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# Asymptotic normalization coefficients and halo radii of $^{12}$B in the excited states

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**Abstract.** We present the results of measurements and analysis of the differential cross sections of the $^{11}\text{B}(d,p)^{12}\text{B}$ reaction leading to formation of the $1^+$ ground state and the 0.953-MeV $2^+$, 1.674-MeV $2^-$, 2.621-MeV $1^-$, 2.723-MeV $0^+$, 3.389-MeV $3^-$ excited states of $^{12}$B at $E_d = 21.5$ MeV. The analysis of the data was carried out within the coupled-reaction-channels method for the direct neutron transfer and the Hauser-Feshbach formalism of the statistical compound-nucleus model. We deduced the spectroscopic factors, asymptotic normalization coefficients, and rms radii of the last neutron in all states studied. The existence of the neutron halos in the 1.674-MeV $2^-$ and 2.621-MeV $1^-$ states was found in consistence with the earlier published data. New information about the enlarged rms radii (6.5 fm) of the last neutron in the unbound 3.389-MeV $3^-$ states of $^{12}$B was obtained, which may indicate the evidence of the neutron halo with the orbital momentum of the last neutron equal to two.

## 1 Introduction

The neutron- and proton-transfer reactions with stable and radioactive beams in the traditional and inverse kinematics are justifiably regarded as an important source of spectroscopic and astrophysical information. An important application of the nucleon-transfer reactions is related to the determination of the last neutron and proton radii, including radii of nuclei in the short-lived excited states [1, 2]. The evidence of enlarged radii of nuclei in the excited states found by different methods [3–5] indicates the existence of neutron halos not only in the ground states of exotic nuclei, but also in the excites states of "normal" nuclei.

## 2 Results

The 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 were measured at incident deuteron energy $E_{\rm lab}$ = 21.5 MeV in the angular range ($\sim 5° - 85°$) at Jyvaskyla University cyclotron using the Large Scattering Chamber (LSC).

The experimental elastic-scattering angular distribution was fitted with the optical potentials of the standard Woods-Saxon form, which included the real, spin-orbital, and imaginary (surface) components. The parameters were chosen on the base of the global parameterization. Calculations were carried out with code FRESCO [6].

The compound-nucleus (CN) analysis of the $^{11}$B$(d,p)^{12}$B differential cross sections was carried out within the statistical Hauser-Feshbach formalism by using the computer code CNCOR [7]. It was found that the CN mechanism provides less than 0.1% of the cross sections at forward angles and about 1-3% at medium angles 60-80°.

The coupled-reaction-channels (CRC) analysis included the finite-range neutron transfer mechanism. The neutron single-particle (sp) overlap wave function in the deuteron with orbital angular momentum $l = 0$ was chosen from Ref. [8]. The normalized sp overlap $^{11}$B+$n$ wave functions were generated by the $^{11}$B+$n$ interaction potential for each state of $^{12}$B.

Figure 1 shows the results of the CRC (dashed lines) and CN calculations (dotted lines) in comparison with the measured differential cross sections of the $^{11}$B$(d,p)^{12}$B reaction populating the 2.723-MeV $0^+$ and 3.389-MeV $3^-$ states. The solid curves represent the incoherent sum of the CN model and direct transfer calculations.

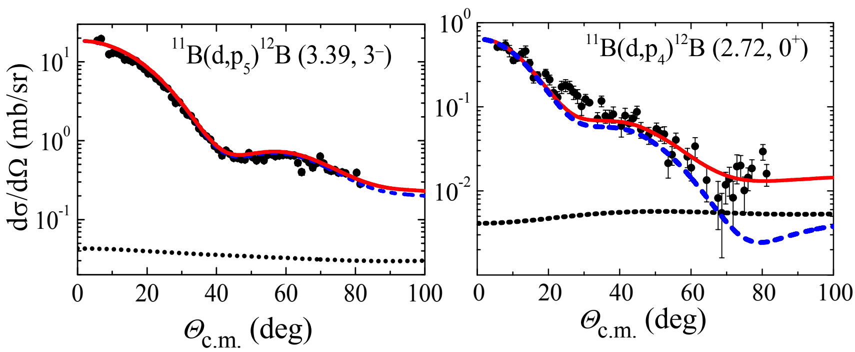


**Figure 1.** Differential cross sections of the $^{11}$B$(d,p)^{12}$B reaction leading to the fourth excited 2.723-MeV $0^+$ state and the fifth excited 3.389-MeV $3^-$ state of $^{12}$B measured in the present work (points) in comparison with the CRC (dashed line), CN (dotted line) calculations, and their sum (solid line).

