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Excited states in neutron rich boron isotopes

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Abstract

New experimental results on in-beam gamma spectroscopy of neutron rich boron isotopes are presented for ^{17}B and its neutron removal fragments ^{14,15}B, after scattering with a H_2 target. A gamma transition for ^{17}B is observed at 1089 ± 15 keV. The fragment ^{15}B is observed abundantly associated with a gamma transition of 1336 ± 10 keV. This suggests for the first time a core-excited structure for ^{17}B thereby providing a new insight into its structure. Observations for ^{12,14}B are also presented. The data set provides a useful systematic study of first excited states of neutron rich boron isotopes showing the dramatic drop in excitation energy beyond $N = 8$.

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Spectroscopic studies of neutron rich nuclei have become important for understanding the nuclear structure evolution far from stability. For exploring excited states of unstable nuclei, measurements on Coulomb excitation and inelastic scattering have been successfully performed using in-beam gamma spectroscopy [1,2]. This is particularly useful for studying nuclei with very low intensities due to the possibility of using thicker targets.

In this Letter we present new results on the gamma-decay transitions obtained from inelastic scattering of ^{17}B nucleus on a proton target. Transitions have also been observed for the neutron removal products $^{15–12}$B. The results delineate the first observation of ^{17}B having a substantial amount of core (^{15}B) excited structure. This is a new information on the ground state structure of ^{17}B. In addition the new gamma-decay transitions for ^{15,17}B provide a means of systematic study of excited states of neutron rich boron isotopes. This helps in delineating changes in structure and single particle orbitals.

Reaction studies, measuring interaction cross section and two-neutron removal momentum distribution [3,4], have indicated interesting structure features for the neutron rich boron isotopes, in particular for ^{17}B, predicting a halo. The analysis of the reaction studies [3,4] however assumes the core ^{15}B to be in its ground state. The structure of ^{17}B is also interesting to investigate because magnetic moment of the isotopic chain shows a rapid decrease as one goes to more neutron rich isotopes [5]. The large quenching for ^{17}B was ascribed to be due to enhanced contribution of two neutrons coupled to $J = 2^+$. If this were true, this would signify that in a core $+ n + n$ model of ^{17}B, the ^{15}B core could have a significant probability of existing in the excited state. This kind of core-excited configuration has so far not been considered in previous structure studies on this nucleus based on interaction cross section [3], and momentum distribution [4] measurements. An experimental investigation of such structure is thus important. The present Letter has indicated an evidence to this conjecture thereby giving us new information on the ground state structure of ^{17}B. Moreover, no information exists in the literature on excited states of boron isotopes beyond ^{14}B. Thus, investigation on excited states for ^{15,17}B isotopes is expected to provide interesting systematics of the isotopic chain. It maybe mentioned here that very recently (while the present Letter was in the process of review) observation of gamma transitions from excited states of ^{15}B, populated by projectile fragmentation, have been reported [6].

The experiment was performed at the RIKEN Ring Cyclotron facility. The secondary beam of ^{17}B was produced by the fragmentation of a ^{22}Ne primary beam with an energy of 110 A MeV, on a 8 mm thick Be production target. The secondary beam at the reaction target was a cocktail with ^{17}B and ^{19}C as the dominant components. The incident beam was identified using the using time-of-flight (TOF) between scintillators placed at the two achromatic foci of the fragment separator, combined with magnetic rigidity and energy loss (ΔE) information. The ^{17}B beam was impinged on a liquid H_2 target of average thickness of 0.180 g/cm^2 sandwiched between two Aramid foil windows, 12.5 μm thick. The beam profile could be monitored by two parallel plate avalanche counters (PPAC) placed upstream of the H_2 target. The H_2 target was surrounded by an array of 158 NaI(Tl) crystals (DALI2) [7] which detected the deexcitation gamma rays. This kind of experimental setup has been previously used for similar inelastic scattering studies [8,9]. In this Letter we refer to gamma-ray multiplicity as the number of different NaI(Tl) crystals hit for a single event. In case of multiplicity = 2, for example, the total gamma energy is given by sum of $E_\gamma^{\mathrm{hit1}} + E_\gamma^{\mathrm{hit2}}$. This includes independent hits in the two different crystals as well as correlated hits. Correlated hits are events where there are Compton scattered gamma rays from one crystal to another. The detection efficiency was measured by placing standard sources at the target position. The full peak efficiency including up to hit multiplicity = 2 was around 26% with the 661 keV line from ^{137}Cs source. The 1173 keV, 1332 keV lines from ^{60}Co source yielded efficiencies of 14% and 12%, respectively. A polynomial fit to these data were used for deriving the efficiency at the observed gamma ray energy for the boron isotopes.

