Conference Paper

Neutron halos in excited states of ^{12}B

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Abstract

An experiment was done to search for states with a neutron halo in ^{12}B. The measurements were carried out at the cyclotron of the University of Jyvaskyla (Finland) using Large Scattering Chamber (LSC). The idea of the work was to search for two states with the expected neutron halo, 1^- and 2^-. Differential cross sections with excitation of ^{12}B states, including abovementioned states, were observed. The preliminary calculations on halo radii by the method of asymptotic normalization coefficients for the 2^- and 1^- states which are in a discrete spectrum gave following values: 5.6 fm and 7.4 fm, which is much larger than the radius of the valence neutron in the ground state. But strictly the presence of a neutron halo can be confirmed only for 1^- state. The 2^- state can be considered only as candidate for halo. An unexpected result was obtained for the 3^-, 3.39 MeV state, which is in continuum 19 keV above the decay threshold $^{12}B \rightarrow {}^{11}B + n$, preliminary estimation for its halo radius is ~ 6.5 fm. This indicates that the halo can be present in this state as well. But strict conditions for neutron halo are not fulfilled in the same way as for 2^- state. Until now, the neutron halo in unbound states has been observed only for the members of the rotational bands.

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, e.g., Ref. [1] and references therein). The existence of neutron halos in the short-lived excited states of some stable and radioactive nuclei

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was revealed, in particular, by the ANC analysis of the neutron-transfer reactions [2–4]. Thus Liu et al. [2] reported the observation of halos in the first ($1/2^+$, E_x = 3.089 MeV) excited state of ^{13}C, and the second (2^-, E_x = 1.674 MeV) and third (1^-, E_x = 2.621 MeV) excited states of ^{12}B using the (d,p) reactions on ^{12}C and ^{11}B, respectively, by analyzing the data with the ANC method.

In this article, we present the results of the measurement and analysis of the ^{11}B(d,p)^{12}B reaction populated the 1^+ g.s. and five excited states up to the neutron-emission threshold: 0.953 MeV 2^+, 1.674 MeV 2^-, 2.621 MeV 1^-, 2.723 MeV 0^+, and 3.389 MeV 3^- states, at incident deuteron energy E_{lab} = 21.5 MeV. We determine preliminary values of the spectroscopic factors and the ANC coefficients by comparing the results with the measured differential cross sections. Afterwards we calculate the preliminary rms radii of the last neutron in the final state of ^{12}B.

One of the main our aims is to estimate the radius of the 3.389 MeV 3^- state located in the continuum spectrum and to answer the question whether there exists a state, in which a neutron halo is formed by the valence neutron occupying the l = 2 orbital.

2. Experiment

The differential cross sections of deutron elastic scattering from ^{11}B and the ^{11}B(d,p)^{12}B reaction leading to formation of the 1^+ g.s. and the excited 0.95 MeV 2^+, 1.67 MeV 2^-, 2.62 MeV 1^-, 2.72 MeV 0^+, and 3.39 MeV 3^- states were measured at incident deutron energy E_{lab} = 21.5 MeV in the angular range (5° - 85°). The measurements were performed at Jyvaskyla University cyclotron using the Large Scattering Chamber (LSC) having a diameter 1500 mm. The scattered particles were detected with four ΔE - E telescopes, each performing measurements at two angles. Self-supporting ^{11}B foil of thickness 0.275 mg/cm^2 served as a target. The beam current was about 20 particle nA. The experiment employed a beam monochromatization system, which made it possible to obtain a total energy resolution of about 70 keV. A typical proton spectrum for the excitation of ^{12}B states up to $E_x \sim 3.5$ MeV obtained at $\Theta_{c.m.}$ = 18° is shown in Fig. 1. The ^{12}B excitation peaks are clearly separated in this spectrum, and contamination from other ions (carbon, oxygen) is well separated. We used the standard expansion procedure to describe peaks with Gaussian functions, whereas the peak positions and widths were fixed in accordance with table values, and the area under the peak was the only free parameter. A separation of the neighbouring 2.62 MeV 1^- and 2.72 MeV 0^+ states of ^{12}B was made possible owing to a good energy resolution assured by the monochromatization of the beam (see Fig. 1, low part). The experimental differential cross sections of d + ^{11}B elastic scattering and the ^{11}B(d,p)^{12}B (g.s., 0.95, 1.67, 2.62, 2.72, 3.39 MeV) reaction are shown in Fig. 2.

