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^{12}B(n,γ) - the influence on r-process nucleosynthesis of light elements

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Because of interest in the ^{11,12}B(n,γ) reaction in seeding r-process nucleosynthesis through light neutron-rich nuclei, we have measured the ^{12}B(d,p) reaction for the first time using the ATLAS in-flight facility at Argonne National Laboratory. We also measured the ^{11}B(d,p) reaction in the same way for calibration. The spectroscopic factors of excited states and the branching ratio of the neutron-unbound state in ^{12}B are obtained from the current experiment and the reaction rate for ^{11}B(n,γ) is discussed in comparison with the theoretical prediction.

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1. Introduction

Determining the possible astrophysical site and understanding the mechanism of heavy elements production are important problems in r-process nucleosynthesis. Due to the predicted high neutron flux and temperature, it has been suggested that the r-process occurs in explosive environments, such as proto-neutron stars in Type II supernovae [1], neutron star mergers [2], neutron-rich jets from supernovae [3,4,5] and following gamma-ray bursts [6], and more. Most of these r-process studies have considered the neutron captures on a couple of thousands of heavy nuclei (Z>Fe) but only a very limited number of light nuclei. However, one of proto-neutron star models that includes a neutrino-driven wind model in a core-collapse supernova with a short dynamic timescale, $\tau_{dyn} = 5.1 \times 10^{-3}$s requires information about neutron captures on light neutron-rich nuclei [7]. The dynamic timescale determines the time spent during the α-process, where the seed nuclei (A∼70-120) are produced by abundant α's [7,8]. Therefore, with a short timescale fewer seed nuclei are produced yielding more neutrons to be captured on light neutron-rich nuclei as a way to bypass triple-alpha production of seed nuclei for the r-process.

Terasawa *etal*. [7] studied different reaction paths by calculating a "full" network, which was extended to include 40 more neutron-rich nuclei up to Z < 10, compared to only 27 light nuclei in a "small" network. This comparison revealed apparent differences in the final r-process abundances of heavy elements, in some cases by a factor of 10. Unfortunately, most reaction rates for neutron-rich radioactive nuclei are still unmeasured or poorly known experimentally in the temperature range of $T_9 < 2$ K. Sasaqui *etal*. [9] have studied the efficiency and sensitivity of such rates involving 18 light neutron-rich elements by comparing the r-process abundances to those from the solar system.

Rauscher *et al.* [10] estimated the uncertainties of the reaction rates for the ^{11}B(n,γ) and ^{12}B(n,γ) reactions to be a factor of 2, based on the limited spectroscopic information on ^{12}B and ^{13}B and considering both direct and resonant captures. Although there have been several investigations of the poorly known structure of ^{13}B [11], such as single-nucleon knockout [12], a proton intruder study [13], and a search for isobaric analog states[14], as well as theoretical efforts in cluster studies [15], the spin-parities of most excited states are not well determined [16].

In this contribution, we present the results of indirect studies of ^{11}B(n,γ) and ^{12}B(n,γ) via neutron-transfer measurements on ^{11}B and ^{12}B with the (d,p) reaction. Preliminary spectroscopic factors and the branching ratio of Γ_n/Γ_γ for the ^{11}B(n,γ) reaction are discussed.

2. Experimental setup

The measurement was performed using the ATLAS facility at Argonne National Laboratory. A radioactive ^{12}B beam was produced using the in-flight method via the (d,p) reaction, by bombarding a deuterium gas cell with a ^{11}B beam. The resulting 75 MeV ^{12}B beam was selected using a dipole magnet and delivered to the scattering chamber with the average intensity of 5×10^5 pps.

The experimental setup consisted of a 150 $\mu g/cm^2$ CD_2 target, three double-sided silicon strip detectors (DSSD) covering the backward angle of $110^\circ - 165^\circ$ in the laboratory system, a telescope of ΔE -E silicon detectors segmented into four quadrants covering the forward angle range of $1.4^\circ - 7.2^\circ$ in the laboratory system, and a silicon surface-barrier-detector (SSB) telescope

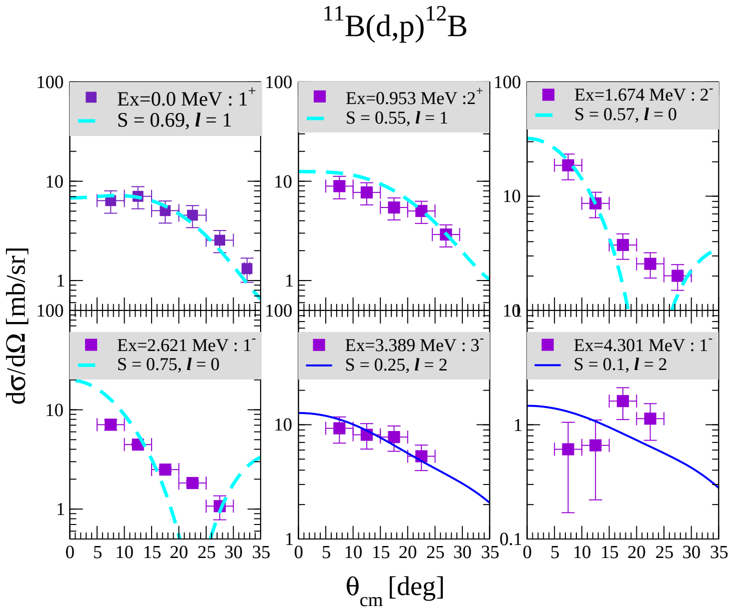

Figure 1: (Preliminary) Angular-distribution data for the ^{11}B(d,p)^{12}B in inverse kinematics with DWBA angular distributions calculated with the code PTOLEMY [17]. Dashed lines correspond to spectroscopic factors from Ajzenberg-Selove *et al.* [18] and solid lines are normalized to the current data. See the text for details.

positioned at 0° with a 1/100th attenuator to monitor the beam intensity. The DSSDs were 500μm thick, and were segmented into 16 annular rings on the front and 16 azimuthal wedges on the back. The energy resolutions of DSSDs were measured to be 35 keV$\sim$45 keV with 6 MeV α particles. The forward telescope detector consisted of a 75μm thick ΔE-detector and 1000 μm of E-detector. The setup and the detection technique are described in detail in Ref. [19].