The TDC spectra, triggered by an incident nucleus and stopped by a gamma ray in the NaI(Tl) crystals in coincidence with the ^{15}B fragment, shows a characteristic two-component peak with H_2 target. A time gate of ~ 10 ns was put around the narrow peak (P_1; $\sigma =$ 1.7 ns) that corresponded to the prompt events resulting from the target. The wider peak (P_2; $\sigma = 4.4$ ns) originates from non-target materials downstream of

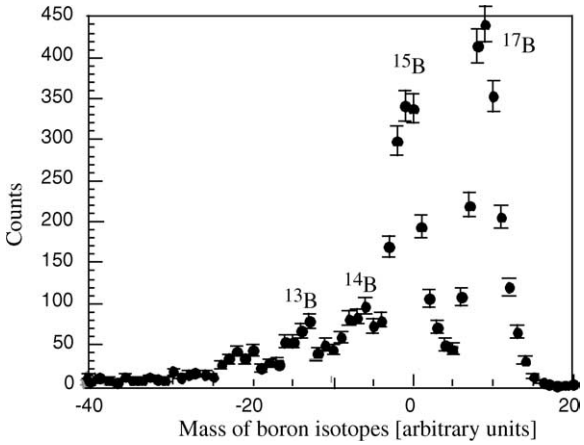

Fig. 1. Identification of boron isotopes after the H_2 target with silicon telescope in coincidence with NaI(Tl) array with single hit. The black filled circles are data with H_2 target, within time gate (P_1).

the target. It was assigned so because only the peak P_2 was observed in the data without H_2 target. The integrated events for P_1 was nearly 2.5 times more than P_2, in the gamma energy region associated with the transitions observed for the boron isotopes.

The ^{17}B scattered projectile and the reaction products after the H_2 target were detected and identified by a silicon telescope (500 μm + 2 mm + 2 mm + 500 μm) placed ∼ 90 cm downstream of the target. The particle identification (PID) was done using ΔE–E. The energy of ^{17}B at the target mid-plane was around 43 A MeV. This energy was further degraded after the target using thick Al plates (3 mm) to ensure the stopping of the beam in the silicon stack. The Al degraders were located at ∼ 67 cm downstream of the target and ∼ 20 cm before the silicon stack. Fig. 1 shows a particle identification spectrum for all particles after reaction target in coincidence with single hit events in the gamma detectors after correction for the ΔE–E correlation. The correction was done by polynomial fit for the ΔE–E hyperbola and rotation, in order to make a modified E-axis which then becomes independent of the modified ΔE-axis.

To search for gamma transitions in the different boron isotopes, energy spectrum corrected for Doppler shift was studied in coincidence with the particular fragment identified at the silicon telescope. A confirmation of the Doppler correction was obtained from the agreement in observed peak position for well-known 953 keV ^{12}B deexcitation gamma rays as discussed later. The Doppler correction was done event by event with the beam energy determined for each event from the calibrated time-of-flight measured between scintillators at the foci. The time-of-flight calibration was done by tuning the separator to $A/Z = 2$ particles and using a very narrow momentum slit. The uncertainty of the target thickness introduces an error of ∼ 5 keV in the peak position determination.

