Experimental evidence for the $^8$B ground state configuration

D. Cortina-Gil $^{a,b}$, K. Markenroth $^c$, F. Attallah $^b$, T. Baumann $^d$, J. Benlliure $^a$, M.J.G. Borge $^e$, L.V. Chulkov $^{b,f}$, U. Datta Pramanik $^b$, J. Fernandez-Vazquez $^a$, C. Forssén $^c$, L.M. Fraile $^e$, H. Geissel $^b$, J. Gerl $^b$, F. Hammache $^b$, K. Itahashi $^g$, R. Janik $^h$, B. Jonson $^e$, S. Karlsson $^c$, H. Lenske $^i$, S. Mandal $^b$, M. Meister $^c$, X. Mocko $^h$, G. Münzenberg $^b$, T. Ohtsubo $^{b,j}$, A. Ozawa $^k$, Y. Parfenova $^c$, V. Pribora $^f$, K. Riisager $^j$, H. Scheit $^m$, R. Schneider $^n$, K. Schmidt $^b$, G. Schrieder $^o$, H. Simon $^o$, B. Sitar $^h$, A. Stolz $^n$, P. Strmen $^h$, K. Sümmerer $^b$, I. Szarka $^h$, S. Wan $^b$, H. Weick $^b$, M. Zhukov $^c$

$^a$ Universidad de Santiago de Compostela, E-15706 Santiago de Compostela, Spain
$^b$ Gesellschaft für Schwerionenforschung (GSI), D-64291 Darmstadt, Germany
$^c$ Avd. för Experimentell Fysik, Chalmers Tekniks Högskola och Göteborgs Universitet, SE-412 96 Göteborg, Sweden
$^d$ NSCL, Michigan State University, East Lansing, MI 48824, USA
$^e$ Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain
$^f$ Kurchatov Institute, RU-123182 Moscow, Russia
$^g$ Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan
$^h$ Faculty of Mathematics and Physics, Comenius University, 84215 Bratislava, Slovakia
$^i$ Institut für Theoretische Physik I, D-35392 Giessen, Germany
$^j$ Department of Physics, Niigata University, 950-2181, Japan
$^k$ RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-01, Japan
$^l$ Institut für Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark
$^m$ Max-Planck Institut für Kernphysik, D-69117 Heidelberg, Germany
$^n$ Physik-Deparment E12, Technische Universität, München, D-85748 Garching, Germany
$^o$ Institut für Kernphysik, Technische Universität, D-64289 Darmstadt, Germany

Received 14 December 2001; received in revised form 18 January 2002; accepted 25 January 2002

Abstract

The $^7$Be fragments produced in one-proton removal from relativistic $^8$B nuclei of 936 MeV/nucleon in a carbon target have been detected in coincidence with $\gamma$ rays emitted by these fragments at the reaction target. It is found that 13 ± 3% of the $^7$Be fragments are released in the 429 keV excited state, $^7$Be*, which gives direct experimental information on the ground state configuration of $^8$B. The longitudinal momentum distributions ($p_\parallel$) of the $^7$Be fragments have been measured, both inclusively.

$^*$ E-mail address: d.cortina@usc.es (D. Cortina-Gil).

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PII: S0370-2693(02)01245-5
The image of a halo nucleus as consisting of valence nucleons coupled to an inert core has had to give way for a more complex concept. The interplay between increasingly detailed experiments and more elaborate theoretical models has made it clear that for most cases, core excitations have to be taken into account to accurately describe all features of halo nuclei. A way to experimentally study the importance of core polarization is in-beam \( \gamma \)-spectroscopy, where the \( \gamma \)-rays emitted from the core are measured as the halo nucleus is broken up into its constituent parts. This type of experiments has been carried out at intermediate energies for neutron-rich beryllium and carbon isotopes at NSCL-MSU [1,2]. No similar studies have up to now been published for high incident energies, or for \(^8\)B.

