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Spectroscopy of ^{16}B from quasi-free (p, pn) reaction with ^{17}B

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Abstract. Spectroscopy of ^{16}B plays an essential role in understanding the halo structure in ^{17}B, but very limited knowledge has so far been obtained. We have carried out a kinematically complete measurement on the spectroscopy of ^{16}B by using quasi-free (p, pn) reaction on ^{17}B. The level scheme of ^{16}B up to 5 MeV was made clear for the first time.

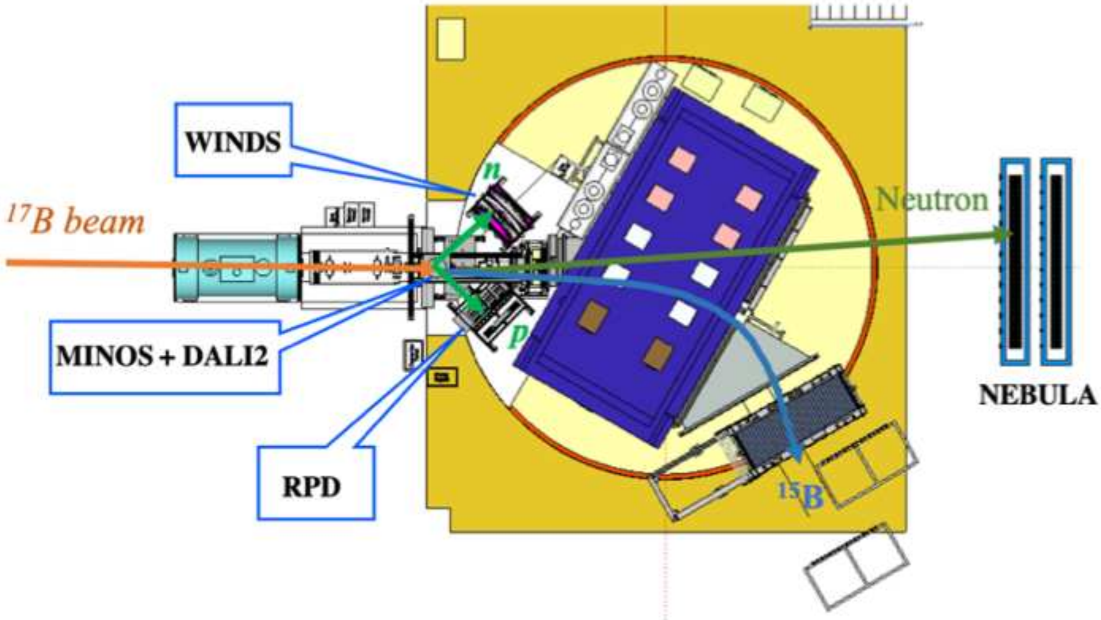

Figure 1. Schematic view of the experimental setup

1. Introduction

Since the first discovery in the 1980s, the neutron halo structure has been at the focus of experimental and theoretical studies (see, *e.g.*, [1, 2, 3, 4, 5]). Of particular interest are nuclei with two-neutron halo structure (also known as Borromean nuclei) such as ^{11}Li and ^{14}Be, for which the strong dineutron correlation between the two valence neutrons is crucial for the binding [4, 5, 6]. It has been suggested that configuration mixing with different-parity single particle orbitals, is essential for the development of dineutron correlation [5, 7, 8]. In this context, the Borromean nucleus ^{17}B, lying in the middle of the *sd*-shell, may provide new perspectives on neutron correlations since the mixing with opposite parity states would be rare as expected with the sequence of conventional single particle orbitals. Well-developed halo structure in ^{17}B has been indicated from the large matter radius [10, 9], thick neutron surface [11] and the narrow longitudinal momentum distribution of the ^{15}B core in the inclusive breakup reaction [12], but detailed understanding still awaits to be grasped. The spectroscopy of the core-plus-one-neutron subsystem ^{16}B is the essential ingredient to understand the structure of ^{17}B. But very limited knowledge has so far been obtained for ^{16}B beyond the low-lying ground state with extremely small width [13, 14, 15].

