Configuration of the valence neutrons of ^{17}B *

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Abstract The reaction cross section of ^{17}B on ^{12}C target at (43.7±2.4) MeV/u has been measured at the Radioactive Ion Beam Line in Lanzhou (RIBLL). The root-mean-square matter radius ($R_{\rm rms}$) was deduced to be (2.92±0.10) fm, while the $R_{\rm rms}$ of the core and the valence neutron distribution are 2.28 fm and 5.98 fm respectively. Assuming a "core plus 2n" structure in ^{17}B, the mixed configuration of ($2s_{1/2}$) and ($1d_{5/2}$) of the valence neutrons is studied and the s-wave spectroscopic factor is found to be (80±21)%.

Key words valence neutron, root-mean-square radius, s-wave spectroscopic factor

PACS 21.10.Gv, 20.10.Jx, 25.60.Dz

1 Introduction

Since the first neutron halo nucleus ^{11}Li was established in 1985, studies of the nuclear structures of unstable nuclei have been extended with the development of the radioactive nuclear beams. Many halo nuclei have been discovered. There are two main classes of halo states: the two-body halo with one nucleon surrounding the core, such as the one-neutron halo of ^{11}Be and ^{19}C and the one-proton halo of ^{8}B; and the Borromean three-body halo with two valence nucleons around the core, such as ^{6}He, ^{11}Li and ^{14}Be. Of the halo systems, two-neutron halo nuclei have received much attention. This is due to their Borromean character where the three-body system is bound with its pairwise subsystems unbound.

As one Borromean candidate, ^{17}B was suggested to be a two-neutron halo nucleus due to its weak binding of the valence two-neutrons (S_{2n} = 1.39±0.14 MeV). Ren et al. have predicted its halo structure by means of the three-body model[1]. The interaction cross sections of ^{17}B have been measured at around 800 MeV/u at GSI by T. Suzuki et al. The effective root-mean-square (rms) matter radius was deduced to be (2.99±0.09) fm. Assuming a "core plus 2n" structure in ^{17}B, the mixing of ($2s_{1/2}$) and ($1d_{5/2}$) of the valence neutrons was studied and the s-wave spectroscopic factor is found to be (36±19)%[2]. The longitudinal momentum distribution of ^{15}B fragments from the breakup of ^{17}B on ^{9}Be was measured at 70 MeV/u at RIKEN. A Glauber-type analysis of the data provides clear evidence of a two-neutron halo structure in ^{17}B and the s-wave spectroscopic factor is found to be (69±20)%[3]. The reaction cross section for the neutron-rich nucleus ^{17}B on a carbon target has been measured at an energy of 77 MeV/u by Yamaguchi and the fraction of the wave function with the valence two-neutron configuration of ($2s_{1/2}$) or ($1d_{5/2}$) was found to be (50±10)% based on a finite-range few-body Glauber-type calculation[4].

It can be seen that the experimental results for

Received 22 August 2007
* Supported by National Natural Science Foundation of China (10475098, 10605033, 10221003), Chinese Academy of Sciences (CXTD-J2005-1, KJCX2-SW-N18) and Hundred Talent Project of CAS (0501080BR0)
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^{17}B are still scarce, especially there are no experiment data at Fermi energy region which in principle is more sensitive for the nucleon distribution. Therefore a ^{17}B experiment at Fermi energies was arranged at RIBLL[5]. The details about the experiment can be found in a previous paper[6]. The reaction cross section of ^{17}B on ^{12}C at (43.7±2.4) MeV/u was measured by the transition method and the value of (1724±93) mb was obtained. In this paper we will discuss the density distribution of the valence neutrons of ^{17}B from the reaction cross section. In the next section $R_{\rm rms}$ of ^{17}B and its valence neutron distribution are deduced. In Section 3 the valence neutrons configuration is discussed and the *s*-wave spectroscopic factor is extracted. Finally a brief summary is given.