Table I shows the deduced spectroscopic factors (SFs), the neutron ANCs and the rms neutron radii in comparison with the results obtained by the DWBA analysis of this reaction in Refs. [1, 9, 10]. We found that the rms radii of the last neutron in all excited states studied are greater than that in the g.s. Thus for the $2^-$ state, the excess is a factor of 1.55, and for the $1^-$ state, it is a factor of 2.05, with respect to the rms radius of the g.s. The rms radius of the last neutron wave function of the fifth 3.389-MeV $3^-$ excited state was found $R_{\rm rms}$ = 6.5 fm. This value is a factor of 1.8 larger than that of the g.s. and exceeds considerably the rms radii of the neutron wave function in the 1.674-MeV $2^-$ state of $^{12}$B.

**Table 1.** Summary of the neutron spectroscopic factors, asymptotic normalization coefficients, rms radii, $D_1$ and $D_2$ coefficients for the states of $^{12}$B.

| $E_x$ (MeV), $J_f^\pi$ | $n_2 l_2$ | $S_{n_2 l_2}^{\mathrm{expt}}$ | $\left(C_{^{11}\mathrm{B}n}^{\mathrm{expt}}\right)^2$ (fm$^{-1}$) | $R_{\mathrm{rms}}$ (fm) | $D_1$ % | $D_2$ % | Ref. |
|---|---|---|---|---|---|---|---|
| 0.0, $1^+$ | 1 1 | | 1.35 ± 0.23 | 3.16 ± 0.32 | 19.9 | 70.2 | [1] |
| | | 0.69 | | | | | [9, 10] |
| | | 0.67 | 1.33 ± 0.07 | 3.6 ± 0.2 | 11 | 58 | this work |
| 1.674, $2^-$ | 2 0 | | 1.80 ± 0.43 | 4.01 ± 0.61 | 53.6 | 91.9 | [1] |
| | | 0.57 | | | | | [9, 10] |
| | | 0.36 | 1.57 ± 0.15 | 5.58 ± 0.26 | 48.5 | 91 | this work |
| 2.621, $1^-$ | 2 0 | | 0.88 ± 0.15 | 5.64 ± 0.90 | 66.8 | 96.3 | [1] |
| | | 0.75 | | | | | [9, 10] |
| | | 0.625 | 1.11 ± 0.10 | 7.40 ± 0.35 | 70 | 97 | this work |
| 3.389, $3^-$ | 2 2 | 0.5 | | | | | [9, 10] |
| | | 0.251 | | 6.5 ± 0.3 | 47 | 94 | this work |

Coefficients $D_1(R_\mathrm{N})$ determining the weight of the asymptotic part of the wave function and $D_2$ estimating the contribution of the asymptotic part of the wave function to the rms radius define a probability of the halo-nucleon to be outside the range of the core potential, which is expected to be more than 50% for halo states.

It is evident that the 2.621-MeV $1^-$ state satisfies all criteria of the halo state with the enormous rms neutron radius, $R(1^-) = 7.4 \pm 0.35$ fm, and $D_1$ and $D_2$ coefficients equal to 70% and 97%, respectively. The 1.674-MeV $2^-$ state apparently also can be considered as the halo state with the last neutron spending about 50% of its time outside the range of the core potential. The neutron rms radius in the 3.389-MeV $3^-$ excited state was found equal to 6.5 fm that is 1.16 larger than that for the 1.674-MeV $2^-$ state. The $D_1$ and $D_2$ are almost the same as for the $2^-$ state. Thus, we can suggest that $^{12}$B in the 3.389-MeV $3^-$ excited state also possesses the neutron halo. Note that this observation reveals the first halo excited state with a non-zero $l_2 = 2$ orbital momentum of the last neutron.

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