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Structure beyond the dripline in the Boron isotopes: ^{16,18,20,21}B

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As part of the first phase program of experiments utilizing the SAMURAI spectrometer and NEBULA neutron array, we have undertaken invariant mass spectroscopy of ^{16,18,20,21}B using the complementary probes of neutron and proton knockout. After a brief introduction to the experimental setup and analysis techniques, the results for ^{16,18}B are discussed and compared to earlier work, where in addition to substantially improving our knowledge of the known threshold states in both systems, evidence for new levels has been found. Finally, the first results for ^{20,21}B are presented, and the influence of the sequential decay of ^{21}B on the low-energy ^{20}B spectrum discussed.

KEYWORDS: SAMURAI, unbound nuclei

1. Introduction

The investigation of the light neutron-rich dripline nuclei, including in particular those exhibiting halos, is a central theme of nuclear structure physics. These studies have, however, been limited for the most part to the He, Li and Be isotopes. With the advent of the RIKEN RIBF [1] and intense energetic beams of ^{48}Ca, the path has been opened to exploring the structure of heavier neutron dripline nuclei, and in particular of nuclei beyond that border. The Boron isotopic chain, starting with the proton halo of ^{8}B and ending with the two-neutron haloes of ^{17,19}B, is of considerable interest. In the present work, measurements aimed at exploring the structure of the unbound neutron-rich Boron isotopes ^{16,18,20,21}B are described. While ^{16,18}B are critical in defining the ^{15,17}B-n interactions for three-body modeling of ^{17,19}B, the structure of ^{20,21}B is of considerable interest in terms of shell-structure below doubly-magic ^{22,24}O.

These measurements were part of the Commissioning and Day-One experimental campaign of SAMURAI that took place at RIKEN RIBF in March-May 2012, and a description of the other physics program and experimental details can be found in Ref. [2]. In brief, various secondary beams were employed to bombard a Carbon target, surrounded by the DALI2 gamma spectrometer [3], and the population of unbound states in the Boron chain was investigated through 1n and/or 1,2p knockout reactions. The Boron fragments were detected using the SAMURAI spectrometer, its eventual bound state excitation using DALI2, and the neutrons using the NEBULA array [4].

2. Experimental technique

Proton knockout reactions at high energy present the advantage of preferentially populating states whereby the neutron configuration remains little perturbed with respect to that of the projectile [5]. In order to maximize the sensitivity to little-known or unknown unbound states, several projectiles with different structural information were used in order to populate the Boron isotopes of interest, when possible, through 1 and 2p knockout. The complementary 1n knockout path and breakup were also explored for the lighter ones. The fragment-neutron relative energy E_{rel} spectrum was reconstructed from the measured momenta, and the coincidence with γ rays detected in DALI2 investigated. Importantly, NEBULA provided a very high acceptance (100% up to $E_{rel} \approx 2$ MeV and still some 30% at 10 MeV), allowing states to be searched for over an energy range much wider than most of the previous experiments.

In addition to the fragment+neutron coincidences arising from in-flight decay of the unbound states, care must be taken to account for uncorrelated events, the non-resonant part of the relative energy spectrum [6, 7]. Such events may arise from a number of sources. For example, in the case of breakup, whereby the outgoing channel of interest has fewer neutrons than the projectile, from the detection of the neutron(s) that do not correspond to the population of fragment+neutron states; in reactions involving proton only removal, from the fragment recoil effect [8] and the scattering of the weakly bound valence neutron by the target. As discussed in detail and demonstrated in Refs. [6,7,9], the distribution of uncorrelated events may be estimated by event mixing using the measured fragment+neutron pairs, provided that care is taken to eliminate the effects of any "residual" correlations arising from the resonant structures themselves [9]. Importantly, this technique involves no *ad hoc* assumptions or parametrizations and the distribution so obtained incorporates explicitly the effects of the experimental response. As such, it may be compared directly with the measured distribution in order to identify features arising from the decay of unbound states.

