Experimental studies of unbound neutron-rich nuclei

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Abstract

The three-body description of two-neutron halo nuclei relies on the two-body interactions between the constituents. In order to provide constraints on calculations devoted to $^{14}$Be and $^{17}$B, the neutron unbound states of $^{13}$Be and $^{16}$B have been investigated by one-proton knockout. The experimental techniques and results are discussed here.

I. INTRODUCTION

In recent years nuclei at the limit of stability have become experimentally accessible. In these regions where systems present an excess of neutrons or protons, the traditional mean-field picture is often no longer valid and the nucleus can be more appropriately described as a few-body system. Halo nuclei, in which one or two nucleons extend far from the rest of the nucleus (the core), are a typical example of such a structure.

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On the neutron-rich side there exist three-body (core-neutron-neutron) systems (Borromean) which are probably the most intriguing halo nuclei: they are bound while none of the two-body subsystems (n-n and core-n) are [1]. In these cases, the structure of the latter is known to play a significant role in the description of the halo nucleus. Thus $^{11}\text{Li}$ cannot be described without assuming the presence of a virtual s-state in $^{10}\text{Li}$ [3]. In the same way, $^{13}\text{Be}$ has been investigated due to the importance of a possible s-state near threshold for the structure of the two-neutron halo nucleus $^{14}\text{Be}$ [4].

Since the measurement of its interaction cross-section [5], $^{17}\text{B}$ has been considered to be the heaviest two-neutron halo nucleus. Little is known about the unbound $^{16}\text{B}$ other than that the (probable) ground state was weakly populated in a multinucleon transfer experiment at HMI [6]. In order to improve our knowledge of the spectroscopy of $^{16}\text{B}$ and $^{13}\text{Be}$ the experiments described here were carried out.

II. EXPERIMENTAL TECHNIQUES

Historically neutron unbound states (resonances) close to the stability line were studied by using beams of neutrons [2]. Obviously this technique is no longer practical near the dripline given that the target itself is $\beta$-unstable (the half-lives of $^{12}\text{Be}$ and $^{15}\text{B}$ are 24 and 10.4 ms).

Multinucleon transfer reactions have been used extensively to access exotic unbound systems. However the reaction mechanism is complex and the missing mass spectrum often exhibits a large background. Unbound states of exotic nuclei can also be populated by removal (or “knockout”) of one or several nucleons from a high-energy beam. The reconstructed fragment-neutron relative energy (or velocity) spectrum will exhibit structures which correspond to the energy of the populated unbound states with respect to the neutron decay threshold.

More recently, two-proton knockout has been used to study $^{9}\text{He}$ [11]. The use of a simpler reaction than projectile fragmentation (e.g. [10]) is advantageous as the backgrounds
are suppressed and as to first order the neutron configuration remains undisturbed by the
reaction, the final-state neutron angular momentum is known, provided the structure of the
projectile is known.

For $^{13}$Be and $^{16}$B one-proton knockout reactions were chosen. The experiments were
performed at GANIL, using a 35 (41) MeV/nucleon $^{17}$C ($^{14}$B) beam impinging on a C
target. The charged fragments arising from the reactions were detected using a Si-Si-CsI
telescope located some 15 cm downstream of the target. The two silicon detectors provided
for good position information (1 mm), and combined with the energy signals derived from
the CsI, unambiguous identification of the fragment. The total energy resolution of the
telescope was 1.2% (fwhm).

The neutrons were detected using 97 elements of the DEMON array [13]. The liquid
scintillator modules were arranged in a staggered configuration covering polar angles up to
39° in the laboratory, providing for a significant detection efficiency up to a few MeV relative
energy (figure 1). The neutron energy was deduced from the time-of-flight with a resolution
of 5%.

III. RESULTS

The relative energy between the $^{15}$B ($^{12}$Be) fragment and the neutron detected in co-
incidence was reconstructed event by event and is shown in figure 2 (3). In the case of
$^{16}$B ($^{15}$B+n coincidences) a strong, narrow peak appears at about 100 keV above neutron
threshold. For $^{13}$Be, one can distinguish two main features: a broad peak around 700 keV
and a second structure at about 2 MeV.

To proceed further it is necessary to take into account the distortions caused by the
finite resolution and acceptance of the detectors. The response of the complete setup was
simulated using the GEANT package [12]. The resolution in relative energy (figure 1) which
increases roughly as $\sqrt{E_{\text{rel}}}$ arises principally from the finite size of the neutron detectors.
The results also show that in both experiments the detection efficiency is a smooth function
of the relative energy, ruling out the possibility that the peaks are instrumental artifacts.

Energy distributions corresponding to uncorrelated fragment-neutron pairs were generated by mixing neutrons and $^{15}$B ($^{12}$Be) fragments arising from different events [14]. In both cases the lineshapes (figures 2 and 3) cannot describe the experimental spectra, which demonstrates that the structures obtained are not due to a trivial phase space effect and correspond rather to fragment-neutron final state interaction.

