neutron halos [1] was one of the dazzling achievements in nuclear physics at the end of the past century. A halo is formed by one or two neutrons with low binding energies, located at anomalously large distances from the nucleus center. The formation of the halo is facilitated because valence neutrons populate s states and therefore are not affected by the centrifugal barrier. As a result, the rms radii of nuclei with halos are larger than those of ordinary nuclei by (1–2) fm.

At present, some 20 nuclear states are more or less definitely known to possess neutron halos, which may be divided into three categories: halos in nuclear ground states (see [2] and references therein), halos in excited states lying in discrete nuclear spectra [3, 4], and those in excited states lying in continuous spectra [5, 6]. Three methods for estimating nuclei radii, whereby halos may be revealed in the most short-lived states, have been recently proposed. These are the modified diffraction model (MDM) [7], the method of inelastic rainbow scattering [8, 9], and the method of asymptotic normalization coefficients [3, 5].The two former methods largely rely on empirical systematics, whereas the latter method has a sound theoretical foundation. For the $1/2^+$ excited state of ^{13}C with E*=3.09 MeV in particular, the recent nalysis [5] demonstrated that all three methods yield similar estimates of the radius, which proves to exceed those of other ^{13}C states.Thereby, the predictions [10] and previous data [3] on the existence of a neutron halo in this state were confirmed.

The formation of a proton halo is a much rarer phenomenon, since significant proton separation from the main body of a nucleus is hampered b the Coulomb barrier. Proton halos have been reliably identified for only two nuclei, ^{8}B [11, 12] and ^{17}F [13–15]. In both cases, the state with a halo lies in a discrete spectrum. Until now, no proton halos in continuous spectra have been detected, though some arguments in favor of a proton halo in the ^{13}N first excited state ($1/2^+$, E*=2.37 MeV) were cited in the theoretical analysis [16].

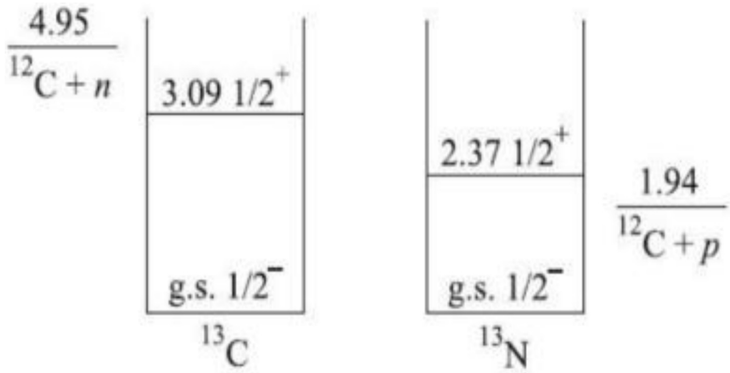

Figure 1. Mirror excited states of the ^{13}C and ^{13}N nuclei with a neutron halo and a possible proton halo, respectively.

There exists a hefty argument in favor of a proton halo in the 2.37-MeV state of ^{13}N. Namely, this state is a mirror state with respect to the 3.09-MeV state of the ^{13}C nucleus, which, as noted above, possesses a neutron halo. Mirror nuclei are known to have a similar structure. However, in the considered case, the situation may prove to be more complex and particularly interesting. The intrigue is that the ^{13}C neutron halo lies in a discrete spectrum, whereas the ^{13}N hypothetical proton halo lies in a continuous spectrum above the $^{13}\mathrm{N} \to (^{12}\mathrm{C} + \mathrm{p})$ threshold by 0.42 MeV (see figure 1). Therefore, the corresponding valence neutron and proton are described by very different wave functions. As a result, these mirror states may significantly differ in structure and radius. Naturally, this does not refer to "ordinary" states of mirror nuclei. By measuring the radius of the 2.37-MeV state of ^{13}N, one may resolve the problem of its supposed proton halo as well as address a more general problem of the structure of continuum states.