The dynamic range of the measurement including Doppler correction was $30 \leqslant E_\gamma \leqslant 2600$ keV. The low threshold was set in order to confirm (to the best of ability) that the observed transition corresponds to the first excited state. In order to set such a low threshold the higher end of the dynamic range had to be restricted to 2600 keV. This however did not impose any severe limitations on the measurement, because the one-neutron separation energy (S_n) of ^{15}B is 2.7 MeV and the two-neutron separation energy (S_{2n}) of ^{17}B is 1.37 MeV. Although, for ^{15}B the dynamic range is slightly below S_n, the first excited state for this nucleus is predicted to be around 1.5 MeV by theoretical models as discussed later. The setting of the low threshold was confirmed by data taken with standard ^{133}Ba source and also checked during setup by ^{241}Am source placed at the target position.

All the gamma energy spectra were observed with the narrow time window (P_1) discussed above for prompt gamma selection. This selection window was kept fixed for both target-in and target-out conditions. This resulted in negligible amount of background events from target-out runs, at the peak positions.

Fig. 2(a) shows a γ-ray spectrum associated with ^{17}B after the target. A clear peak is seen at 1089 ± 15 keV. The error includes 5 keV statistical contribution and 14 keV systematic contribution. The energy add-back of gamma ray multiplicity 2 events yields 25% more statistics. No other significant peak is observed within our dynamic range. The observed peak appears consistent with the one observed in inelastic scattering with carbon target [10]. The grey points are target-in data and black ones are the data after subtraction of the background from target-out condition. The difference is negligibly small between grey and black data at the peak region. This shows that the prompt time-gated (P_1) data without H_2 target does not show any appreciable number of counts for a peak at 1089 keV. Hence, the excitation is primarily associ-