Here we report a new measurement on the spectroscopy of ^{16}B based on the quasi-free (p, pn) reaction on ^{17}B complemented by kinematically complete measurements of all the reaction products including γ-rays emitted from the excited ^{15}B core.

2. Experimental setup and measurements

The experiment was carried out at Radioactive Isotope Beam Factory (RIBF), which is operated by the RIKEN Nishina Center and the Center for Nuclear Study (CNS), University of Tokyo. A schematic view of the experimental setup is presented in Fig. 1. The secondary ^{17}B beam with an energy of 277 MeV/nucleon and an intensity of around 10^4 pps was produced from the fragmentation of ^{48}Ca, and then transported through the BigRIPS beam line [16, 17] onto the vertex-tracking liquid hydrogen target system - MINOS [18], which is 150-mm thick. The recoil proton after the (p, pn) reaction was analyzed by the TPC of MINOS and also the RPD spectrometer composed of a multi-wire drift chamber and a plastic scintillator array, and the recoil neutron partner was detected by the neutron detector array WINDS [19]. The charged fragments were analyzed by the SAMURAI spectrometer and the associated detectors [20] . The decay neutrons with beam velocity were detected by the plastic scintillator array NEBULA, located at ~12 m downstream of the target. A γ-ray detector array, constructed from 68 NaI crystals of the DALI2 in-beam γ-ray spectrometer [21], was also installed at the target region to detect prompt γ-ray emitted from excited ^{15}B residuals. Details of the setup and performance of the detectors can be found in [22].

The relative energy $E_{\rm rel}$ of ^{16}B is reconstructed from momentum vectors of the ^{15}B fragment and the decay neutron using the invariant-mass method. To obtain the decay energy ($E_{\rm d}$) with respect to the ^{15}B+n emission threshold, $E_{\rm x}(^{15}\rm B)$ should be added when the fragment ^{15}B is populated in a bound excited state ($E_{\rm d} = E_{\rm rel} + E_{\rm x}(^{15}\rm B)$), and in this case the emitted γ-ray will be recorded by the DALI2 array.