For the interpretation of the data, we have employed the same formalism as in ref. [11]. Starting from the sudden approximation, the relative energy distribution is given by the overlap of the initial bound-state wave function, describing the relative motion between a neutron and the rest of the projectile, and the final-unbound state wave function (neutron-fragment motion). Realistic wave functions were obtained by using Woods-Saxon potentials adjusted to reproduce either the projectile neutron separation energy for the initial state or the resonance energy (or the scattering length for virtual s-states) for the final state. The theoretical energy distributions were then folded with the simulated response of the experimental setup.

As mentioned earlier, to first order the neutron configuration of the projectiles is preserved in proton knockout. The structures of $^{17}$C and of $^{14}$B are relatively well known to be mainly $|^{16}\text{C}^*(2^+)> \otimes \nu d_{5/2}$ ($\ell=2$) and $|^{13}\text{B}(gs)> \otimes \nu sd$ ($\ell=0,2$). Hence only $d$ states for $^{16}$B and $s$ and $d$ states for $^{13}$Be should be significantly populated in our experiments.

The $^{16}$B spectrum was fit with a lineshape corresponding to a $d$-wave resonance and the distribution obtained by event-mixing which was the best description of the “background” lying below the narrow peak in the spectrum$^1$. The resonance energy $E_r$ and the ratio between the two components were allowed to vary freely. The result obtained was $E_r=85\pm15$ keV (above neutron threshold). At this energy the single-particle width is very small ($\sim0.5$

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$^1$This background could be due to other overlapping $^{16}$B states or to uncorrelated $^{15}$B–neutron events (continuum).
keV) and is dominated by the experimental resolution (∼100 keV).

This resonance can most probably be identified as the ground state of $^{16}\text{B}$. In terms of the shell model the very small spectroscopic factor for neutron decay (0.08) of the predicted $0^-$ ground state would be responsible for such a very narrow width [17]. This result should furnish a first constraint on the $^{15}\text{B}$-$n$ interaction used in three-body calculations of the structure of $^{17}\text{B}$.

Turning to $^{13}\text{Be}$, the structure seen at around 2 MeV was identified as the $d$-wave resonance seen in previous experiments [7–9]. The broad peak at lower energy requires more attention. As its large width is incompatible with a $d$-wave resonance at this energy, only an $s$-state remains possible. Hence a fit was first attempted including a virtual $s$-state, a $d$-wave resonance and a “background” resulting from event-mixing. It was found, however, that such a prescription could not adequately describe the data [16].

In the simple model considered so far, no $s$-wave resonance can exist owing to the absence of a centrifugal barrier. However $^{12}\text{Be}$, is well known to be a deformed nucleus in which $N=8$ is no longer magic [15]. It is likely, therefore, that $^{12}\text{Be}$ is not an inert core in $^{13}\text{Be}$, which might explain the appearance of resonant $s$-states.

A second fit was thus carried out with the $d$-wave resonance but replacing the virtual $s$ state by a resonance described by an $\ell = 0$ Breit-Wigner lineshape. The results are shown in figure 3. The agreement with the data is nearly perfect. Unlike the $^{16}\text{B}$ case, the magnitude of the “background” could not be uniquely determined (the two-fold figure shows the two extreme cases) and the resonance parameters are consequently difficult to deduce exactly. Nevertheless this experiment confirms the presence of a broad $s$-state at low energy (about 700 keV above threshold) in $^{13}\text{Be}$ and, consequently, that the $s_{1/2}$-$d_{5/2}$ inversion in the $N=9$ isotones $^{14}\text{B}$ and $^{15}\text{C}$ persists in $^{13}\text{Be}$. We note that such a low-lying $s$ state was also seen in a recent experiment in GSI [18], in contradiction with the earlier observation of a very low-lying virtual $s$-state [10]. More theoretical work and experiments such as $d(^{12}\text{Be},^{13}\text{Be})p$ would help clarifying the structure of $^{13}\text{Be}$. 
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FIG. 1. Setup efficiency and resolution simulated using GEANT. Left panel: detection efficiency as a function of relative energy between the fragment (solid line: $^{15}$B, dashed line: $^{12}$Be) and the neutron. Right panel: relative energy resolution as a function of relative energy. The curves are fits of the form $\text{FWHM} \propto \sqrt{E_{\text{rel}}}$.

FIG. 2. $^{15}$B-$n$ relative energy spectrum. The points are the data, the thick solid line the result of a fit including a $d$-wave resonance (thin solid line) and an event-mixing distribution (dotted line).
FIG. 3. $^{12}$Be-$n$ relative energy spectrum. The points are the data, the thick solid line the result of a fit including an $s$-wave resonance (thin solid line) and a $d$-wave resonance (dashed line) and in the right panel, an event-mixing "background" (dotted-dashed line). The parameters shown are those of the $s$-wave resonance Breit-Wigner lineshape. Note: a third resonance was tentatively introduced near 4 MeV (dotted line) but is not statistically significant. Its presence does not modify the fit in the region of interest.