One-neutron removal reactions on neutron-rich psd-shell nuclei

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Abstract

A systematic study of high energy, one-neutron removal reactions on 23 neutron-rich, psd–shell nuclei (\(Z = 5–9, A = 12–25\)) has been carried out. The longitudinal momentum distributions of the core fragments and corresponding single-neutron removal cross sections are reported for reactions on a carbon target. Extended Glauber model calculations, weighted by the spectroscopic factors obtained from shell model calculations, are compared to the experimental results. Conclusions are drawn regarding the use of such reactions as a spectroscopic tool and spin-parity assignments are proposed for \(^{15}\)B, \(^{17}\)C, \(^{19–21}\)N, \(^{21,23}\)O, \(^{23–25}\)F. The nature of the weakly bound systems \(^{14}\)B and \(^{15,17}\)C is discussed.

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Fragment momentum distributions have long been recognised as signatures of the large spatial extent of the valence nucleons in halo nuclei [1]. Recently, measurements of one-nucleon removal reactions on light targets have been proposed as a spectroscopic tool for high-energy radioactive beams [2,3]. This approach has arisen from the development of reaction calculations in which the strong absorption limit [4] and core excited states are accounted for [3]. More specifically, the integrated cross sections are related to spectroscopic factors using an extended version [3,5] of the spectator core model [6], whilst the momentum distributions are derived in the opaque limit of the Serber model [7,8]. To date, this approach has been applied to a few near dripline and halo nuclei [2,9–11].

In this Letter the results of an investigation of high-energy one-neutron removal reactions over a broad range of light, neutron-rich psd-shell nuclei are reported. The goals of the work were twofold. Firstly, to explore the evolution in structure, and the manner in which it is manifested in the core fragment observables, from near stability to dripline and halo systems. Secondly, for many of the near stable nuclei the ground state structure is well established and, consequently, it has been possible to test the validity of one-neutron removal reactions as a spectroscopic tool.

In the following, measurements of the core fragment longitudinal momentum distributions and integrated cross sections resulting from reactions on a C target are presented. Comparison is made for both observables to the results of extended Glauber type calculations incorporating second order noneikonal corrections to the JLM parameterisation of the optical potential [12]. In the case of those systems with unknown, or poorly defined ground state structures, probable spin-parity assignments have been made.

The secondary beams were produced via the fragmentation on a 490 mg/cm$^2$ thick C target of an intense ($\sim 1 \mu$Ae) 70 MeV/nucleon $^{40}$Ar$^{17+}$ beam provided by the GANIL coupled cyclotron facility. The reaction products were collected and selected according to magnetic rigidity using the SISSI device coupled with the alpha-shaped beam analysis spectrometer. A mean rigidity of 2.880 Tm was selected to allow for the transmission of nuclei from $^{12}$B to $^{25}$F with energies in the range of 43 – 71 MeV/nucleon (Table 1). The energy

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∥ The term “knockout”, which has been employed to refer to such reactions [2], is not adopted here as it has long been used for $(p,2p)$ and $(e,e'p)$ reactions, the description of which is very different from that of absorption and diffraction in one-nucleon removal.
spread in the secondary beams, as defined by the spectrometer acceptances, was \( \Delta E/E = 2\% \).

The measurements of the momentum distributions and one-neutron removal cross sections were performed using the SPEG spectrometer [13]. Owing to the large energy spread in the secondary beam, SPEG was operated in a dispersion matched energy-loss mode [14] for which a resolution in the momentum measurements of \( \delta p/p = 3.5 \times 10^{-3} \) was obtained. Importantly the large angular acceptances of the spectrometer (4° in the vertical and horizontal planes) provided for complete collection of the core fragments, obviating any ambiguities in the integrated cross sections and longitudinal momentum distributions that would arise from limited transverse momentum acceptances [15]. Furthermore, the broad momentum acceptance of the spectrometer (\( \Delta p/p = 7\% \)) allowed the momentum distributions for one-neutron removal on all the nuclei of interest to be obtained in a single setting (B\(\rho_{\text{SPEG}} = 2.551 \text{Tm} \)). A secondary C reaction target of thickness 170 mg/cm\(^2\) was employed for the measurements described here (the results obtained with a Ta target will be reported elsewhere [12]).