The proton dripline nucleus \(^8\)B is currently of interest in many respects. Knowing the structure of its ground state (\( I^\pi = 2^+ \)) is of vital importance to both halo physics and astrophysics, a fact reflected by the many recent experimental and theoretical papers devoted to this nucleus. With only one bound state and a one-proton separation energy of 137 keV, \(^8\)B is the only nucleus known so far that has a proton halo structure in its ground state. Experimental evidence for an extended structure of \(^8\)B are provided by measurements of a large one-proton removal cross section of 98 ± 6 mb (on carbon) and a narrow longitudinal momentum distribution of 93 ± 5 MeV/c [3,4]. Being an \( A = 8 \) nucleus, reactions involving \(^8\)B are important in understanding how the nucleosynthesis bridges the \( A = 8 \) mass gap. In particular, the astrophysical interest in \(^8\)B stems from its key role in the production of high-energy solar neutrinos in the context of the solar neutrino deficit problem [5]. Only 0.02% of the pp-cycles in the Sun result in a \(^8\)B, but its \( \beta \) decay is responsible for virtually all neutrinos above 1 MeV, the part of the spectrum most neutrino detectors are sensitive to. This and the deficiency of measured neutrinos as compared to the number calculated from solar theories, has made it important to know the production rate of \(^8\)B as accurately as possible. The proton capture rate of \(^7\)Be strongly depends on the structure of \(^8\)B. In particular, any component in the \(^8\)B ground-state involving \(^7\)Be core-excited states has zero overlap with the \(^7\)Be ground state (from which the proton capture takes place) and therefore leads to a reduction of the astrophysical \( S_{17} \) factor.

Describing \(^8\)B as a one-proton halo system, one should keep in mind that the \(^7\)Be core is in itself a weakly bound system, which can be considered as a two-body system (\(^4\)He + \(^3\)He). The \(^7\)Be 3/2\(^-\) ground state is bound by 1.587 MeV, and the only bound state below this \( \alpha + \(^3\)He \) threshold is the 1/2\(^-\) state at 429 keV. Considering \(^8\)B as a two-body system, there are three possibilities to couple a proton to the \(^7\)Be core: the last proton in \(^8\)B can be in either a \( p_{3/2} \) or a \( p_{1/2} \) state, and the possible ground state configurations of \(^8\)B (\( I^\pi = 2^+ \)) thus are:

(a) \(^7\)Be(3/2\(^-\)) \( \otimes \) p(3/2\(^-\)),
(b) \(^7\)Be(3/2\(^-\)) \( \otimes \) p(1/2\(^-\)),
(c) \(^7\)Be(1/2\(^-\)) \( \otimes \) p(3/2\(^-\)).

A coincident measurement of the 429 keV \( \gamma \)-rays and the \(^7\)Be fragments from the one-proton removal process of \(^8\)B gives direct information about the contribution from configuration (c) to the \(^8\)B ground state wave function (WF). It should be noted that simple two-body models, in which effects of core excitations and deformations are not incorporated, cannot give the weights and the relative-motion wave functions of the configurations (a)–(c). During the last years, few-body microscopic models which incorporate effects of the core excitation and deformation, have been developed and applied to \(^8\)B [6–9]. All these models describe the bulk properties of \(^8\)B well. In papers [6,9], the \(^7\)Be–p relative motion wave functions for all three configurations (a)–(c) are obtained by projecting the calculated \(^8\)B WF onto the corresponding \(^7\)Be WFs. These relative-motion WFs have already been used for comparison with experimental one-proton removal cross sections and \(^7\)Be longitudinal momentum distributions, and demonstrated good agreement with the experimental data [3]. The current experiment gives
the possibility to measure the component (c) of the $^8$B ground state directly. As the experiment is performed at high energy, any influence from reaction mechanism is minimized. Note that the feeding of $^7$Be* in intermediate energy Coulomb dissociation was measured by Kikuchi et al. [10,11]. However, no conclusions for the $^8$B ground state configuration was drawn by these authors.

