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Investigation of the proton radius of the Borromean halo nucleus ^{19}B

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Abstract

The charge-changing cross-section (σ_{cc}) of the dripline nucleus, ^{19}B, was measured using the transmission technique at RIBF, RIKEN, to understand its root mean square proton radius (R_p). This new measurement will be the first determination of the R_p for the Borromean nucleus, ^{19}B. The new value of R_p will help determine the geometrical structure of ^{19}B and the neutron-neutron correlation in the Borromean nucleus.

1. Introduction

A nearly symmetric combination of protons and neutrons forms β-stable nuclei on the Segrè chart. However, some short-lived neutron-rich nuclei exhibit striking structural properties. The neutron-halo nuclei are an intriguing quantum system with a large radial extent caused by the valence neutron. The three-body system of two-neutron Borromean halo nuclei is particularly interesting as any two sub-systems are unbound. Exotic phenomena have been reported for such nuclei, such as the emergence of new magic numbers and the disappearance of conventional magicity [1, 2]. Further, the Borromean nuclei are the test bench for probing the neutron-neutron correlation.

^{17}B and ^{19}B are Borromean nuclei at the neutron-dripline of boron isotopes. A cascade of Borromean systems at the dripline is a unique condition observed only for boron and helium (^{6}He[3] and ^{8}He[4]) isotopes. The root-mean-square matter (R_m) and proton (R_p) radii are the structural properties of the nuclei that help to understand these halo systems. The experimental observations suggest that the R_p increases for Borromean nuclei on the isotopic chain, for example, ^{6}He [3], ^{11}Li [5], and ^{17}B [6]. Interestingly, the proton radius of ^{8}He is smaller compared to ^{6}He

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while having a larger matter radius [7]. This phenomenon concluded that ^{8}He has a $\alpha + 4n$ arrangement. The mass measurement [8] and interaction cross-section [9] studies have hinted at a similar structure for the ^{19}B nucleus. Further, both studies claim that the valence neutrons in ^{19}B occupy a $1d_{5/2}$ orbital, meaning it follows the traditional shell model. However, the recent measurement of the Coulomb dissociation of ^{19}B nucleus found 35% $2s_{1/2}$ contribution [10], contradicting the previous studies. These observations caused a stir in theoretical studies. H. T. Fortune et al. support predominantly $1d_{5/2}$ characteristics of the valence neutrons [11]. Recent studies [12–15] had mild success in reproducing the observations from K. J. Cook et al. [10]. Considering the deformation effects, X. X. Sun shows the ^{19}B nucleus has a more complex structure than the ^{17}B + $2n$ system [16]. The knowledge of the proton radius of ^{19}B will assist in concluding this discrepancy.

As depicted in Fig.1, theoretical predictions for the proton radius of ^{19}B vary greatly. Earlier calculations from the Relativistic Hartree-Bogoliubov (RHB) model [17], Skyrme-Hatree-Fock (SHF) model [18], Antisymmetrized Molecular Dynamics + Variation After spin and parity Projections (AMD+VAP) model [19], Hartree-Fock-Bogoliubov (HFB) model with SLy4 and UNEDF1 forces [20], Glauber model with harmonic-oscillator Slater determinants [21], predict a significantly lower value of R_p for ^{19}B than experimentally known R_p value 2.67(2) fm for ^{17}B [6]. However, the recent measurement of the Coulomb dissociation of ^{19}B improved theoretical models [10]. The new predictions from the AMD model [22] and ^{19}B modeled as a ^{17}B + n + n system [13] suggest ^{19}B to have slightly higher R_p than ^{17}B, contradicting the previous results. Further, the first observation of ^{20}B and ^{21}B nuclei as resonances has sparked a renewed interest in the search for magic numbers N = 14 and 16 for Z = 5 [23, 24]. For these reasons, it is crucial to experimentally determine the proton radius of ^{19}B.