2 $R_{\rm rms}$ of ^{17}B

The root-mean-square radius $R_{\rm rms}$ is defined with the formula:

$$R_{\rm rms}=\langle r^2\rangle^{1/2}=\left(\frac{4\pi\int r^4\rho(r){\rm d}r}{4\pi\int r^2\rho(r){\rm d}r}\right)^{1/2}. \qquad (1)$$

According to this definition, for a halo nucleus, we have

$$R_{\rm rms}=\left\{\frac{A_{\rm c}R_{\rm c}^2+(A-A_{\rm c})R_{\rm h}^2}{A}\right\}^{1/2}, \qquad (2)$$

where $A_{\rm c}$ and A are the nucleon number in the core and that of the nucleus respectively, while $R_{\rm c}$ and $R_{\rm h}$ are the rms radii of the core and the halo respectively.

For the data analysis, the zero-range Glauber model with Coulomb effects included[7] is employed, which is a standard tool to extract the nucleon distribution from the reaction cross section. For light stable nuclei, usually the nucleon distribution with the Gaussian or harmonic oscillator types is assumed as the input of the Glauber model, and both distributions give essentially equal effective rms matter radii.

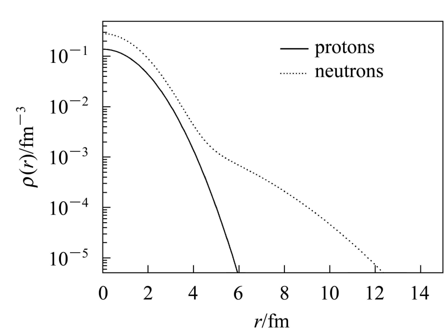
To investigate the reaction cross section of ^{17}B, we assume ^{17}B has a structure of a core (^{15}B) plus valence neutrons due to the low separation energy. The core and halo density distributions are described by the Gaussian functions:

$$\rho_{\rm j}=\left(\frac{3}{2\pi R_{\rm j}^2}\right)^{3/2}\exp\left(-\frac{3r^2}{2R_{\rm j}^2}\right),\quad {\rm j}={\rm c,h} \qquad (3)$$

where c and h denote the core and the halo respectively. This form was adopted for ^{6}He and ^{8}He by Alkhazov et al. to fit the small-angle proton elastic scattering experimental results[8].

By tuning $R_{\rm c}$ and $R_{\rm h}$, the excitation function of ^{17}B can be fitted quite well in the whole energy range. In Fig. 1 the nucleon distribution and the energy dependence of the total reaction cross section σ are displayed. The best fitting results of $R_{\rm c}$ and $R_{\rm h}$ are 2.28 fm and 5.98 fm respectively, and the $R_{\rm rms}$ of ^{17}B is 2.92 fm. Here $R_{\rm c}$ is consistent with Tanihata's result of ^{15}B within error[9], where while $R_{\rm rms}$ = (2.40±0.25) fm. With $R_{\rm c}$ changed, σ will be changed more significantly in high energy region than in medium energy region. The σ in medium energy region is more sensitive with $R_{\rm h}$, i.e. the nucleon distribution on the surface of the nucleus.

Figure 2 shows how to determine the error bar of $R_{\rm rms}$. By fixing $R_{\rm c}$ to be 2.28 fm and tuning $R_{\rm h}$, σ and $R_{\rm rms}$ can be calculated. According to the experimental error bar of σ, the error bar $R_{\rm rms}$ can be deduced. The result of $R_{\rm rms}$ of ^{17}B is (2.92±0.10) fm. Our result is consistent with Ozawa's (3.0±0.6) fm with optical limitation Glauber model[10], and Suzuki's (2.90±0.06) fm with optical limitation Glauber model and (2.99±0.09) fm with few-body Glauber model[2].



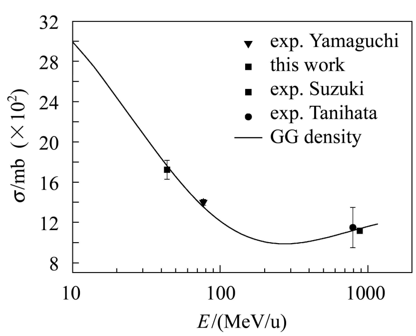


Fig. 1. Left: The protons (solid line) and neutrons (dotted line) density distributions of ^{17}B with double Gaussian forms. Right: The excitation function calculated with the Glauber model (solid line), and the existing experimental data (solid points).

