*Proc. 13th Int. Conf. on Nucleus-Nucleus Collisions*
JPS Conf. Proc. **32**, 010031 (2020)
https://doi.org/10.7566/JPSCP.32.010031

# Triplet $^{12}$B-$^{12}$C-$^{12}$N: Search for States with Halo

Andrey N. DANILOV[1*], Alla S. DEMYANOVA[1], Alexey A. OGLOBLIN[1], Sergey A. GONCHAROV[2], Tatiana L. BELYAEVA[3], and Wladislaw H. TRZASKA[4]

[1]*National Research Centre "Kurchatov Institute", Moscow 123182, Russia*
[2]*Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow 119991, Russia*
[3]*Universidad Autónoma del Estado de México, C.P. 50000, Toluca, México*
[4]*Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland*

**E-mail: danilov1987@mail.ru*

(Received July 20, 2019)

Previously in [1] neutron halo was confirmed for the $2^-$, 1.67 MeV and $1^-$, 2.62 MeV states in $^{12}$B on base of Asymptotic Normalization Coefficients (ANC) method analysis of the obtained experimental data. An unexpected result was received for the unbound $3^-$, 3.39 MeV state. Its halo radius was found to be increased and equal to ~ 5.9 fm. This result can be considered as an evidence of the halo-like structure in this $^{12}$B state. It should be noted that last neutron in this state has a non-zero orbital momentum (l=2). So question arises about possible existence of states with halo in other members of the isobaric triplet $^{12}$B - $^{12}$C - $^{12}$N. We can expect the formation of a proton halo in the $2^-$, 1.19 MeV and $1^-$, 1.80 MeV states of $^{12}$N and $2^-$, 16.62 MeV and $1^-$, 17.23 MeV states of $^{12}$C. To check this prediction preliminary Modified Diffraction Model (MDM) analysis of existing ($^3$He,t) and ($^3$He,$^3$He') experimental data was done.

**KEYWORDS:** asymptotic normalization coefficients, neutron and proton halo; MDM model; radii of excited states

## 1. Introduction

Recently 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 Ref. [2] 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 [3,4]. Thus Liu et al. [3] reported the observation of halos in the second ($2^-$, $E_x$ = 1.67 MeV) and third ($1^-$, $E_x$ = 2.62 MeV) excited states of $^{12}$B using the (d,p) reaction on $^{11}$B at $E_{lab}$ = 11.8 MeV by analyzing the data with the ANC method.

Results of the our group ANC analysis of the $^{11}$B(d,p)$^{12}$B reaction data at $E_{lab}$ = 21.5 MeV are shown in [1]. Radii of the valence neutron for the first 5 excited states of $^{12}$B were determined. In current work obtained results for excited states of $^{12}$B [1] are compared with preliminary results of MDM analysis of existing ($^3$He,t) and ($^3$He,$^3$He') literature data for isobar analog states in $^{12}$N and $^{12}$C.

## 2. Results and discussions

### *2.1 $^{12}$B states*

Calculations [1] showed that the rms radii of the last neutron in the second $2^-$, 1.67 MeV and third $1^-$, 2.62 MeV excited states of $^{12}$B far exceed those for the g.s. and the first $2^+$, 0.95 MeV excited state. Exactly, for the $2^-$ state, the excess is a factor of 1.7, and for the $1^-$ state, it is a factor of 2.1, with respect to the rms radius of the ground state. Summary on values of halo radii $R_h$ and probabilities of the last neutron to be outside the range of the interaction radius $D_1$ from ANC analysis of 21.5 MeV data [1] in comparison with results from [3] can be seen in Table 1.

**Table I.** Results of our group ANC calculations [1] in comparison with results of [3]. Values of halo radius $R_h$ and $D_1$ are shown.

| State | $R_h$ (fm) [3] | $D_1$ (%)[3] | $R_h$ (fm) [1] | $D_1$ (%)[1] |
|---|---|---|---|---|
| g.s. | 3.16 ± 0.32 | 19.9 | 3.55 ± 0.20 | 11 |
| 1.67 | 4.01 ± 0.61 | 53.6 | 5.9 ± 0.3 | 53 |
| 2.62 | 5.64 ± 0.90 | 66.8 | 7.4 ± 0.4 | 62 |
| 3.39 | | | 5.9 ± 0.3 | 39 |

The large values of $D_1$ coefficient, more than 50% (formal condition of halo), indicate that the last neutron spends more than 50% of its time outside the range of the core potential. In this case we can conclude that the rms radius of the last neutron wave function can be associated with the halo radius. From results of [1] condition $D_1 > 50\%$ is strictly fulfilled for the $2^-$, 1.67 MeV and $1^-$, 2.62 MeV states. It confirms existence of halo for these states and a conclusion made in Ref. [3]. Nevertheless, analysis [1] indicated that the halo radii in these states are considerably large.

The fifth $3^-$, 3.39 MeV excited state is localized 0.02 MeV above the neutron-emission threshold. As this state belongs to the continuum spectrum, it made impossible a correct estimation of the ANC. In [1] the calculation was carried out with a very small positive neutron binding energy ($\varepsilon$ = 0.1 MeV) and an estimation of the rms radius of the last neutron wave function was done. It was found to be $R_h$ = 5.9 fm, which is a factor of 1.7 larger than that of the g.s. But $D_1$ is less than 50%. Thus we propose that the $3^-$, 3.39 MeV excited state in $^{12}$B is a neutron halo-like state with the orbital momentum l = 2 of the last neutron.