Results and discussions

The aim of this investigation is to estimate the radius of the ^{13}N first excited state and to decide whether or not it possesses a proton halo. Unfortunately, the method of asymptotic normalization coefficients involving the reactions of neutron transfer, which is most adequate for this task, is not applicable to unbound states. Directly applying the MDM method is conceptually feasible, but would require measuring the cross sections for inelastic and elastic scattering of ^{13}N radioactive nuclei on a ^{3}He target. Such data are lacking at present and will hardly be obtained in the near future. For this reason, a novel approach had to be developed. We decided to invoke the known analogy between inelastic scattering and charge-exchange reactions for mirror states [17], rooted in a common reaction mechanism and similar state structure, and for the first time to try to apply the MDM to the $^{13}C(^3He, t)^{13}N$ reaction toward estimating the radius of the 2.37-MeV state. We analyze the differential cross sections for the $^{13}C(^3He, t)^{13}N$ reaction, where ^{13}C is in the ground state and ^{13}N is in the 2.37-MeV excited state, and for the inelastic scattering of ^3He ions on ^{13}C, as measured in [18] at an initial energy of 43.6 MeV. Selected for the required comparison are the differential cross sections for elastic scattering of ^3He ions on ^{13}C and for the $^{13}C(^3He, t)^{13}N$ charge-exchange reaction with ^{13}N in the ground state, as measured in [19] at an initial energy of 39.6 MeV.

The goal of the MDM analysis is to determine the so-called diffraction radii (dif) from the positions of minima and maxima of angular distributions at small angles (in the diffraction region) and then extract from these data the values of rms radii $< R^* >$ of the investigated excited states (see [7] for details). The diffraction radii of the ground and excited states, $R_{0.0}(dif)$ and $R^*(dif)$, are extracted from the data on elastic and inelastic scattering of the incident particle, respectively. The rms radii of these states, $< R_{0.0} >$ and $< R^* >$, differ from their diffraction radii by certain correction terms for the dynamic and structural effects not affecting the diffraction radii. The MDM is based on the assumption that these correction terms are the same for the elastic and inelastic channels of the reaction. Then, the rms radius of the excited state may be expressed as [7]:

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

This expression enabled us to successfully determine the radii of excited states of a number of nuclei, including the 3.09-MeV state of ^{13}C (see, e.g., review [20]). When applying the MDM formalism to the (^3He,t) reaction toward extracting nuclear radii, the maxima and minima of its angular distribution are assumed to be of diffractive origin. As in the case of inelastic scattering, these extrema are associated with squared extrema of a Bessel function of the corresponding order L, $J_L^2(qR_{dif})$, where L and q are the angular-momentum and momentum transfers, respectively. In analogy with the scattering reaction, the rms radius of the excited state is estimated using Eq.(1).

In the considered case, $<R^*>$ and $<R_{0.0}>$ in Eq. (1) are the rms radii of the excited and ground states of ^{13}N, respectively. The latter is (2.31 ± 0.04) fm according to the experiments with radioactive beams reported in [21]. The diffraction radius of the 2.37-MeV state, $R^*(dif)$, has to be estimated by analyzing the data on the (^3He, t) reaction [18]. In accordance with the MDM, the diffraction radius of the ground state $R_{0.0}(dif)$ should be extracted from the data on (^3He+^{13}N) – elastic scattering, which, as noted above, are not available. There exist two substitute methods, both of which are employed in this work. The first and second methods rely on (^3He+^{13}C) – elastic scattering and on the (^3He,t) reaction involving the ^{13}C and ^{13}N ground states, respectively. Let us consider them in some detail. Since the mirror ground states have virtually equal radii ($<R_{0.0}(^{13}C)>$ = (2.28 ± 0.04) fm and $<R_{0.0}(^{13}N)>$ = (2.31 ± 0.04) fm [21]), their diffraction radii should differ by a small correction for different Coulomb interactions for the triton and ^3He nucleus in the final states.