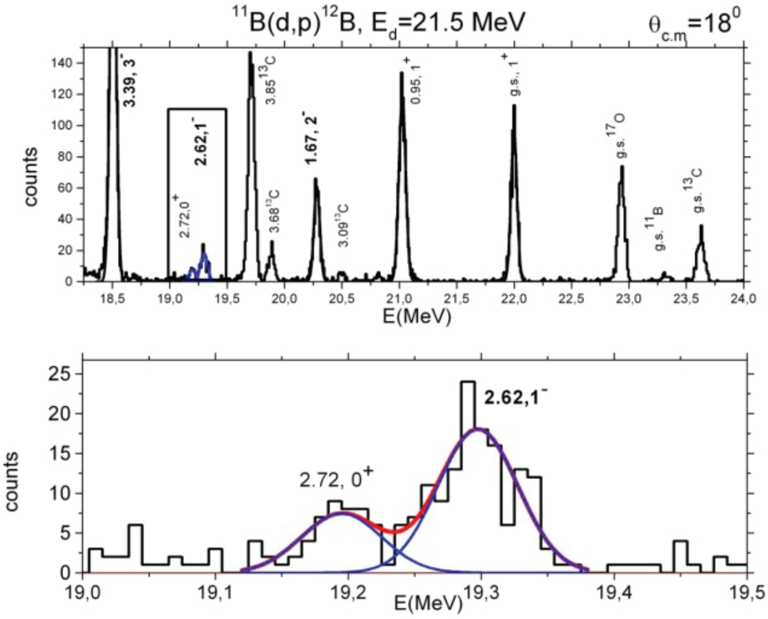

Figure 1: A typical proton spectrum at $\Theta_{c.m.}$ = 18°.

3. Analysis of the results

Compound-nucleus (CN) analysis of the differential cross sections is carried out within the Hauser-Feshbach formalism of the statistical CN model by using the computer code CNCOR [5]. In Fig. 2, the results of CN calculations (dotted lines) are shown in comparison with the experimental differential cross sections at beam energy 21.5 MeV. The analysis showed that the CN mechanism provides less than 0.1% of the cross section values at forward angles and about 1-3% at medium angles 60°-80°. So the transfer mechanism predominates for this reaction at given energy.

The Coupled-reaction-channels (CRC) method for direct reactions includes the one-step DWBA as a special case, so the finite-range neutron transfer mechanism and the elastic scattering in the entrance and exit channels are calculated within the same formalism. CRC calculations are carried out with the code FRESCO [6] to fit the data.

Four first excited states studied belong to the discreet spectrum, whereas the last 3.39 MeV 3$^-$ state lying 0.019 MeV above the neutron-emission threshold is located in the continuum. Nevertheless, in view of the small positive energy and the structure

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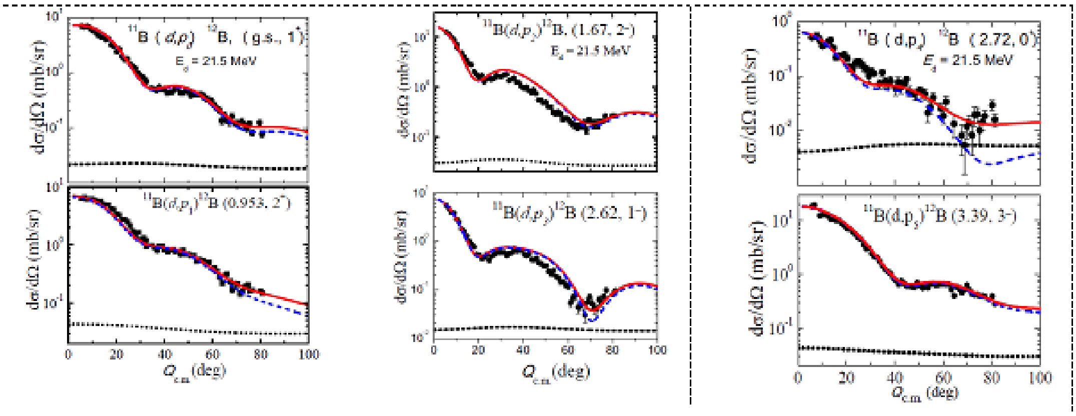

Figure 2: Differential cross sections of the $^{11}B(d,p)^{12}B$ reaction at E_{lab}= 21.5 MeV leading to the 1^+ ground state and excited 0.954 MeV 2^+, 1.674 MeV 2^-, 2.621 MeV 1^-, 2.723 MeV 0^+, and 3.389 MeV 3^- states of ^{12}B obtained in the present work (points) in comparison with the CRC (dashed line) and CN (dotted line) calculations, and their sum (solid line).

of the proton angular distribution similar to those of the preceding bound states, we used the effective positive small (0.01 MeV) binding energy of valence neutron.