### *2.2 $^{12}$N states*

To study isobar analog states of $^{12}$B in $^{12}$N we propose to use MDM [5,6]. To study $^{12}$N states, this method can be applied to the reaction ($^3$He,t). Its first application made it possible to determine the proton halo in an unbound state of $^{13}$N [7].

We have studied existing literature data on $^{12}$C($^3$He,t)$^{12}$N reaction [8,9]. This data is incomplete and there is no possibility to make definite answer on question about halo in $2^-$ and $1^-$ states of $^{12}$N. Literature data with excitation of the $2^-$ and $1^-$ states is present only for 2 energies: 49.8 [8] and 81 MeV [9]. 49.8 MeV data contains angular distribution only for the $2^-$, 1.20 MeV state. 81 MeV data contains all needed states interested for us ($2^-$, 1.20 MeV and $1^-$, 1.80 MeV) but the problem is that only one oscillation in angular distributions is present.

We applied MDM [5,6] to existing experimental data on $^{12}$C($^3$He,t)$^{12}$N at E($^3$He) = 49.8 and 81 MeV [8,9]. Preliminary results of analysis are present in Table 2 with comparison to data obtained for $^{12}$B [1]. Note that the rms matter radii ($R_{rms}$) of $^{12}$B and $^{12}$N in the ground states are adopted as 2.39 and 2.47 fm, respectively [10].

**Table II.** Preliminary results of MDM analysis on $^{12}$C($^{3}$He,t)$^{12}$N experimental data [8,9] in comparison to results obtained for $^{12}$B from Ref. [1]. Values of root mean square radii are present.

| State | $^{12}$B | $R_{rms}$ (fm) [1] | $^{12}$N | $R_{rms}$ (fm) |
|---|---|---|---|---|
| $1^+$ | g.s. | 2.39 ± 0.02 | g.s. | 2.47 ± 0.07 |
| $2^-$ | 1.67 | 2.58 ± 0.11 | 1.19 | 2.7 ± 0.3 |
| $1^-$ | 2.62 | 2.86 ± 0.11 | 1.8 | 2.8 ± 0.2 |

As can be seen from Table 2, close radii were obtained for isobar analog states in $^{12}$B and $^{12}$N by 2 independent methods: MDM and ANC. This preliminary result can be an argument for possible proton halo in $2^-$ and $1^-$ states in $^{12}$N. But further analysis is needed. It should be mentioned that new experiment on $^{12}$C($^{3}$He,t)$^{12}$N reaction at E($^{3}$He)=40 MeV was done by our team at the end of 2018, now analysis is in progress.

### *2.3 $^{12}$C states*

We found only one work with experimental data on inelastic scattering with excitation of the $2^-$, 16.62 MeV state in $^{12}$C: $^{12}$C($^{3}$He,$^{3}$He')$^{12}$C at E($^{3}$He)=49.8 MeV [8]. Preliminary MDM analysis of this data gave increased radius $R_{rms}$ > 3 fm for $2^-$ state.

## 3. Conclusion

Previously in [1] neutron halo was confirmed for $2^-$ and $1^-$ states in $^{12}$B and probable halo-like structure was seen for $3^-$ state of $^{12}$B (unbound, l=2). In this work MDM was applied to existing literature $^{12}$C($^{3}$He,t)$^{12}$N and $^{12}$C($^{3}$He,$^{3}$He')$^{12}$C data with the excitation of isobar analog states $2^-$ and $1^-$ in $^{12}$N and $^{12}$C. Preliminary results of MDM analysis for $^{12}$N states showed that rms radii are close to corresponding values of rms radii obtained by ANC for $^{12}$B. This fact can be an argument for possible proton halo in $2^-$ and $1^-$ states in $^{12}$N. MDM analysis also showed increased radius for the $2^-$, 16.62 MeV state in $^{12}$C.

## Acknowledgment

The work was supported by the Russian grant RSF 18-12-00312.

## References

[1] T.L. Belyaeva et al., Phys. Rev. C **98**, 034602 (2018).
[2] A.A. Ogloblin et al., Nuclear Particle Correlations and Cluster Physics, pp. 311-338 (2017).
[3] Z. Liu et al., Phys. Rev. C **64**, 034312 (2001).
[4] T.L. Belyaeva et al., Phys. Rev. C **90**, 064610 (2014).
[5] A.N. Danilov et al., Phys. Rev. C **80**, 054603 (2009).
[6] A.S. Demyanova et al., Yad. Fiz. **80**, 427 (2017) [Phys. At. Nucl. **80**, 831 (2017)].
[7] A.S. Demyanova et al., JETP Letters **104**, 526 (2016).
[8] G. Ball and J. Cerny, Phys. Rev. **177**, 1466 (1969).
[9] W. Sterrenburg et al., Nucl. Phys. A **405**, 109 (1983).
[10] A. Ozawa, T. Suzuki, and I. Tanihata, Nucl. Phys. A **693**, 32 (2001).