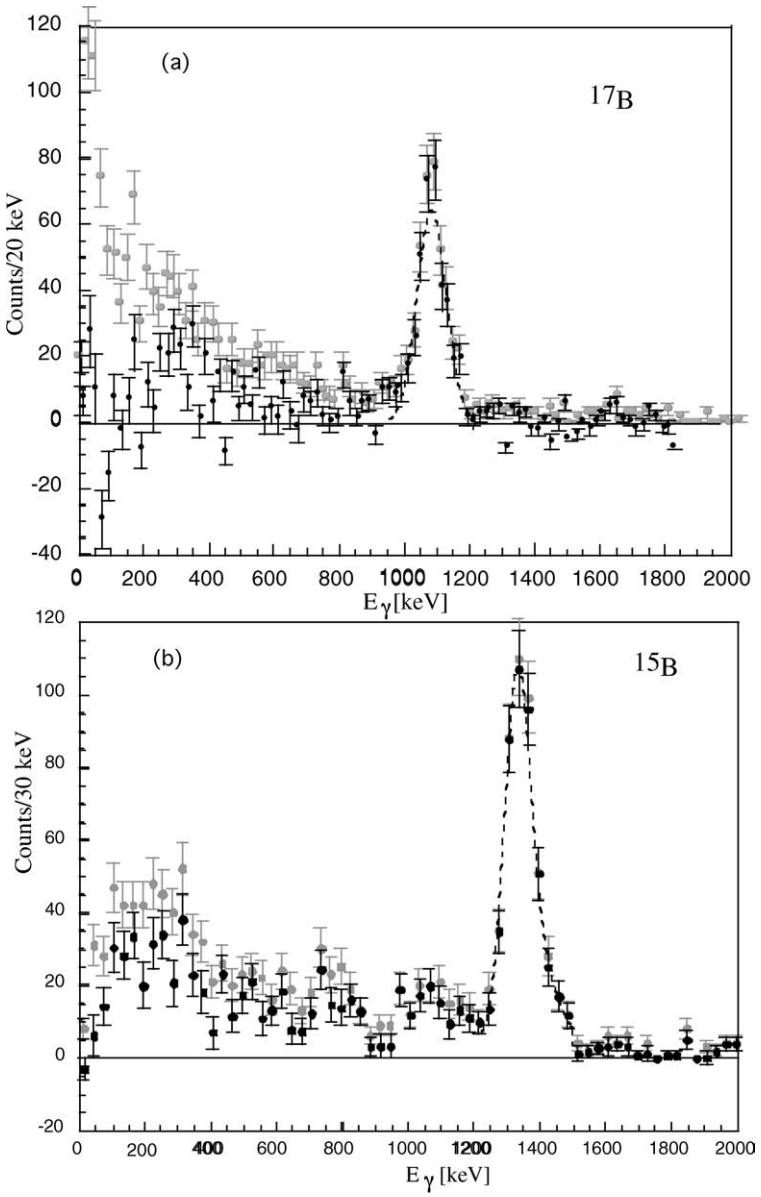

Fig. 2. The Doppler corrected gamma transition spectrum for (a) ^{17}B and (b) ^{15}B after interaction of ^{17}B with H_2 target, for single hit. The grey points denote condition with H_2 target. The black points denote spectrum after subtraction of non-target contribution. The dashed lines are Gaussian fits to the peak.

ated with the H_2 target. A large target-out background is observed only at very low γ-ray energies.

The gamma ray spectrum in coincidence with the two-neutron removal fragment ^{15}B shows a strong peak around 1343 keV (Fig. 2(b)) fitted by a single Gaussian. However, the high energy tail of the peak might contain a small fraction of the second excited state. Incidentally, some independent investigations suggest that the second excited state for ^{15}B decays by a gamma cascade 1407 and 1328 keV [6,10]. Thus, we fit the observed peak in Fig. 2(b) by a two-component Gaussian keeping the higher gamma energy fixed to

1328 keV. This yields a value of 1336 ± 10 keV for the strong peak in ^{15}B. The peak fitting is shown by the dashed line. Thus, a strong population of a level at 1336 ± 10 keV is suggested. It is also found that the population of the second excited state is rather small ($\sim 20\%$ of the total excitation). The total cross section to both the excited states of ^{15}B was found to be 18 ± 2 mb.

Similar to the ^{17}B case, as seen from the small difference of the grey and black points in Fig. 2(b), the non-target background is very small. Furthermore, it is interesting to see, that the large background peak at low gamma energies is absent in case of ^{15}B and will also later be seen to be absent for the other neutron removal boron fragments as well. The origin of the low energy background gamma peak is not fully understood. As a tentative explanation it is felt that the peak most likely originates from the deexcitation gamma rays from ^{28}Al, which maybe formed by capture of neutrons on ^{27}Al (degraders). So it is a random background. Since the events associated to the beam nucleus is much more than the fragments observed, it is observed appreciably for the events in coincidence with the beam only.

Excited states and gamma transitions are also observed for the products ^{14}B and ^{12}B as shown in Fig. 3(a) and (b), respectively. The observed γ-ray energy 956 ± 10 for ^{12}B is perfectly consistent with the excited state of ^{12}B at 953.1 ± 0.6 keV [11] and thus confirms the validity of the energy calibration of the present measurement. The energy for the ^{14}B transition is found to be 654 ± 9 keV. This is slightly lower than the previous observation (740 ± 40 keV) by multi-nucleon transfer reaction [12]. Unlike the well established ^{12}B excited state, there exists only one previous measurement on the low-lying excited state of ^{14}B where experimental uncertainty is large. Thus, the present value might be considered to be a new determination of transition energy for ^{14}B. No peaks were observed for ^{13}B since the first excited state of ^{13}B (3.48 MeV) is outside our dynamic range.

