Structure of the neutron-rich $N = 7$ isotones

$^{10}\text{Li}$ and $^9\text{He}$

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Abstract. The near threshold structure of the unbound $N=7$ isotones $^{10}\text{Li}$ and $^9\text{He}$ has been investigated using proton removal and breakup from intermediate energy (35 MeV/nucleon) secondary beams of $^{11}\text{Be}$ and $^{14,15}\text{B}$. The coincident detection of the beam velocity $^9\text{Li}$ and $^8\text{He}$ fragments and neutrons permitted the relative energy of the in-flight decay of $^{10}\text{Li}$ and $^9\text{He}$ to be reconstructed. Both systems were found to exhibited virtual $s$–wave strength near threshold together with a higher-lying resonance.

Introduction

The light nuclei have long provided a test bench for our understanding of nuclear structure. From an experimental point of view, this is the only region for which nuclei lying beyond the neutron dripline are presently accessible. Theoretically, models incorporating explicitly the continuum are being developed [1]. Furthermore, the structure of unbound systems, such as $^{10}\text{Li}$, is a key ingredient of three-body descriptions of two-neutron halo, such as $^{11}\text{Li}$, and related nuclei [2].

The lightest $N = 7$ isotones, where the neutron $1s_{1/2}$ state from the $1s0d$-shell is found to intrude into the $p$-shell states, are of particular interest. This phenomenon has long been known in $^{11}\text{Be}$ [3] and there is now, as cited below, good evidence that this inversion occurs in $^{10}\text{Li}$. In the case of $^9\text{He}$, experiment suggests that low-lying $s$–wave strength occurs, although there is not agreement as to its strength [4, 5]. In the following we describe briefly a new experimental investigation of the low-lying level structure of $^{10}\text{Li}$ and $^9\text{He}$.

Experiment

One of the techniques well suited to the study of nuclei far from stability is that of nucleon removal or breakup of a high-energy radioactive nuclear beam. The few-nucleon breakup of such beams can be employed to populate, and study through the fragment–neutron final-state interaction (FSI), unbound nuclei. In addition to benefiting from significant cross sections (typically $\sim 10$–100 mb), the high energies result in the strong forward focussing of the reaction products (increasing the effective detection acceptances) and permit the use of thick targets ($\sim 100 \text{ mg/cm}^2$). Consequently measurements with beam intensities as low as $\sim 100$ pps are feasible. Here we report on measurements using secondary beams of $^{11}\text{Be}$ and $^{14,15}\text{B}$ to investigate the low-lying level structures of $^{10}\text{Li}$ and $^9\text{He}$.

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The experiments employed 35 MeV/nucleon beams delivered with intensities of some $10^4$–$10^5$ pps by the LISE3 separator at GANIL. The beam velocity charged fragments and neutrons emitted in the forward direction from the reactions on a carbon target were identified and the momenta determined using a Si-Si-CsI array coupled to a large-scale neutron array. These measurements allowed the fragment+neutron ($f+n$) relative energy spectra to be reconstructed. In order to interpret the spectra, simulations, which were validated using the in-flight decay of well established resonances (such as $^7$He$_{g.s.}$), were developed to model the response function of the experimental setup. Detailed accounts of the work presented here may be found elsewhere [6, 7].

Figure 1. Relative energy spectra for the $^9$Li+n and $^8$He+n systems for the different reactions indicated. The dotted lines represent the uncorrelated background distribution obtained by event-mixing. The thin solid lines are the virtual $s$–states, while the dashed lines are the resonances. The thicker solid line is the overall adjustment.

Results
The results obtained for the $^8$He+n and $^9$Li+n systems are shown in Figures 1 and 2. As demonstrated in our work on the C($^{17}$C,$^{15}$B+n) single-proton removal reaction [8], the
description of the relative energy spectra require, in addition to discrete final states, a broad and rather featureless continuum of uncorrelated events which may be generated via event mixing [9]. Qualitatively the origin of these events may be attributed to scattering on the target of the (weakly bound) valence neutron and the population of very broad overlapping states. In the case of breakup involving both proton and neutron removal from the projectile (such as the \(^{14,15}\text{B}\) reactions here), the detection of neutrons arising from the decay of more neutron-rich systems will also contribute.