3. Results and discussions

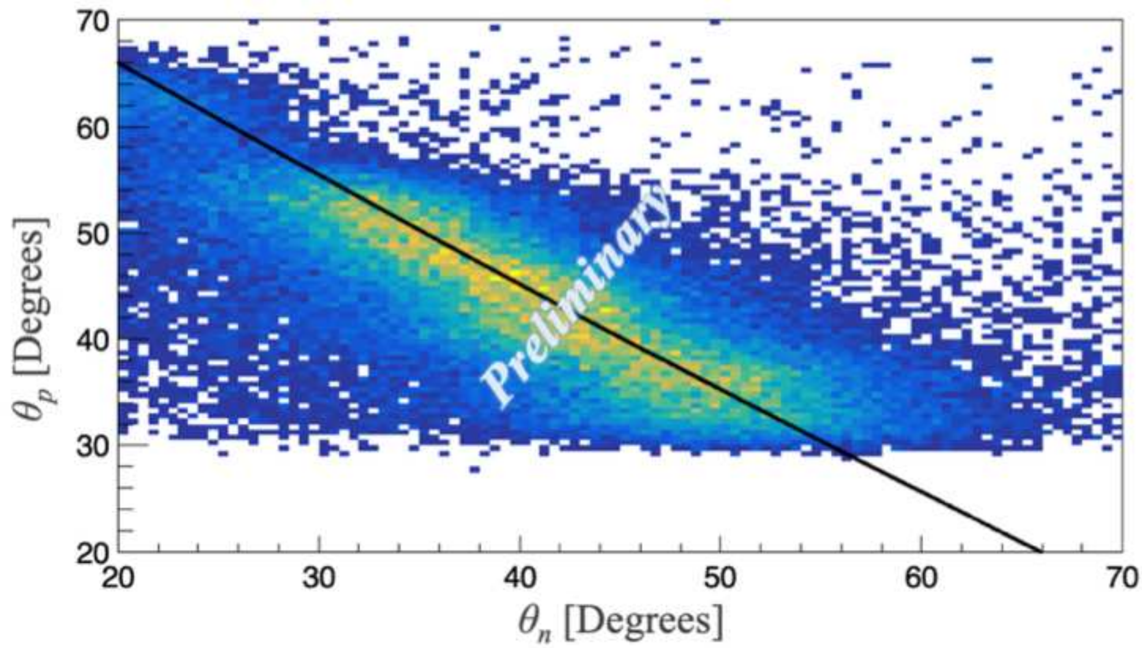

Figure 2. Correlations between the polar angles of the recoil proton and recoil neutron (θ_p, θ_n) in the present measurement. The black solid line indicates the correlation pattern from the kinematical calculation.

When studying the core-plus-one-neutron binary systems populated in the breakup of Borromean nuclei like ^{17}B, some non-resonant component is generally included to account for the background resulted from reaction processes other than the quasi-free neutron removal, such as inelastic breakup of ^{17}B followed by emission of beam-velocity neutrons. In the present analysis, we first checked the angular correlation between the recoil proton and neutron to confirm the dominance of the quasi-free (p, pn) reaction. As shown in Fig.2, the correlation pattern between the polar angles, θ_p and θ_n, follows closely the kinematical simulation assuming the quasi-free

(p, pn) reaction on ^{17}B. Therefore, it can be concluded that the current measurement is indeed dominated by the quasi-free (p, pn) reaction.

The ^{16}B relative energy spectrum from the present measurement exhibits clearly a narrow peak at ~ 0.04 MeV, and two broader peaks at ~ 1 MeV and ~ 3 MeV (see the blue histogram in Fig. 3(b)). The peak located at ~ 0.04 MeV should correspond to the ground state of ^{16}B reported in the literature [13, 14, 15], while the other two peaks could not be evidenced in the published E_{rel} spectrum of ^{16}B [14, 15].

Before we move on to the detailed analysis of the E_{rel} spectrum, we would like to discuss the γ-ray coincidence, since strong population of excited ^{15}B fragments has already been reported in an earlier breakup experiment of ^{17}B[23].The Doppler-corrected γ-ray energy spectrum associated with ^{15}B fragments is shown in Fig. 3(a). A sum of contributions from two known gamma rays of ^{15}B, 1327 KeV associated with the first excited state and 1407 KeV from the cascade decay of the second excited state [24], and a background modeled with a two-exponential function provided a good reproduction of the experimental spectrum. From the relative intensities of the two gamma rays, a ratio of $\sim 15\%$ was extracted for the second excited state of ^{15}B, which is consistent with the estimation ($\sim 20\%$) in the previous inclusive breakup experiment [23].