In Figs. 2, 3, we find that the gamma line associated with ^{17}B (1089 keV) also appears as a small peak in ^{15,14}B. To understand the origin of the appearance of gamma lines of a boron isotope for lighter boron isotopes too, we look at the correlation between the particle identification and the Doppler corrected gamma energies in Fig. 4. If one observes the gamma energy around 1089 keV, then a peak is prominently seen for ^{17}B, but weak peaks also appear $^{15–13}$B. The gamma energy around 1336 keV shows a strong peak for ^{15}B and it appears weakly in ^{13,14}B too. Interestingly, the ^{15}B gamma line does not appear for the heavier ^{17}B isotope. It is further noticed in Fig. 4, that extension of the 1089 keV (of ^{17}B) and 1336 keV (of ^{15}B) gamma lines to lighter boron isotopes is not a uniform distribution along the particle identification axis, but appear as discrete peaks. This confirms that the weak peaks in lighter boron isotopes do not originate from a tail in particle identification. Furthermore, it can be observed that these peak statistics is more for ^{13}B but less for ^{14}B. This is expected if we assume that those nuclei are produced by fragmentation reactions. The production cross section of the odd–odd nucleus (^{14}B) is usually less than even–odd nucleus (^{13}B). Thus, the observation of the ^{17}B (1089 keV) γ-line for the lighter boron isotopes is not due to a background from particle identification but due to the tertiary reactions. It means that, ^{17}B was first excited to the 1089 keV state by the H_2 target, and after that it fragmented further into $^{15–13}$B before reaching the SSD stack. The tertiary fragmentation may occur from the reaction target itself or from non-target materials downstream of the target. The fraction of tertiary fragmentation in the target and Al degrader can be roughly estimated to be about a few percent using the fragmentation cross section of ^{17}B. Larger contribution comes from the Al degrader. This estimate is close to the observed ratio.

We now compare our observations to the shell model [13] and AMD [14]. The predicted excited states are shown in Fig. 5. Although the energy of the first excited state in ^{15}B and ^{17}B are different between two models, they lay not far from the presently observed energy. The decreasing tendency of the excitation energy from ^{15}B to ^{17}B predicted by the models, is also consistent with the data. Therefore we can safely assume that the γ-rays observed for ^{15,17}B are from the first excited state of these nuclei. This is further confirmed experimentally from the fact that no other lower energy gamma transition (above 30 keV) was observed for these nuclei. In addition, both the models predict the spin-parity of the first excited state to be $5/2^-$. Therefore it might be possible to tentatively assign these γ-ray transitions from the $(5/2)^-$ first excited states of ^{15}B and ^{17}B. A confirmation on this as-