For this experiment, a 936 MeV/nucleon $^8$B beam was produced by fragmentation of a $^{12}$C primary beam (with energy 1.0 GeV/nucleon), delivered by the heavy-ion synchrotron SIS, in a 8 g/cm$^2$ Be target. The Fragment Separator (FRS) at GSI was used in its energy-loss mode to transmit the $^8$B secondary beam to the reaction carbon target (4405 mg/cm$^2$) at the intermediate focal plane (F2) and the $^7$Be fragments to the final focal plane (F4). The detector setup at the FRS, shown in Fig. 1 and described for example in Ref. [12], includes position sensitive time projection chambers (TPC) which give complete particle tracking and are used to deduce longitudinal momentum ($p_\parallel$) distributions. Other elements of the setup are ionization chambers (IC) and MUSIC in F2 and F4 for determining the fragment charge, and scintillators that give the time of flight between the different parts of the FRS. Using the magnetic rigidity and the time-of-flight information together with the energy loss data from the IC in F2 and the MUSIC in F4, a complete particle identification is available throughout the spectrometer. For the present experiment, an array of 32 NaI crystals was set up behind the reaction target in F2 for detection of $\gamma$-rays emitted by the fragments. The measurement of $\gamma$-rays in coincidence with fragments in F4 give information about the number of fragments emitted in an excited state compared to the ground state, and thus about the relative contribution of core-excited states in the projectile ground state. The geometrical coverage of the NaI array is 1.0% of $4\pi$, which is enhanced to 10.9% for the fragments decaying in-flight due to kinematic focusing ($\beta \approx 0.86$). The total detection efficiency of the NaI array was simulated using GEANT [13], and was found to be 2.9% for $E_\gamma = 428$ keV. In the analysis, a selection in the NaI time signal made it possible to discriminate $\gamma$-rays from the neutron background. Time-of-Flight (ToF) and particle tracking was used to Doppler-correct the $\gamma$-energies, and a summing procedure was implemented to collect signals from $\gamma$ rays scattered between neighboring detectors. The measured Doppler-corrected $\gamma$-spectrum is shown in Fig. 2. The peak from the known $1/2^-$ state at 429 keV is clearly visible in spite of the exponential background, present due to limited time resolution.

The longitudinal momentum distributions were deduced by measuring the position distribution at the experimentally determined focal plane in F4 and trans-
Fig. 2. Spectrum of γ rays in coincidence with 7Be fragments after one-proton removal reactions of $^8$B in a carbon target. The spectrum is obtained from the measured γ spectrum after Doppler correction. The solid line is a fit to the data with a Gaussian and a decaying exponential.

forming these distributions into fragment momentum distributions in the projectile frame. Without any conditions, the inclusive spectrum contains all components of the $^8$B ground state. The experimental width of $p_{\text{total}}^\parallel$ distribution is obtained as 95 ± 5 MeV/c (FWHM) (points, upper panel in Fig. 3) in agreement with previous results [3,4]. To extract the longitudinal momentum distribution of the 7Be fragments that emitted 429 keV γ-rays, the following steps were taken. First, a $p_{\text{total}}^\parallel$-distribution was deduced under the condition that a 429 keV γ-ray was emitted. The background contribution to the 429 keV-peak is 69%. To eliminate this contamination, the corresponding longitudinal momentum distribution with events coming only from the background (at high γ-energy) was created as well. The background distribution was then subtracted from the one obtained in coincidence with the 429 keV peak. The resulting curve represents the longitudinal momentum distribution of 7Be in the excited 1/2$^-$ state. This distribution, which has a width of 109 ± 7 MeV/c (FWHM) is shown in the lower panel of Fig. 3 (points). The increase in width for the $p_{\text{exc}}^\parallel$ distribution as compared to the $p_{\text{total}}^\parallel$ distribution is expected, since the excitation of the core effectively increases the binding energy of the last proton by 429 keV, resulting in a larger width of the $p_{\text{exc}}^\parallel$ momentum distribution.

The same conditions, as well as corrections for transmission efficiency and NaI detection efficiency, were used to find the cross sections $\sigma_{-1p}$ for the inclusive and exclusive channels. The total one-proton removal cross section obtained in this way is $\sigma_{-1p}^\text{total} = 94 ± 9$ mb, in excellent agreement with earlier results [3,14].

By selecting events that were measured in coincidence with the 429 keV γ-rays, subtracting the background and correcting the number of 7Be in F4 for NaI and transmission efficiencies an exclusive one-proton removal cross section of $\sigma_{-1p}^{\text{exc}} = 12 ± 3$ mb was deduced.

The relative weight of the component of the core-excited configuration in the ground state of 8B, can be obtained from the ratio of $\sigma_{-1p}^{\text{exc}}/\sigma_{-1p}^\text{total}$, which is 13 ± 3%, where the error includes statistical errors and the precision of the GEANT simulation.