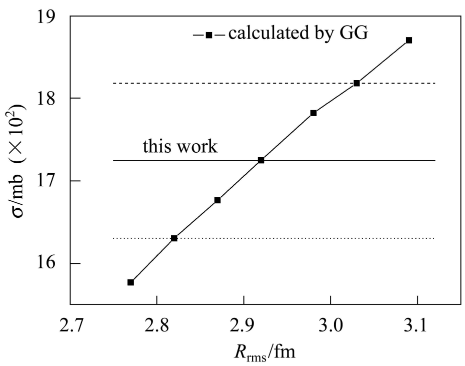


Fig. 2. The relation of σ and $R_{\rm rms}$ by fixing $R_{\rm c}$ and tuning $R_{\rm h}$. The horizontal solid line indicates the experimental result and the tilted solid line with points is the calculated result. The dashed and dotted lines indicate the upper and lower errors.

3 The valence neutrons configuration

The moving of valence neutrons around the core can be described with the Schrödinger equation:

$$\frac{{\rm d}^2R(r)}{{\rm d}r^2}+\frac{2\mu}{\hbar^2}\left[E-U(r)-\frac{l(l+1)\hbar^2}{2\mu r^2}\right]R(r)=0\ , \quad (4)$$

where $U(r) = -V_0f(r)+V_{ls}(l\cdot s)r_0^2\frac{1}{r}\frac{\rm d}{{\rm d}r}f(r)+V_{\rm Coul}$ is the potential of the core. $V_{\rm Coul}$ is the Coulomb potential, and V_{ls} is the orbit-spin coupling potential. The value of V_{ls} is chosen to be 17 MeV according to Ref. [11]. $f(r) = \left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}$, where $R=r_0A_{\rm c}^{1/3}$. Usually r_0 = 1.2 fm is adopted. For the core ^{15}B, R = 2.96 fm, which is consistent with the interaction radius of ^{15}B of (2.83±0.25) fm obtained by Tanihata[9] (notice that the interaction radius is different with $R_{\rm rms}$). The depth of the potential, V_0, is adjusted to reproduce the experimental neutron separation energy. Assuming there is no correlation between the two valence neutrons of ^{17}B, the one neutron separation energy is set to be half of the two-neutron separation energy, i.e. 0.7 MeV. The wave function of the halo neutrons can be obtained by solving the equation, and then the density distribution can be obtained.

According to the normal shell model, the valence neutrons of ^{17}B should occupy the $1d_{5/2}$ orbit. While for nuclei far from the stability line, the order of the orbits occupation could be changed. It is expected that the valence neutrons of ^{17}B could have a wave function contributed largely by the intruder $2s_{1/2}$ state. The density distributions of the valence neutrons in $2s_{1/2}$ and $1d_{5/2}$ orbits are displayed in Fig. 3. It can be seen that the neutrons in $2s_{1/2}$ extend much farther outside the core than neutrons in $1d_{5/2}$ due to the low centrifugal barrier.

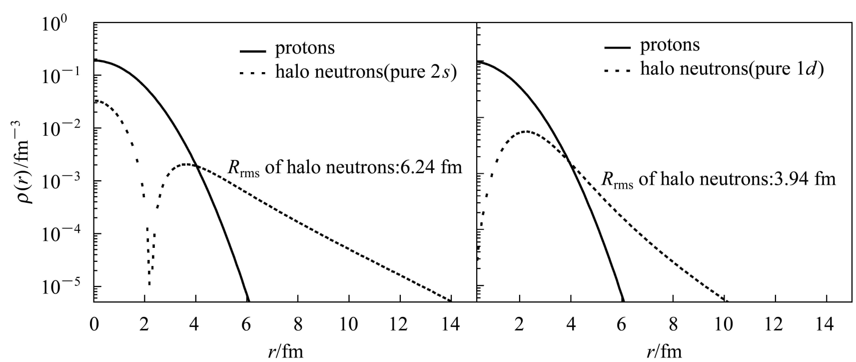


Fig. 3. The density distributions of the valence neutrons in $2s_{1/2}$ and $1d_{5/2}$ respectively.