3. Results

3.1 Boron 16

The halo neutrons wave function of ^{17}B contains roughly equal admixtures of $\nu 1d^2_{5/2}$ and $\nu 2s^2_{1/2}$ [10]. The observation of the γ-ray de-excitation of the two bound excited states of ^{15}B in the dissociation of ^{17}B suggests that core excitations may also play a role [11]. Little, however, is known about ^{16}B, beyond its unbound nature [12]. Evidence for a very low-lying state, at 0–100 keV above the ^{15}B+n threshold, together with indications for a higher lying level at 2.4 MeV, was found in a heavy-

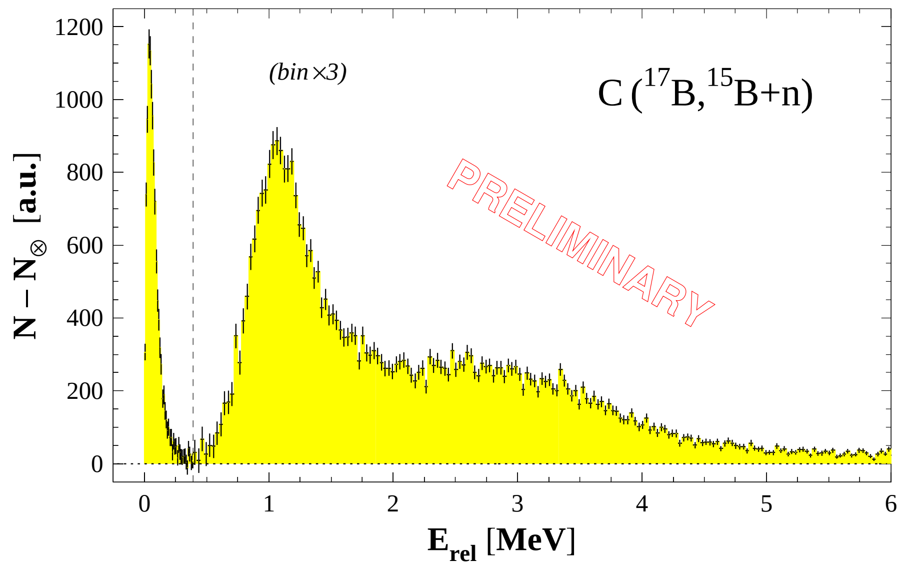

Fig. 1. Reconstructed ^{15}B-n relative energy spectrum after 1n removal from ^{17}B. The non-resonant contribution, obtained by event mixing, has been subtracted from the data (see text).

ion multi-nucleon transfer reaction study [13]. The 1p knockout from ^{17}C has been more recently used to populate the ground state of ^{16}B [6, 14]. In both experiments significant low-lying strength was found below 100 keV. However, the statistics, resolution [6] and acceptance [14] were not sufficient to precisely characterize the state nor observe other resonant excited states. This low-lying strength was attributed to the state observed close to threshold in Ref. [13], although no coincident γ-ray detection was available, introducing an ambiguity in the calculated excitation energy of ^{16}B.

The ^{15}B-n relative-energy spectrum from neutron knockout from ^{17}B is shown in Fig. 1, where the non-resonant contribution, reconstructed by event mixing [6, 7, 9] and preliminary normalized to the data at high relative energy, has been subtracted. Three prominent features appear: a very narrow, low-lying peak, at about 40 keV; a second peak at about 1.1 MeV; and a broader structure at about 2.8 MeV. The very high statistics and the use of DALI2 allowed three-particle coincidences, ^{15}B+n+γ, to be recorded. Although the analysis is still ongoing, some conclusions can already be made. First, the γ-ray energy spectrum in coincidence with ^{15}B+n exhibits a clear peak at about 1.3 MeV, characteristic of the excitation of ^{15}B [11]. The analysis of the correlation between the energies of the γ ray and the ^{15}B-n pair shows that the 1.3 MeV γ rays are in coincidence only with the two structures at higher energy, but not with the low-lying one (Fig. 1).