The results of the transfer calculations in the CRC model (dashed lines) are shown in Fig. 2. The solid curves represent the incoherent sum of the CN model and direct transfer calculations. The calculations reproduce the positions and shapes of the first extremes very well.

Neutron-transfer reactions with light nuclei are mainly peripheral, that is they actually sensitive only to the surface part of the neutron-core potential.

Calculations of the ANCs with different sp wave functions allow us to answer the question whether there exist states in ^{12}B that are formed due to the peripheral neutron transfer reactions.

As in the sp approximation, the exact overlap function is approximated by the two-body sp wave function, the rms neutron radius is approximately determined by the rms radius of the sp wave function of neutron. To estimate the weight of the asymptotic part of the wave function a coefficient is introduced called D_1. It characterises the spatial extension of the neutron wave functions to the asymptotic potential region. It is accepted in Refs. [2] that if $D_1(R_N) > 50\%$, than the state is assumed to be a “real” halo.

Our preliminary calculations showed that the rms radii of the last neutron in the second 1.674 MeV 2^- and third 2.621 MeV 1^- excited states of ^{12}B far exceed those for the g.s. and the first 0.953 MeV 2^+ excited state. Exactly, for the 2^- state, the excess is a factor of 1.6, and for the 1^- state, it is a factor of 2.1, with respect to the rms radius of the ground state. Summary on preliminary values of R_h and D_1 for current work in comparison with results from [2] can be seen in Table 1.

Table 1: Preliminary results of ANC calculations (last 2 columns) in comparison with results of [2].

State	R_h (fm) [2]	D_1 (%)[2]	R_h (fm) current work	D_1 (%) current work
g.s. 1^+	3.16 ± 0.32	19.9	3.6 ± 0.2	11
0.953 2^+			3.95 ± 0.20	16
1.674 2^-	4.01 ± 0.61	53.6	5.57 ± 0.26	38
2.621 1^-	5.64 ± 0.90	66.8	7.4 ± 0.4	53
2.723 0^+			5.6 ± 0.3	30
3.389 3^-			6.5 ± 0.3	28

The large values of D_1 coefficient, more than 50%, 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 preliminary results of current work condition $D_1(R_N) > 50\%$ is strictly fulfilled only for the 2.621 MeV 1^- state and $R_h(1^-)$ = 7.4 ± 0.2 fm. For 1.674 MeV 2^- state $D_1(R_N)$ is a bit less than 50% but R_h is rather large so this state can be a candidate for halo. This result partly confirms a conclusion made by Liu and collaborators in Ref. [2] that the second (1.674 MeV 2^-) and third (2.621 MeV 1^-) excited states in ^{12}B are the neutron halo states. Nevertheless, our analysis indicated that the halo radii in these states are considerably large.

Let us pay particular attention to the fifth 3.389 MeV 3^- excited state that is localized 0.019 MeV above the neutron-emission threshold. As this state belongs to the continuum spectrum, it makes impossible a correct estimation of the ANC, even though the calculation was carried out with a very small positive neutron binding energy (ε = 0.1 MeV) and the asymptotic behaviour of the sp and Hankel functions become the same at very long distance, about 50 fm. Nevertheless, we could approximately estimate the rms radius of the last neutron wave function by determining the rms radius of the sp wave function. It was found to be R_{rms} = 6.5 fm, which is a factor of 1.8 larger than that of the g.s. and is comparable with the rms radii of the last neutron wave function in the 1.674 MeV 2^- state and the 2.621 MeV 1^- state of ^{12}B. But D_1 is less than 50%. Thus the ^{12}B the 3.389 MeV 3^- excited state can only be considered as probable candidate to neutron halo. If this state is truly neutron halo, this observation would indicate to the first halo excited state with a nonzero orbital momentum l = 2.

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