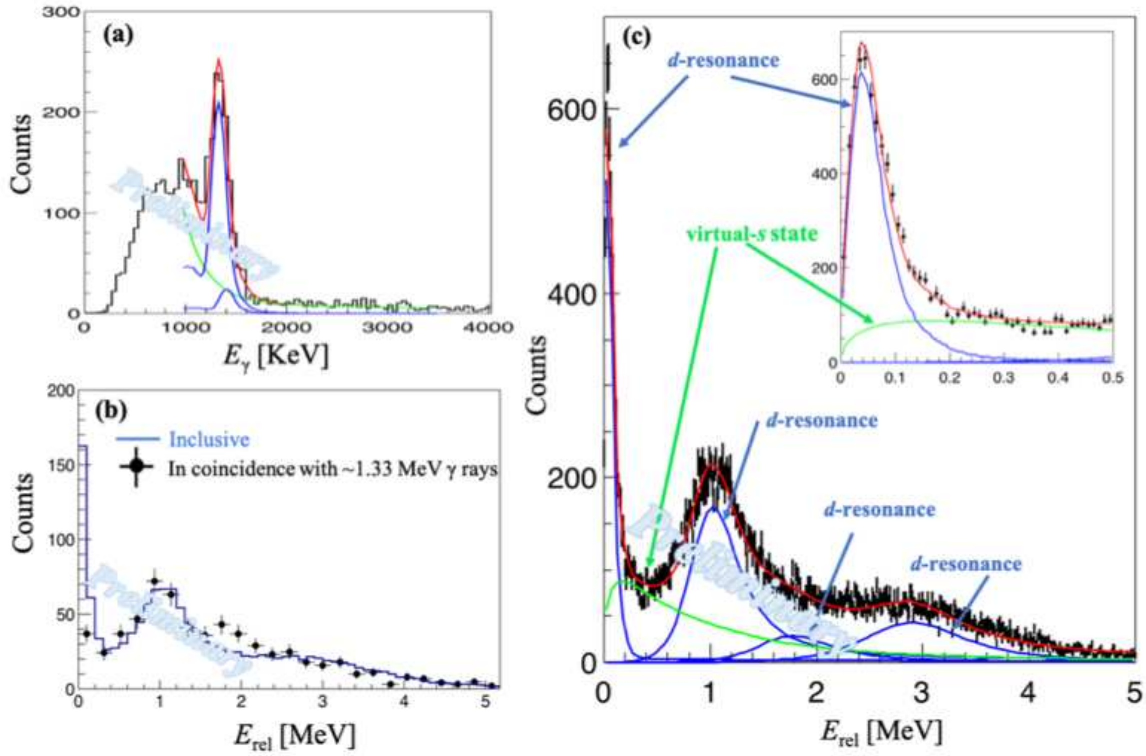

Figure 3. (a) The γ-ray spectrum of ^{15}B observed in the present measurement. (b) ^{16}B E_{rel} spectra gated by the 1.33-MeV γ-ray (filled circles). The inclusive spectrum is also shown after proper normalization for comparison (Blue solid histogram). (c) Analysis of the ^{16}B E_{rel} spectrum. The spectrum is fitted with a sum of four d-wave and one s-wave components. The inset shows a zoom-in view of the close-to-threshold region.

Fig. 3(b) shows the E_{rel} spectrum of ^{16}B gated by the 1.33-MeV γ-ray peak (1100 KeV $\leq E_\gamma \leq$ 1600 KeV), and the inclusive E_{rel} spectrum is also shown for comparison after proper normalization. It should be noted that ^{15}B fragments in both first and second excited states will be included in the applied E_γ gate. Obviously, the $\sim$ 0.04 MeV peak shows no correlation with the gamma ray and therefore corresponds to the low-lying ground state reported by Kalpakchieva *et al.* [13]. Meanwhile, the $E_{\rm rel} \sim 1$ MeV peak is clearly correlated, associating this peak to the excited state of ^{16}B at $\sim$ 2.32 MeV observed in the multi-nucleon transfer experiment[13]. The $\sim$ 3 MeV peak of the $E_{\rm rel}$ spectrum also shows correlation with the 1.33 MeV gamma ray peak. One interesting observation in the γ-gated $E_{\rm rel}$ spectrum is the peak-like structure located at $\sim$ 1.8 MeV, which could not be clearly identified when coincidence with γ ray was omitted. One possible explanation is that the $\sim$1.8 MeV peak is associated with the second excited state of ^{15}B, and therefore it gets relatively enhanced by a factor of around 2 with respect to the $\sim$ 1.0 MeV peak when requiring the γ-ray coincidence since the two gamma rays (1327 KeV and 1407 KeV) from the cascade decay can both be accommodated in the applied γ-ray gate ($1100\ KeV \leq E_\gamma \leq 1600\ KeV$). But direct analysis of the γ-γ coincidence could not be achieved because of the limited statistics for events with a γ-ray multiplicity of two.