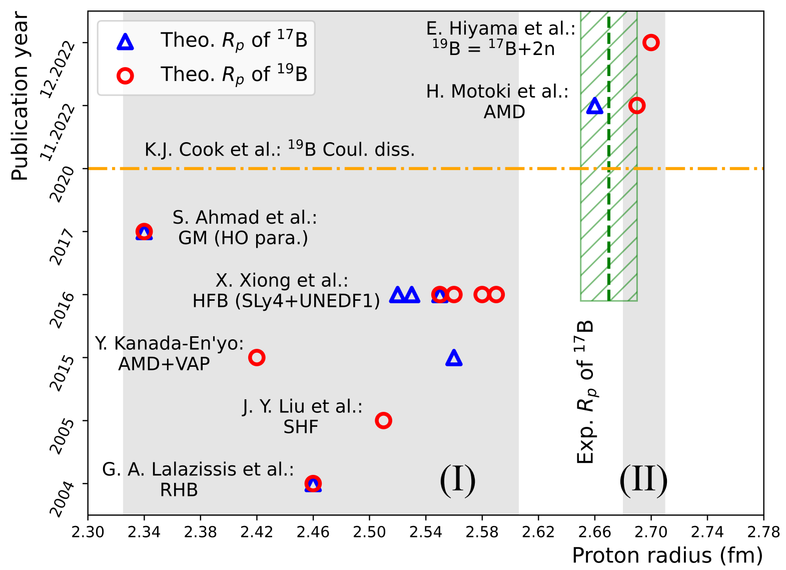

Figure 1: Theoretical predictions of proton radius for ^{17}B (blue triangles) and ^{19}B (red circles). Values in the shaded region-I, are mainly guided by the observed S_{2n} [8] and matter radius [9]. The references in shaded region-I are [17–21]. Predictions in the shaded region-II are the new values considering the dineutron correlation, suggested in Ref [10]. The references in shaded region-II are [22, 13]. The green hatched region is the experimentally determined proton radius of ^{17}B: 2.67(2) fm [6].

2. Measurement of charge changing cross-section (σ_{cc})

The traditional methods for measuring the proton radius R_p (e.g., electron scattering, isotope shift) are challenging for the drip line nuclei due to short half-lives and weak beam intensities. For exotic nuclei, an extraction of R_p via Glauber model analysis of the charge-changing cross-section (σ_{cc}) is a reliable method [2]. The σ_{cc} is the total cross-section of all reactions that change the proton number of the nucleus. The R_p can be extracted with the finite range Glauber model within OLA (Optical-Limit Approximation) [25–27].

Transmission technique enables the experimental measurement of the σ_{cc}. The σ_{cc} is determined from the measurement of transmission with ($Tr_{\rm in}$) and without ($Tr_{\rm out}$) target. Mathematically,

$$\sigma_{cc} = \frac{1}{t} \ln\left(\frac{Tr_{\rm out}}{Tr_{\rm in}}\right) \tag{1}$$

where, t is the reaction target thickness. The transmission Tr is the ratio of number of incoming nuclear species ($N_{\rm inc}$) and outgoing unreacted particles. For the σ_{cc} measurement, in addition to unreacted boron isotopes, nuclei with $Z > 5$ are also considered as unreacted, as the proton pick-up and charge exchange reactions are not sensitive to the proton distribution of the projectile nucleus. Hence, $Tr = N_{Z\geq5}/N_{\rm inc}$.

The experiment was performed at the RI Beam Factory (RIBF) at RIKEN using the BigRIPS fragment separator and the Zero-Degree Spectrometer (ZDS). The secondary beam of ^{19}B was produced via projectile fragmentation of the ^{48}Ca primary beam at ~345A MeV on a ^{9}Be production target. ^{19}B was identified and selected in-flight using the BigRIPS separator and ZDS spectrometer. To improve the purity of the secondary beam, wedge-shaped Al degraders were placed at the dispersive foci F1 and F5. The thicknesses of the production target and the Al wedges at F1 and F5 were 10, 20, and 8 mm, respectively.

As depicted in Fig.2 this measurement was performed at the F11 focal plane with 2.5 g/cm^2 carbon target. Before the final target at F11, the incoming beam particles ($N_{\rm inc}$) were identified with the $TOF-B\rho-\Delta E$ method [28]. Plastic scintillators at F8 and F11 were used to measure the Time Of Flight (TOF). The magnetic rigidity ($B\rho$) of incoming particles was determined by trajectory reconstruction using Parallel Plate Avalanche Counters (PPAC) at dispersive focus F9 and achromatic focus F11 [29]. MUlti Sampling Ionization Chamber (MUSIC) identified Z at F11 before the target. After the reaction target, the MUSIC detector was used to count the number of nuclei with $Z \geq 5$ ($N_{Z\geq5}$).