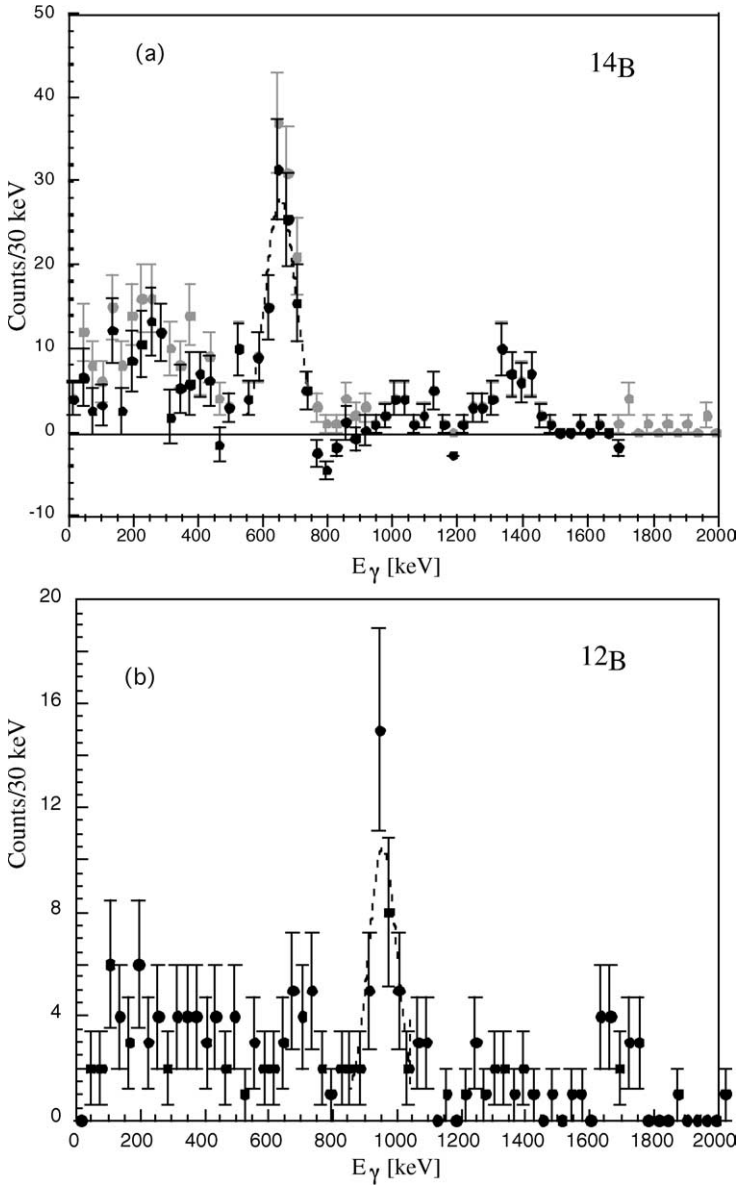

Fig. 3. The Doppler corrected gamma transition spectrum for (a) ^{14}B (b) ^{12}B fragments after interaction of ^{17}B with a H_2 target. The grey points denote condition with H_2 target for single hit. The black points denote spectrum after subtraction of non-target contribution. The dashed lines are Gaussian fit to the peak.

signment by different experimental investigation will be useful.

The choice for the appropriateness of a particular model (AMD or shell model) to be more favorable for explaining the structure of these nuclei seems to be a difficult judgment from a comparison with the data, in terms of excitation energy alone. The data seems to lie in between the values predicted by the two models. On the other hand it is felt that such data will be able to provide a guidance to refine these theoretical models.

The two-neutron separation energy for ^{17}B is 1.34 ± 0.170 MeV while the one-proton separation energy is 21.22 ± 0.530 MeV. In addition to this extremely weak binding of the neutrons, the neutron

pairing energy is reduced for neutron rich nuclei [15]. These conditions suggest that those states are made mainly by neutron excitation. The decreasing trend of the excitation energy, of the $5/2^-$ state, with neutron excess for the boron isotopes is also a reflection of this fact. Whether it is solely a neutron excitation or not however needs further study. Table 1 summarizes the observations on gamma-ray peaks as discussed above.

An abundant production of the 1336 ± 10 keV (first excited) state of ^{15}B with small fraction of the second excited state, makes it an important observation since it suggests a new configuration for a core $+ n + n$ model of the ^{17}B ground state. The yield of ^{15}B excited state is nearly twice as much as ^{17}B excited state, which shows that the production of ^{15}B in its excited state is not a process of excitation followed by breakup or vice versa. The observation suggests that the ^{17}B has a large component of the $5/2^-$ excited state of ^{15}B core combined with the valence two-neutrons coupling to $J = 2^+$. A quantitative estimate on the amount of ^{15}B excited component in ^{17}B from this data is

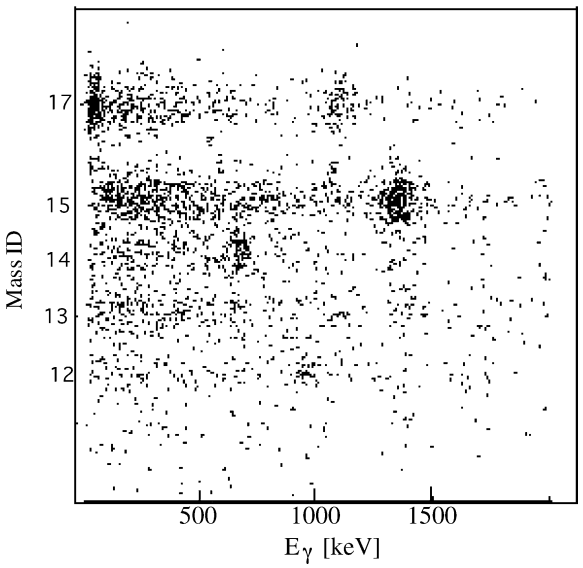

Fig. 4. Correlation of mass ID and Doppler corrected gamma transition energies. Weak peaks are seen for 1089 keV in ^{15}B and ^{13}B. Weak peaks are also seen in ^{14}B and ^{13}B for 1343 keV.