For comparing the data in this Letter with a theoretical model we choose to use the 8B wave function calculated in the extended three-body model (4He + 3He + p) [6,9]. As the experiment is performed at high energies and with a light target, the eikonal approximation of the Glauber model is used when calculating
core fragment momentum distributions and breakup cross sections [15–18]. The main ingredients of the eikonal approximation are the core (here $^7\text{Be}$) and the proton profile functions, which take into account the interaction of the fragments with the target, and the $(^7\text{Be} - p)$ relative motion wave functions.

\[
F_{j_xj_y}(Y) = \langle \psi_{j_I}^{4\text{He}}(X, Y) | \psi_{j_x}^{7\text{Be}}(X), \{Y, \hat{\eta}(Y), \chi_S\} | j_I \rangle,
\]

where the variables $X$ and $Y$ are the Jacobi coordinates defined in paper [6]. The $^7\text{Be}$ profile functions were obtained by folding the $^4\text{He}$ and $^3\text{He}$ profile functions with their relative motion WFs $\psi_{j_x}^{7\text{Be}}(X)$ [9]. The profile functions for $^4\text{He}$ and $^3\text{He}$ were obtained using the NN interaction cross sections from Ref. [19, 20] and the corresponding charge densities. To reproduce the $^4\text{He}$ reaction cross sections at light targets, the $^4\text{He}$ density has been scaled with a factor 0.8, which is the single adjustable parameter of the model. Similar scaling was used in [18] to reproduce the $^7\text{Be}$ reaction cross section at 285 MeV/u. Note that with the scaled $^4\text{He}$ density we obtain good agreement with experimental values for both $^7\text{Be}$ and $^8\text{B}$ reaction cross sections on carbon targets at 285 MeV/u [21].

The stripping and diffraction cross sections were calculated separately for each of the components (a)–(c) of the $^8\text{B}$ wave function, and the corresponding momentum distributions from the stripping processes were deduced. These calculations give $\sigma_{\text{exc}}^{\text{1p}} = 11.5$ mb and $\sigma_{\text{total}} = 82$ mb. Even though the calculated $\sigma_{\text{total}}$ is smaller than the experimental result, the ratio of the theoretical cross sections is 0.14, in good agreement with the experimental number, 0.13 ± 3. The calculated shapes of the $p_{\text{p}}^{\text{exc}}$ distributions are shown as full drawn curves in Fig. 3. Their widths are 99 MeV/c and 130 MeV/c for the inclusive and exclusive distributions, respectively. In Table 1, our experimental values for one-proton removal cross sections and $p_{\text{p}}$ are listed together with the same quantities predicted by the theory for comparison.

In summary, we have in this Letter reported results of measurements of cross sections and longitudinal momentum distributions of $^7\text{Be}$ fragments from one-proton removal of a relativistic $^8\text{B}$ beam. Registering the $\gamma$-rays around the target and selecting those corresponding to $^7\text{Be}$ in the excited 429 keV state made possible the extraction of the weight of the component in the $^8\text{B}$ ground state wave function for which the $^7\text{Be}$ core is in its excited state. It is found that the total one-proton removal cross section $\sigma_{\text{total}} = 94 \pm 9$ mb, coincides with previous measurements. Further, the shape of the calculated $p_{\text{p}}^{\text{total}}$ distribution is in very good agreement with the experimental data. The shape of the calculated $p_{\text{p}}^{\text{exc}}$ distribution is also close to the experimental result and the cross section agrees with the measured value, $\sigma_{\text{exc}}^{\text{1p}} = 12 \pm 3$ mb.

Table 1 Comparison between experimental (exp.) and the theoretical (theo.) values for $\sigma_{\text{1p}}$ and $p_{\text{p}}$ (FWHM) for $^7\text{Be}$ fragments after one-proton removal of $^8\text{B}$. The first row refers to quantities measured inclusively (without any condition on $\gamma$’s in F2) and the second to the feeding to the first excited state of $^7\text{Be}$. The theoretical widths include the experimental resolution.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\text{1p}}$ (mb)</th>
<th>$\sigma_{\text{1p}}$ (mb)</th>
<th>$p_{\text{p}}$ (MeV/c)</th>
<th>$p_{\text{p}}$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>94  ± 9</td>
<td>82</td>
<td>95  ± 5</td>
<td>99</td>
</tr>
<tr>
<td>Exc.</td>
<td>12  ± 3</td>
<td>11.5</td>
<td>109  ± 7</td>
<td>130</td>
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</tbody>
</table>

Acknowledgements

This work was supported by EU under contract ERBFMECT95 0083, and by Internationales Büro Osteuropa-Verbundverbüro des BMBF bei den DLR under contract WTZ Bonn SLA-002-96, BMBF under contract number 06DA9151 and NFR, Sweden, contract F5102-1484/2001.

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