Both the spectra obtained for the \(^9\text{Li+n}\) channel (Figures 1(a), 1(b) and 2), as well as that for \(^8\text{He+n}\) derived from two-proton removal from \(^{11}\text{Be}\) (Figure 1(c)), exhibit significant strength just above threshold, which can be most satisfactorily described by the presence of a virtual s-wave scattering state. The results for the \(\text{C}(^{11}\text{Be},^{9}\text{Li+n})\) and \(\text{C}(^{11}\text{Be},^{8}\text{He+n})\) reactions are in line with what may be expected on the basis of simple considerations, whereby proton only removal from the projectile should leave the neutron configuration undisturbed [4, 10]. Given the dominant s–wave neutron component in \(^{11}\text{Be}_{g.s.}\), proton removal to \(^{10}\text{Li}\) and \(^{9}\text{He}\) should populate preferentially s–wave final states. In the case of \(^9\text{Li+n}\), a scattering length \((a_s)\) around -14 fm was deduced, whereas for \(^8\text{He+n}\) is close to 0 fm \((a_s = -3 \pm 0\text{ fm at the 3-sigma level})\), signifying a very weak fragment-neutron interaction. The \(^{10}\text{Li}\) result is in line with other studies, including high-energy neutron removal from \(^{11}\text{Li}\) [11, 12], whilst that for \(^{9}\text{He}\), despite being in some conflict with very similar work [4] to that presented here\(^2\), is in good accord with a very recent report of a study at relativistic energies employing \(^{11}\text{Li}\) breakup [5].

Figure 2. Relative energy spectra for the \(^9\text{Li+n}\) from breakup of a \(^{15}\text{B}\) beam. The dotted lines represent the uncorrelated background distribution obtained by event-mixing, whilst the thin solid lines are the virtual s–state and resonance (see text). The thicker solid line is the overall adjustment.

The \(^9\text{Li+n}\) relative energy spectrum from the breakup of \(^{14}\text{B}\) (Figure 1(b)) clearly displays

\(^2\) The original investigation of the \(\text{Be}(^{11}\text{Be},^{8}\text{He+n})\) reaction at 25 MeV/nucleon deduced a stronger FSI, corresponding to a scattering length \(a_s < 10\text{ fm}\) [4].
the presence of a higher lying state some 0.5 MeV above threshold, which may be identified with the expected $p$-wave resonance observed in other studies [11, 12, 13]. Interestingly, breakup of $^{15}\text{B}$ exhibits an enhanced yield to this resonance relative to the $s$-state, as displayed in Figure 2 [7]. Despite suffering from limited statistics, the $^{8}\text{He}+\text{n}$ relative energy spectrum obtained from breakup of $^{14}\text{B}$ (Figure 1(d)) is consistent with the presence of the weakly interacting $s$-wave strength identified above in the two proton-removal from $^{11}\text{Be}$ and a resonance around 1.2 MeV above threshold. The latter is in line with the original observations made using pion double-charge exchange [14] and heavy-ion multi-nucleon transfer and reactions [15, 16].

Conclusions
In summary, in the present work the $\nu s_{1/2}$ character of the $^{10}\text{Li}$ ground state and the existence of a resonance some 0.5 MeV above threshold have been confirmed. In addition, evidence for low-lying $s$-wave strength in $^{9}\text{He}$, corresponding to a rather weak fragment-neutron interaction, has been found. Indications of a resonance some 1.2 MeV above threshold have also been observed.

More generally, the results obtained for $^{10}\text{Li}$ populated via proton removal from the $^{11}\text{Be}$ beam support the validity at intermediate energies of simple selection rule arguments [4, 10] – namely, the final-states produced in proton-removal reactions are dominated by those with the same character as the projectile neutron configuration. The very weakly bound nature of $^{11}\text{Be}$ suggests that such considerations are valid even in the case of removal of a deeply bound proton from a projectile with a loosely bound valence neutron.

Finally, it was also seen that other final states may be populated in breakup involving proton and neutron removal. However, as discussed elsewhere, care must be taken in terms of the neutron decay of more neutron-rich systems leading to that of interest [7, 17].

Acknowledgments
The authors would like to thank their many colleagues in the LPC–CHARISSA–DEMON Collaboration and acknowledge the excellent support provided by the technical staff of LPC and GANIL.

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