Therefore, in accordance with the aforementioned analogy [17] and Eq. (1), the diffraction radius of the ^{13}N 2.37-MeV state can be represented as

$$< R^*(^{13}N) >=< R_{0.0}(^{13}N) > +[R^*(^{13}N)(dif)\check{\ } R'_{0.0}(^{13}N)(dif)]. \tag{2}$$

According to [22], the "corrected" diffraction radius of the ^{13}N state should be substituted in the form

$$R'_{0.0}(^{13}N)(dif) = n/k + \{[R_{0.0}(^{13}C)(dif)]^2 + [n/k]^2\}^{1/2}, n/k = Z_1 Z_2 e^2/2E. \quad (3)$$

Shown in figure 2 are the measured differential cross sections for the ^{13}C(^{3}He,t)^{13}N reaction involving the formation of the 2.37-MeV state of ^{13}N, for ^{13}C(^{3}He,^{3}He')^{13}C inelastic scattering with the excitation of the mirror 3.09-MeV state of ^{13}N at an initial energy of 43.6 MeV [18], and for (^{13}C+^{3}He) elastic scattering at 39.6 MeV [19].

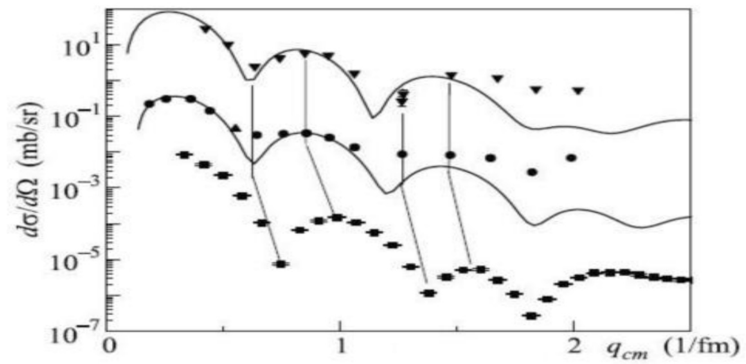

Figure 2. Measured differential cross sections (circles) for the ^{13}C(^{3}He,t)^{13}N reaction with the formation of the 2.37-MeV state of ^{13}N, (triangles, scaled by a factor of 10) for ^{13}C(^{3}He, ^{3}He')^{13}C inelastic scattering with the excitation of the mirror 3.09-MeV state of ^{13}C at an energy of 43.6MeV [18], and (squares, scaled by a factor of 2x10^{-6}) for (^{13}C + ^{3}He)–elastic scattering at an energy of 39.6 MeV [19] as functions of the momentum transfer. Statistical errors are shown (when unseen, they are overshadowed by the data-point markers). The lines connect the minima and maxima used for estimating the diffraction radii. The curves depict the cross sections computed with the distorted-wave method.

These are compared with the results of our computations in the distorted-wave approximation. To render the cross sections measured at different energies comparable, they are plotted as functions of the momentum transfer rather than the emission angle. The computations employed the DWUCK4 code [23] and relied on the standard microscopic approach, in which the form factor is derived from the single-particle wave-functions of the target and final nucleus, and a Gaussian form is assumed for the nucleon–nucleon interaction. The single-particle wave-functions of the target and final nucleus are derived using the standard procedure for fitting the potential-well depth with a fixed single-particle binding energy, as implemented in the DWUCK4 code. This also applies to single-particle states in a continuous spectrum, for which a renormalization procedure based on the algorithm [24] is automatically carried out in DWUCK4.

According to the fact that the measured cross sections for the (^{3}He, t) reaction and (^{3}He, ^{3}He') inelastic scattering are adequately reproduced by the calculation with the distorted-wave method confirms the diffractive origin of their maxima and minima. As expected, the two angular distributions have similar diffraction patterns, which results in almost equal values of diffraction radii (see table).

The minima and maxima of angular distributions are shifted toward smaller momentum transfers (or angles) with respect to elastic scattering, suggesting that the mirror excited states have larger radii than the ground state. Assuming the aforementioned value of $< R_{0.0} >$=2.31 fm for the rms radius of the ^{13}N ground state, for that of the 2.37-MeV state, we obtain $< R^* >$=(2.9 $\pm$ 0.14) fm.