Inputting the density distributions of neutrons calculated above into the Glauber model, the σ with pure $2s_{1/2}$ and pure $1d_{5/2}$ orbits can be obtained. In Fig. 4 the calculated σ by assuming the valence neutrons in $2s_{1/2}$ or $1d_{5/2}$ orbits is displayed. The solid points show the diffusion parameter a of the Woods-Saxon potential fixed to be 0.7 fm. The tilted lines indicate pure wave with a changed from 0.6 to 0.9 fm (from left to right). It can be seen with higher a the calculated σ is also higher. The $2s_{1/2}$ is more close to the experimental result, while the pure $2s_{1/2}$ wave function overestimates the measured σ and the pure $1d_{5/2}$ wave function underestimates it.

We define the s-wave spectroscopic factor f with equation,

$$\phi(r)=\sqrt{f}\phi_s(r)+\sqrt{1-f}\,\phi_d(r)\ , \quad (5)$$

where ϕ_s and ϕ_d are $2s_{1/2}$ and $1d_{5/2}$ wave function respectively. By fitting the experimental results, the s-wave spectroscopic factor f is obtained to be (80±21)%. With the parameter a to be higher, the s-wave spectroscopic factor f will be lower.

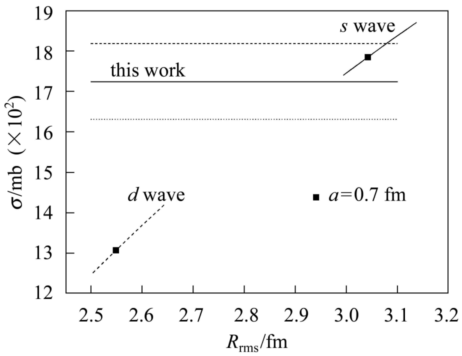


Fig. 4. The relation of σ and $R_{\rm rms}$ by assuming the valence neutrons in $2s_{1/2}$ or $1d_{5/2}$ orbits. The horizontal solid line is the experimental result. The dashed and dotted lines indicate the upper and lower error. The solid points show the diffusion parameter a of the Woods-Saxon potential fixed to be 0.7 fm. The tilted lines indicate pure wave with a changed from 0.6 to 0.9 fm (from left to right).

Our result of the s-wave spectroscopic factor f is consistent with Suzuki's result of (69±20)% extracted from the longitudinal momentum distribution of ^{15}B fragments from the breakup of ^{17}B[3], while larger than Suzuki's result[2] and Yamaguchi's result[4] extracted from the reaction cross section measurements in higher energy region. Our result supports that the valence neutrons of ^{17}B have a wave function contributed mainly by the intruder $2s_{1/2}$ state.

4 Summary

The reaction cross section of ^{17}B on ^{12}C target at (43.7±2.4) MeV/u has been measured at RIBLL. The $R_{\rm rms}$ is deduced to be (2.92±0.10) fm, while the $R_{\rm rms}$ of the core and the valence neutrons are 2.28 fm and 5.98 fm respectively. The valence neutrons extend far outside the core. This result confirms the halo structure of ^{17}B.

Assuming the valence neutrons in $2s_{1/2}$ or $1d_{5/2}$ orbits, the neutrons distributions are calculated by solving the Schrödinger equation. The $R_{\rm rms}$ of neutrons in $2s_{1/2}$ and $1d_{5/2}$ are 6.24 fm and 3.94 fm respectively. The neutrons in $2s_{1/2}$ extend much farther outside the core than neutrons in $1d_{5/2}$ due to the low centrifugal barrier. The mixed configuration of $(2s_{1/2})$ and $(1d_{5/2})$ of the valence neutrons is studied and the s-wave spectroscopic factor is found to be (80±21)%.

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