Ion identification at the focal plane of SPEG was achieved using the energy loss derived from a gas ionisation chamber and the time-of-flight between a thick plastic stopping detector and the cyclotron radio-frequency. Additional identification information was provided by the residual energy measurement furnished by the plastic detector and the time-of-flight with respect to a thin-foil microchannel plate detector located at the exit of the beam analysis spectrometer. Two large area drift chambers straddling the focal plane of SPEG were employed to determine the angles of entry of each ion and, consequently, allowed the focal plane position spectra to be reconstructed. The momentum of each particle was then derived from the reconstructed focal plane position. Calibration in momentum was achieved by removing the reaction target and stepping the mixed secondary beam of known rigidity along the focal plane. This procedure also facilitated a determination of the efficiency across the focal plane for the collection of the reaction products.

The intensities of the various components of the secondary beam were measured in runs taken with the secondary reaction target removed and the spectrometer set to the same rigidity as the beamline. These were calibrated in terms of the primary beam current, which was recorded continuously throughout the experiment using a non-interceptive beam monitor. Checks were also provided by the counting rates in the microchannel at the exit of the beam analysis spectrometer and a second located just upstream of the secondary reaction target. Typical secondary beam intensities ranged from \( \sim 600 \ 15\text{C}/\text{s} \) to \( \sim 1 \ 25\text{F}/\text{s} \).

The longitudinal momentum distributions for the core fragments arising from one-neutron removal are displayed in figure 1 and the extracted widths (FWHM
| $^A Z$ | Energy | FWHM$_{cm}$ | $\sigma_{-1n}$ | $\sigma_{Glauber}^{1n}$ | $J^\pi$ |
|-------|--------|-------------|-----------------|-------------------|----------|
|       | [MeV/nucleon] | [MeV/c] | [mb] | [mb] | |
| $^{12}$B | 67 | 142 ± 3.5 | 81 ± 5 | 91 | 1$^+$ |
| $^{13}$B | 57 | 135 ± 7 | 59 ± 4 | 62 | 3/2$^-$ |
| $^{14}$B | 50 | 56.5 ± 0.5 | 153 ± 15 | 185 | 2$^-$ |
|          | 86 | 57 ± 2$^a$ | 48 ± 5$^a$ |        |          |
|          | 59 | 55 ± 2$^b$ | 176 ± 16$^b$ |        |          |
| $^{15}$B | 43 | 73 ± 2.5 | 108 ± 13 | 89 | 3/2$^-$ $^c$ |
| $^{14}$C | 71 | 180 ± 5 | 65 ± 4 | 89 | 0$^+$ |
| $^{15}$C | 62 | 63.5 ± 0.7 | 159 ± 15 | 168 | 1/2$^+$ |
|          | 85 | 67 ± 3$^a$ | 33 ± 3$^a$ |        |          |
| $^{16}$C | 55 | 108 ± 2 | 65 ± 6 | 75 | 0$^+$ |
| $^{17}$C | 49 | 111 ± 3 | 84 ± 9 | 71 | 3/2$^+$ $^c,a$ |
|          | 84 | 145 ± 5$^a$ | 26 ± 3$^a$ |        |          |
|          | 96.8 | 94 ± 19$^d$ | 41 ± 4$^d$ |        |          |
|          | 904 | 141 ± 6$^e$ | 129±22$^f$ |        |          |
| $^{18}$C | 43 | 126 ± 5 | 115 ± 18 | 119 | 0$^+$ |
|          | 86.2 | 110 ± 12$^d$ | 35 ± 2$^d$ |        |          |
| $^{17}$N | 65 | 141 ± 4 | 55 ± 5 | 67 | 1/2$^-$ |
| $^{18}$N | 59 | 168 ± 3 | 109 ± 11 | 91 | 1$^-$ |
| $^{19}$N | 53 | 177 ± 3 | 86 ± 9 | 83 | 1/2$^-$ $^c,g$ |
| $^{20}$N | 48 | 162 ± 4 | 98 ± 13 | 101 | 2$^-$ $^c$ |
| $^{21}$N | 43 | 149 ± 7 | 140 ± 44 | 151 | 1/2$^-$ $^c$ |
| $^{19}$O | 68 | 190 ± 8 | 104 ± 12 | 80 | 5/2$^+$ |
| $^{20}$O | 62 | 219 ± 5 | 112 ± 11 | 96 | 0$^+$ |
| $^{21}$O | 56 | 210 ± 6 | 134 ± 14 | 123 | 5/2$^+$ $^c,g$ |
| $^{22}$O | 51 | 206 ± 4 | 120 ± 14 | 140 | 0$^+$ |
| $^{23}$O | 47 | 114 ± 9 | - $^k$ | 122 | 1/2$^+$ $^c$ |