Table 1.
Diffraction radii obtained by analyzing the data on the $^{13}C(^{3}He, t)^{13}N$ reaction and on the ($^{13}C+^{3}He$)–scattering.

Reaction	Initial energy (MeV)	Final state	Diffraction radius (fm)
$^{13}C(^{3}He, t)^{13}N$	43.6	Ground state (ΔL=0)	5.43±0.14
$^{13}C(^{3}He, t)^{13}N$	43.6	2.37 MeV (ΔL=1)	5.94±0.12
$^{13}C(^{3}He, ^{3}He')^{13}C$	43.6	3.09 MeV (ΔL=1)	5.89±0.06
$^{13}C(^{3}He, ^{3}He)^{13}C$	39.6	Elastic	5.22±0.09
$^{13}C(^{3}He, t)^{13}N$	39.6	Ground state (ΔL=0)	5.44±0.18

The second method is based on the use of the $^{13}C(^{3}He, t)$ ^{13}N reaction with the formation of the ^{13}N ground state instead of the ($^{3}He+^{13}N$)– elastic scattering. It is simpler in the sense that no corrections in the exit channel are required. On the other hand, an analogy between the (^{3}He, t) reaction and elastic scattering is less obvious and anyway needs to be critically tested. Shown in figure 3 are the differential cross sections for the $^{13}C(^{3}He, t)^{13}N$ reaction with ^{13}N in the ground state, measured at energies of 43.6 MeV [18] and 39.6 MeV [19]. Also shown are those for ($^{13}C+^{3}He$) elastic scattering.

Differential cross sections for the $^{13}C(^{3}He, t)^{13}N$ reaction with ^{13}N in the ground state and for ($^{13}C+^{3}He$) elastic scattering reveal diffractive oscillations and signatures of rainbow scattering at the largest angles. Transitions between the 1/2 ground states of the ^{13}C and ^{13}N nuclei involve no angular-momentum transfer (L = 0). Correspondingly, the cross sections for the $^{13}C(^{3}He, t)^{13}N$ reaction and elastic scattering in the diffraction region have opposite phases to high precision. In contrast to the situation observed in figure 2, no shift of the cross-section maxima and minima with respect to elastic scattering is observed, which indicates that the ^{13}C and ^{13}N ground states have very similar radii. The diffraction radius of the ^{13}N ground state is extracted as (5.44 ± 0.18) fm and (5.43 ± 0.14) fm for the energies of 39.6 MeV and 43.6 MeV, respectively.

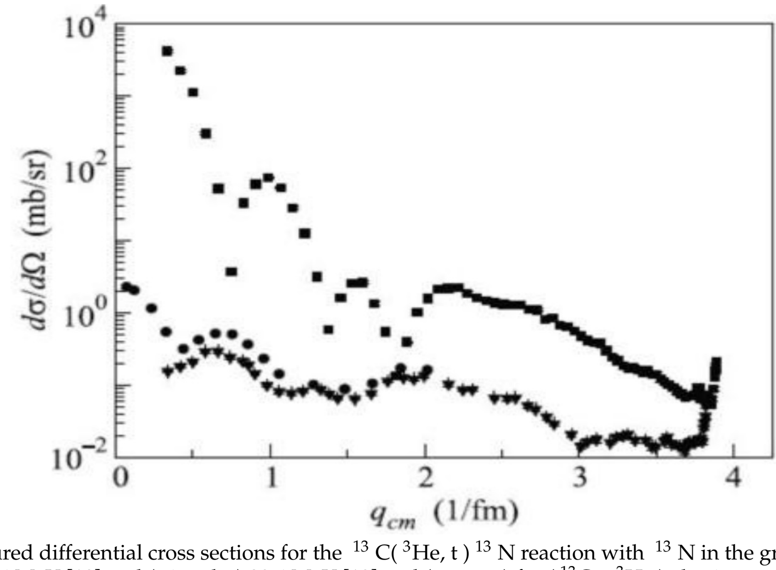

Figure 3.Measured differential cross sections for the $^{13}C(^{3}He, t)^{13}N$ reaction with ^{13}N in the ground state at energies of (circles) 43.6 MeV [18] and (triangles) 39.6 MeV [19] and (squares) for ($^{13}C + ^{3}He$) elastic scattering at an energy of 39.6 MeV [19] as functions of the momentum transfer. The shown statistical errors are partially over shadowed by the data-point markers.