Based on the discussions above, four d-wave resonances accounting for the peaks at $\sim$0.04 MeV, $\sim$1 MeV, $\sim$1.8 MeV and $\sim$ 3 MeV and one s-wave component are included in the current fitting of the $E_{\rm rel}$ spectrum. Breit-Wigner line shapes with energy-dependent width was adopted for the d-wave resonances, while the s-wave component (s-wave virtual state) is formulated with the effective-range approximation [25]:

$$\begin{aligned} \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\rm rel}} &\propto k_{\rm rel}[\frac{1}{k^2+k_{\rm rel}^2}]^2[\cos(\delta)+\frac{k}{k_{\rm rel}}\sin(\delta)]^2. \\ k_{\rm rel}\cot(\delta) &= -\frac{1}{a_{\rm s}}+\frac{1}{2}r_0 k_{\rm rel}^2. \end{aligned} \tag{1}$$

with $a_{\rm s}$ being the scattering length and r_0 being the effective-range parameter, and k and $k_{\rm rel}$ defined as $k=\sqrt{2\mu \mathrm{S_{2n}}}$ and $k_{rel}=\sqrt{2\mu E_{\rm rel}}$.

Since the width of the d-wave resonance at $\sim$ 0.04 MeV is much smaller than the current resolution ($\sim$ 40 KeV for $E_{\rm rel} = 0.04$ MeV), it is fixed to 1 KeV in the fitting, and the upper limit is estimated to be around 40 KeV. The best fit was obtained from χ^2 analysis as shown in Fig. 3 (c), and the results are tabulated in Table 1. As discussed above, the second and fourth peaks (1.0(1) MeV and 2.9(1) MeV) of the $E_{\rm rel}$ spectrum are associated with ^{15}B*(1.33MeV) while the third peak (1.8(1) MeV) is associated with ^{15}B*(2.73 MeV). The total energy $E_{\rm d}$ of each state with respect to the ^{15}B($g.s.$)+n threshold can thus be determined as $E_{\rm d} = E_{\rm rel} + E_{\rm x}(^{15}\mathrm{B})$, which is also listed in Table 1.

Table 1. Energy levels of ^{16}B observed in the current measurement.

	a_s or $E_{\rm r}$	$\Gamma_{\rm r}$ [MeV]	Final state of ^{15}B	$E_{\rm d}$	Published data
s-wave	-7.5(1) fm	–	g.s.	0.4(1)[a]	–
d-wave	0.04(1) MeV	< 0.04	g.s.	0.04(1)	0.04(4) [13] 0.085(15) [14] 0.06(2) [15]
d-wave	1.0(1) MeV	0.8(2)	1.33 MeV	2.4(1)	2.40(7)
d-wave	1.8(1) MeV	0.6(2)	2.73 MeV	4.5(1)	–
d-wave	2.9(1) MeV	0.6(1)	1.33 MeV	4.2(1)	–

[a] For virtual s-wave state, the resonance energy $E_{\rm r}$ is estimated as $E_{\rm r} \approx \frac{\hbar^2}{2\mu a_{\rm s}^2}$.

The low-lying 0.04(1) MeV state agrees well with the early reports with similar invariant-mass method [14, 15]. The anti-coincidence with gamma ray verified in the present measurement and the well correspondence to the 0.04(4) MeV state observed in the multi-nucleon transfer reaction by Kalpakchieva et al. [13], which is free from gamma ray measurement, demonstrate firmly that it is the ground state of ^{16}B. The 2.4(1) MeV state also agrees well with the result of Kalpakchieva et al. [13]. But the 4.5(1) MeV, 4.2(1) MeV and s-wave virtual state are newly observed in the present measurement. It is worthwhile to emphasize that inclusion of the s-wave virtual state is essential to provide a good reproduction of the observed energy spectrum, as illustrated in the inset of Fig. 3(c). It has been pointed out in many studies that the s- or p-wave components play the key role for the formation of neutron halo [1, 2, 3, 4, 5].

Now the analysis of the momentum distribution and extraction of the spectroscopic factors incorporated with reaction theories are in progress.

Acknowledgments

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