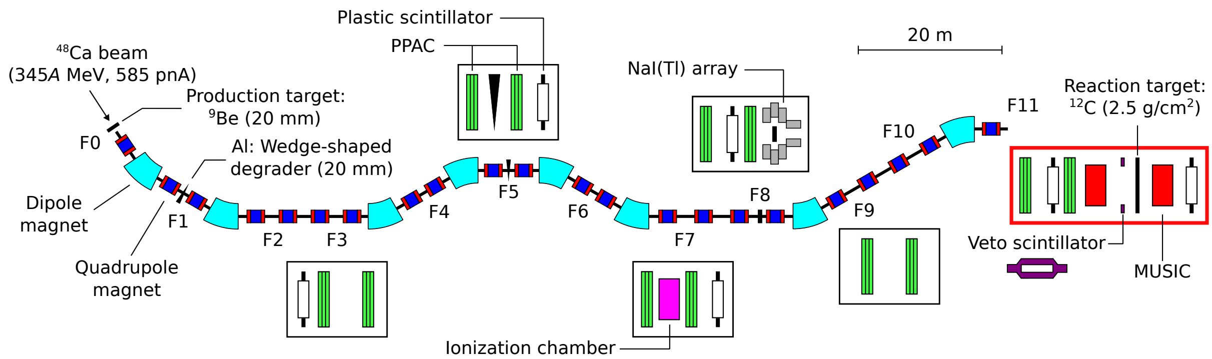

Figure 2: BigRIPS (F0 to F7) and ZDS spectrometer (F8 to F11) schematic showing detector arrangement for σ_{cc} measurement of ^{19}B at the F11 focal plane.

3. Preliminary observation

As shown in particle identification plot Fig.3(a), the ^{19}B events are well separated from other nuclear species and have a sufficient count rate of 48 pps at F11. Fig.3(b) is the Z spectrum for the outgoing particles from the downstream MUSIC placed after the reaction target. The charge-changing reactions are visibly increased for the spectrum with target compared to that without target.

The proton radius of ^{19}B will be extracted from the measured σ_{cc} using the Glauber model reaction framework. The combined knowledge of matter radius and proton radius (this work) will determine the geometrical structure of the nucleus, enabling us to understand the short-range forces acting between two neutrons and core and neutrons. Further, the complete evolution of the neutron skin thickness of neutron-rich boron isotopes ($^{12-19}$B) will help to guide theoretical models. As shown in Fig.1, theoretical prediction for the proton radius of ^{19}B varies widely. Hence, this measurement will be the test bench for theoretical models. The $N = 14$ is a new magic number observed in neutron-rich oxygen isotopes [24]. Hence, by studying the proton radius trend for the boron isotope, one can determine if $N = 14$ magicity holds for $Z = 5$.

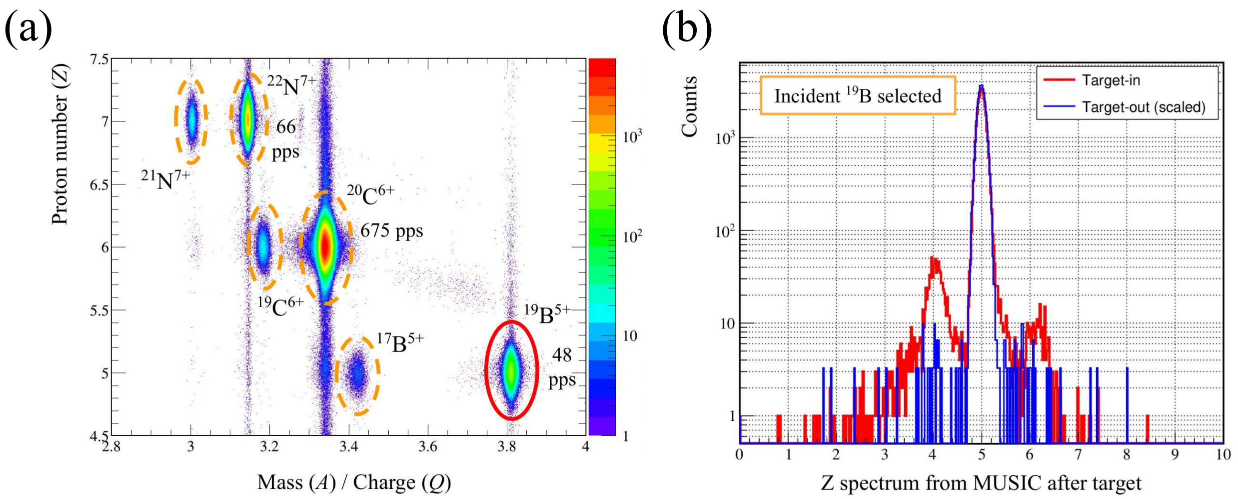

Figure 3: **(a)** Particle identification with ZDS detectors before the reaction target. Nuclear species and their rate are indicated **(b)** Z spectrum of the MUSIC after the reaction target for with (red) and without (blue) target conditions.

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