The mean value of (5.44 ± 0.16) fm is in a reasonable agreement with the ^{13}C ground-state radius of (5.22 ± 0.09) fm. The latter method for estimating the radius is certainly promising, but still involves large uncertainties.

Conclusion

In summary, the MDM formalism was used for the first time for extracting the radii of excited nuclear states from the data on (^{3}He, t) charge-exchange reactions, and this new approach proved to be successful.

The radius of the ^{13}N excited state with excitation energy of E*=2.37 MeV, which lies above the (^{13}N $\rightarrow^{12}$C + p)–dissociation threshold, was estimated. The radius of this state proved to be equal to that of the mirror 3.09-MeV state of the ^{13}Ń nucleus, which possesses a neutron halo but lies below the (^{13}C $\rightarrow^{12}$C + n)–breakup threshold. Thereby, the 2.37-MeV state of the ^{13}N nucleus has been shown to possess a proton halo. This is the third observation of a nucleus proton halo and the first ever observation of a proton halo in a continuous rather than discrete spectrum.

References

[1] I. Tanihata et al., Phys. Rev. Lett. **55** (1985) 2676.
[2] I. Tanihata et al., Prog. Part. Nucl. Phys. **68** (2013) 2294.
[3] Z. H. Liu et al., Phys. Rev. C **64** (2001) 0134312.
[4] T. L. Belyaeva et al., Phys. Rev. C **90** (2014) 064610.
[5] A. A. Ogloblin et al., Phys. At. Nucl. **74** (2011) 1548.
[6] A. A. Ogloblin et al., Phys. Rev. C **84** (2011) 054601.
[7] A. N. Danilov et al., Phys. Rev. C **80** (2009) 054603.
[8] S. Ohkubo, Y. Hirabayashi, Phys. Rev. C **70** (2004) 041602.
[9] A. S. Demyanova et al., Int. J. Mod. Phys. E **17** (2008) 2118.
[10] T. Yamada and Y. Funaki, Int. J. Mod. Phys. E **17** (2008) 2101.
[11] T. Minamisono et al., Phys. Rev.Lett. **69** (1992) 2058.
[12] F. Negoita et al., Phys. Rev. C **54** (1996) 1787.
[13] R. Lewis and A. C. Hayes, Phys. Rev. C 59, 1211 (1999). **59** (1996) 1211.
[14] Zh. Dongmei et al., J. Phys. G: Nucl. Part. Phys. **34** (2007) 523.
[15] E. Ryberg et al., arXiv: 1308.5975v1 [nucl-th] (2013).
[16] J. G. Chen et al., Chin. Phys. Lett. **20** (2003) 1021.
[17] A. M. Lane, Nucl. Phys. **35** (1962) 676.
[18] R. J. Peterson, Nucl. Phys. A **377** (1982) 41.
[19] A. S. Demyanova et al., Phys. Scr. **T32** (1990) 89.
[20] P. D. Kunz, Report (Univ. Colorado, 1974), J. R. Comfort, unpublished.
[21] A. Ozawa et al., Nucl. Phys. A **608** (1996) 63.
[22] G. R. Satchler, Introduction to Nuclear Reactions (McMillan Education, Hampshire, London, 1990).
[23] P. D. Kunz, Report (Univ. Colorado, 1974), J. R. Comfort, unpublished.
[24] C. M. Vincent and H. T. Fortune, Phys. Rev. C **7** (1973) 865.