Table 1
Summary of γ-ray peaks observed for the different boron isotopes

Nucleus	γ-ray peak energy [keV]	Spin/parity
^{17}B	1089 ± 15	$(5/2^-)^*$
^{15}B	1336 ± 10	$(5/2^-)^*$
	1407	$(7/2^-)^*$
^{14}B	654 ± 9	1^- [a]
^{12}B	956 ± 10	2^+ [b]

* Tentative assignment from comparison to models, see text for details.
[a] Ref. [12].
[b] Ref. [11].

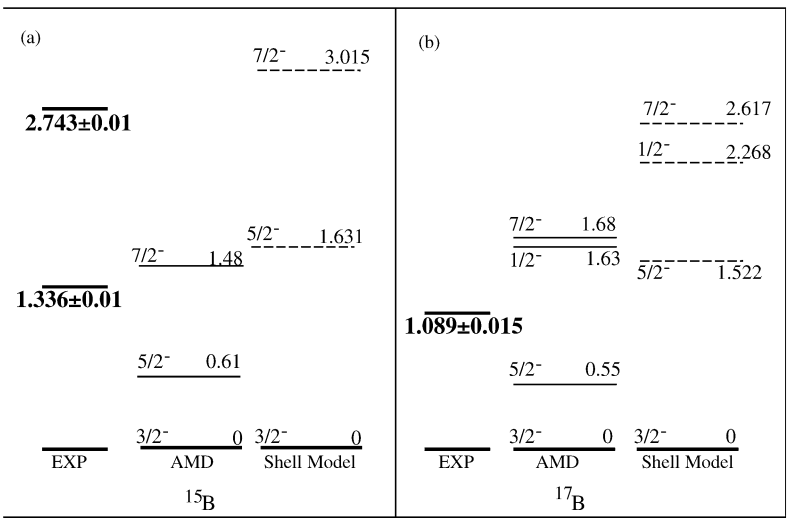

Fig. 5. Level scheme of (a) ^{15}B, (b) ^{17}B. The thick solid/thin solid/dashed lines are the levels predicted from experiment/AMD [13]/shell model [12]. The energy units are in MeV.

discussed in the subsequent paragraphs. This observation also agrees with the conjecture from the magnetic moment studies [5] on the importance on valence neutrons coupled to $J = 2^+$. Thus a new configuration in the structure of ^{17}B ground state, compared to the conclusions from Refs. [3,4], has to be included.

In order to estimate the fraction of core (^{15}B) excited component in ^{17}B, we derive the inclusive cross sections of the total amount of ^{17}B and ^{15}B nuclei after the target. The interaction cross section of ^{17}B is found to be 830 ± 250 mb. The inclusive two-neutron removal cross section of $^{17}\text{B} \rightarrow {}^{15}\text{B}$, (at 43 A MeV) is 33 ± 15 mb. In comparison, the cross section of Ref. [4] at 80 A MeV, scaled by an $A^{2/3}$ factor for target difference, suggests a probable value of 42 ± 9 mb. The cross sections are thus found to agree within error bars. Glauber calculations for ^{19}C [16] show a rather mild energy dependence of the neutron removal cross section, thus the comparison of the neutron removal cross sections of the present data and that of Ref. [4] is justified.

A rough estimate for the fraction of core excited component in the ground state of ^{17}B is made using the overlap region of the inclusive cross section for ^{15}B from present data (33 ± 15 mb) and the scaled cross section of Ref. [4] discussed above (42 ± 9 mb). The ratio of this ^{15}B inclusive cross section (40 ± 8 mb) and the cross section of ^{15}B in coincidence with gamma rays (18 ± 2 mb) shows that nearly 33–47% of the core might be in the excited state. It maybe mentioned here that neutron evaporation leading to two-neutron removal might be an alternative reaction possibility. This however does not contradict the main conclusion about ^{15}B core being in its excited state inside ^{17}B.