Protons were detected at backward angles in coincidence with recoiling B ions in the forward detectors. Bound and unbound states in ^{13}B are easily separated by selecting identified ^{12}B and ^{13}B nuclei in the ΔE-E telescopes. Estimates of the detection efficiency and absolute normalization were obtained from Monte Carlo simulations of the detector setup, as well as measurements of the (d,p) reaction with the primary ^{11}B beam at a beam energy of 81 MeV.

3. Discussion

From measurements of the ^{11}B(d,p)^{12}B reaction, we obtained angular distributions for the states at E_X=0.0, 0.953, 1.674, and 2.621 MeV, below the neutron threshold, and for the unbound states at E_X = 3.389 and 4.301 MeV. As shown in Figure 1, most bound states are well described by DWBA calculations. The minima in the ℓ=0 angular distributions are likely smeared out by the angular resolution of the setup which is indicated by the horizontal error bars in Figure 1. The spectroscopic factors for the bound states show good agreement within 25 % uncertainty with the values from Ref. [18] (dashed lines). The preliminary spectroscopic factors for the unbound

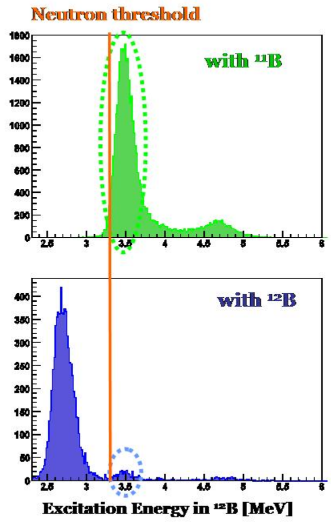

Figure 2: Proton yield vs. the excitation energy in ^{12}B. The upper and lower panels show counts in coincidence with ^{11}B and ^{12}B, respectively. The neutron threshold is drawn in vertical line and the dashed circles show the peaks of the unbound 3.389 MeV state.

states are estimated using the PTOLEMY code [17] with a form factor for the unbound neutron approximated by one with 50 keV binding energy and the analysis is ongoing.

For the unbound state at 3.389 MeV in ^{12}B, the ratio of neutron emission to gamma emission (Γ_n/Γ_γ) was estimated to be 124 by Rauscher *et al.* [10]. The high statistics of the current measurement permit an experimental determination of this quantity. The branching ratio Γ_n/Γ_γ was obtained by gating on the proton groups in coincidence with ^{11}B recoils (neutron emission) or with ^{12}B recoils (gamma emission), as illustrated in the top and bottom panels of Fig. 2, respectively. The reduced branching ratio from the current measurement results in a resonance strength enhanced by 50 %, with a similarly enhanced reaction rate, as compared with the theoretical prediction [10].

For the ^{12}B(d,p)^{13}B reaction, angular distributions for the states up to E_X =5.388 MeV were obtained in the same way as the measurements with the ^{11}B beam. The ^{12}B(n,γ) reaction rate in Ref. [10] was estimated by considering s-wave direct capture to the ground state and the resonant captures to the first two neutron unbound states at 5.106 MeV and 5.388 MeV. The direct capture cross section was calculated using first-order perturbation theory and the nuclear correction for the final bound state was obtained from the spectroscopic factor, which was predicted using the shell model [20]. Our current measurement will provide an experimental value for the ^{13}B ground-state spectroscopic factor, but these data are still being analyzed. The initially-assigned negative parities of two neutron unbound states were based on the shell model prediction [20] and the comparison with the mirror nucleus in Ref. [21]. The present data suggest, however that the measured widths are consistent with near single-particle configurations if ℓ=2. If the states have ℓ=0, their spectroscopic factors must be small. Therefore, the parities of these neutron unbound states are assigned to be even. The reaction rate for ^{12}B(n,γ) will be finalized in the near future.

4. Conclusions and Future Outlook

Using the method of inverse kinematics, the neutron-stripping spectroscopic factors for states in ^{12}B and ^{13}B were determined, including those for neutron-unbound states. For the first time the branching ratio of the unbound 3.389 MeV state in ^{12}B was determined experimentally resulting in an enhancement of the ^{11}B(n,γ) reaction rate. We will shortly determine the spectroscopic factor for the ground state of ^{13}B, which previously has only been estimated from shell-model calculations. Since a large (d,p) cross section implies even parity, the states of 5.106 MeV and 5.388 MeV in ^{13}B above the neutron threshold, formerly assigned to have odd parities, are expected to have even parities from our measurement.

In the future we plan to determine the reaction rates of ^{11}B(n,γ) and ^{12}B(n,γ) using the updated spectroscopic factors and branching ratios extracted from the current measurement. Also we will do the same for the existing ^{7}Li(n,γ) and ^{8}Li(n,γ) data. With new information for these reaction rates, we will run new r-process network calculations in order to determine the impact of the light neutron-rich elements.

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