An accurate description (including the non-resonant contribution and all the experimental effects) of the peak at about 40 keV will therefore provide the mass of ^{16}B with an uncertainty as low as $\sim$ 10 keV. The structure at about 1.1 MeV, when adding the ^{15}B* excitation energy, may correspond to the higher lying level suggested in Ref. [13]. The analysis of the data from the $-1p$ reaction from a ^{17}C beam is in progress.

3.2 Boron 18

Very little is known about the structure of the heaviest Boron isotope, ^{19}B, besides its two-neutron halo character [15] and mass [16]. A recent search for states in ^{18}B using 1p knockout from ^{19}C proposed an upper limit for the scattering length of the ^{17}B-n system of -50 fm [14]. Other than this s-wave virtual state, no other structures were observed.

In the present work, three different reaction channels were investigated: 1p knockout from ^{19}C,

$2p$ knockout from ^{20}N, and $1n$ knockout from ^{19}B. The relative energy spectrum from $1p$ knockout exhibits a characteristic s-wave virtual state similar to that observed in Ref. [14]; however, the higher statistics and broader relative-energy range, together with the non-arbitrary determination of the non-resonant background, should lead to a very precise value for the ^{17}B-n scattering length. No γ rays from ^{17}B [11] were observed in coincidence.

The other two reaction channels (^{19}B and ^{20}N beams) exhibit different structures above and beyond the non-resonant distribution. In some of those, the ^{17}B+n are in coincidence with a γ ray of $\sim$ 1.1 MeV, characteristic of the excitation of ^{17}B [11]. The analysis in progress should provide a precise characterization of the ^{18}B ground state, as well as the excitation energies of several levels below 5 MeV.

3.3 Boron 20 and 21

The $2p$ knockout reaction from ^{22}N lead to some 300 ^{19}B+n events, that exhibit a prominent peak at a relative energy of about 2.5 MeV, plus a less well populated structure at about 5 MeV. Before associating these to the ground and first-excited states, respectively, of ^{20}B, other reaction channels should be investigated in order to confirm that no other low-lying states exist that were not populated due to the selectivity of the $2p$ knockout reaction. The $3p$ knockout from ^{23}O and the $-2p1n$ breakup of ^{23}N did not, however, lead to any appreciable number of ^{19}B+n events.

Another reaction channel, $-1p1n$ from ^{22}C, has been explored. Some 250 ^{19}B+n events were acquired. The relative energy spectrum, however, does not exhibit the two peaks observed in the $-2p$ channel, nor any other peak. On the contrary, a plateau appears, from $\sim$ 0–2 MeV. The preliminary interpretation of this is that $1p$ knockout from ^{22}C has populated a resonance slightly beyond 2 MeV in ^{21}B, the 3-body decay of which into ^{19}B+n+n has lead to the plateau in the ^{19}B-n relative energy. A preliminary description of the spectrum under this hypothesis is consistent with a ^{21}B resonance at some 2.4 MeV. One should note that, even if this hypothesis is confirmed, the plateau could hide lower-lying resonances that have indeed been populated.

4. Summary and perspectives

The Commissioning and Day-One experimental campaign of SAMURAI at RIKEN RIBF has provided structural information for a wide range of nuclei around the neutron dripline, going from ^{16}B up to ^{25,26}O, including the heaviest two-neutron haloes ^{19}B and ^{22}C. Here we have presented the investigation of states in the unbound neutron-rich Boron isotopes. The preliminary results for the two lighter ones, ^{16,18}B, confirm the known threshold states and, with the help of the γ rays measured in coincidence, should provide a more complete spectroscopy. For the unknown, heavier isotopes, ^{20,21}B, states have been observed for the first time. These results, guided by Shell Model calculations, should shed light on the structure of these nuclei.

Acknowledgments

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