The observed fraction of ^{15}B core in excited state may make it possible to explain the observed magnetic moment for ^{17}B. For example, if there is 40% core excited state component. Then, from the above discussion on two excited states, we may expect 32% of this to be associated with the first excited state and 8% to the second excited state. This may give, $\mu_{\text{calc}} = (0.60)^*\mu_{p3/2} + (0.32)^*\mu([\pi p_{3/2}]^{-1} \otimes [(\nu d_{5/2})_3^{5/2+}(\nu s_{1/2})]^{2+}) + (0.08)^*\mu([(\pi p_{3/2})_2^{0+}(\pi p_{1/2})]^{1/2-} \otimes [(\nu d_{5/2})_4]^{2+})$. In the first term, $\mu_{p3/2}$ is the single particle value and is given by 3.80. It arises from configurations of the form $\mu([\pi p_{3/2}]^{-1} \otimes [(\nu d_{5/2})_4]^{0+})$ or $\mu([\pi p_{3/2}]^{-1} \otimes [(\nu d_{5/2})_2^{0+}(\nu s_{1/2})_2^{0+}]^{0+})$ corresponding to the ^{15}B core in ground state. The magnetic moment for the second term is 0.45 and third term is -1.22 [5,17]. These correspond to the excited states of ^{15}B. Thus the observed mixing ratio coefficients lead to $\mu_{\text{calc}} = 2.33\mu_N$ which agrees with the experimental value of $(2.45 \pm 0.20)\mu_N$. It should be noted that the exact configuration of the excited states is not known. So in the above estimation we have chosen the two components with neutrons forming $J = 2^+$, which have the larger probability predicted by shell model. The present data shows a larger fraction of core excited component compared to shell model predictions for the different configurations [17]. It maybe mentioned here that the magnetic moment predicted by AMD calculation [14] also agrees with the experimental value.

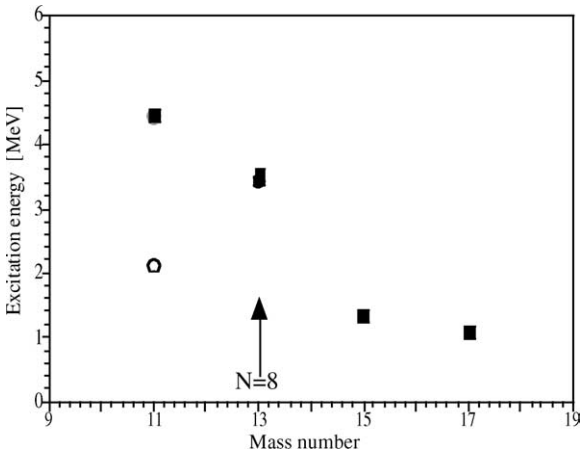

Fig. 6. Excitation energies of the odd-mass boron isotopes. The filled squares show the possible $5/2^-$ states, while the open circles are the $1/2^-$ states.

In summary, new observations on excited states of ^{17}B and its fragments ^{15,14,12}B are reported from gamma spectroscopy measurements following interactions of ^{17}B with a hydrogen target. The gamma transitions were observed for ^{17}B at 1089 ± 15 keV, and for ^{15}B at 1336 ± 10 keV, which can be associated with the $5/2^-$ first excited states for these nuclei predicted by the shell model and by the AMD model. The gamma transition observed for ^{14}B at 654 ± 9 keV is slightly lower than the excited state observed by multi-nucleon transfer reactions. Fig. 6 shows a sum-

mary of the excited states for the odd mass boron isotopes. The decrease in the excitation energy of the first $(5/2^-)$ excited state, with increase of neutron number is observed beyond $N = 8$. This is interesting since it shows that these excited states in ^{15,17}B (nuclei with odd Z and even N), is possibly due to neutron excitation. If this is true, then the low E2 excitation reflects the onset of a large deformation. This is consistent with largely deformed configurations for increase in neutron number, which is predicted by AMD [14].

The two-neutron removal fragment, ^{15}B was found to exist in the $5/2^-$ excited state. The measured cross sections indicate the possibility of the ^{15}B core, in ^{17}B nucleus, having sizable probability of existing in the excited state with two valence neutrons coupled to $J^\pi = 2^+$. This is a new insight into the structure of ^{17}B, and is in consonance with expectations from magnetic moment studies. The present observation also makes it possible to explain the observed moment.

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