in the projectile frame) are summarised in Table 1. The widths were derived from Gaussian fits to the central regions of each distribution. The effects arising from the target (straggling etc), efficiency along the focal plane and instrumental resolution have been taken into account in deriving the final values.
| A\ Z | Energy  | FWHM$_{cm}$ | $\sigma_{-1n}$ | $\sigma_{\text{Glauber}}$ | J$^\pi$ |
|------|---------|-------------|---------------|----------------|---------|
|      | [MeV/nucleon] | [MeV/c] | [mb] | [mb] |
| $^{22}\text{F}$ | 64 | 185 ± 14 | 121 ± 16 | 61 | 4$^+$ |
| $^{23}\text{F}$ | 59 | 235 ± 4 | 114 ± 12 | 106 | 5/2$^+$ c,h,i |
| $^{24}\text{F}$ | 54 | 129 ± 4 | 124 ± 16 | 109 | 1$^+$ c, 3$^+$ c,j |
| $^{25}\text{F}$ | 50 | 106 ± 8 | 173 ± 46 | 154 | 5/2$^+$ c |

$^a$ ref. [17] (Be target), $^b$ ref. [10] (Be target)  
$^c$ assignment from present experiment, $^d$ ref. [16] (Be target)  
$^e$ ref. [18] (C target), $^f$ ref. [19] (C target), $^g$ ref. [20], $^h$ ref. [21], $^i$ ref. [22]  
$^j$ ref. [23], $^k$ no beam intensity normalisation available

Table 1  
Summary of results for one-neutron removal.

The corresponding one-neutron removal cross sections are listed in Table 1 and displayed in figure 2. The uncertainties quoted include the contributions from both the statistical uncertainty and that arising from the determination of the secondary beam intensity (∼7%).

A number of features are immediately apparent on inspection of figures 1 and 2. Firstly, the crossing of the N=8 shell and N=14 sub-shell closures are associated with a marked reduction in the widths of the core momentum distributions (viz, $^{14,15}\text{B}$, $^{15}\text{C}$, $^{23}\text{O}$ and $^{24,25}\text{F}$). Secondly, with respect to the neighbouring isotopes, $^{14}\text{B}$ and $^{15}\text{C}$ exhibit enhanced one-neutron removal cross sections. The former effects arise from the large $\nu^2s_{1/2}$ admixtures expected in the ground states of the Z=4-6, N=9 isotones [24] (see below), which may also persist for N=10, as suggested by recent studies of $^{14}\text{Be}$ [25,26]. A narrowing of the momentum distributions may also be expected for N=15 and 16 as in a simple shell model picture the valence neutrons occupy the $\nu^2s_{1/2}$ orbital. In general terms, the enhanced cross sections may be attributed to a combination of weak binding ($^{14}\text{B}$: $S_n=0.97$ MeV; $^{15}\text{C}$: $S_n=1.22$ MeV) and the large $\nu^2s_{1/2}$ admixtures in the ground state wavefunctions, which may be related to extended valence neutron density distributions, as discussed below.

As noted in Table 1, the present measurements may be compared to those made for $^{14}\text{B}$ [10,16] and $^{15,17,18}\text{C}$ [16–18]. While agreement is found for the momentum distributions, the integrated cross sections are systematically some 3-5 times higher than those reported at similar energies using the A1200 fragment separator [16,17]. Analysis of the transverse momentum distributions obtained in the present experiment demonstrate that the rather limited ac-
ceptances of the A1200 are the origin of this discrepancy [12]. In the case of $^{14}$B, the present results and those of ref. [10], also obtained using a high acceptance spectrometer, are in good accord.

In order to make a more quantitative analysis of the measurements and examine the utility of such reactions as a spectroscopic tool, extended Glauber type calculations have been carried out. The calculations, the principal features of which follow refs. [3,27,28]\footnote{A similar spectator core description and treatment of core excited states was developed earlier by Sagawa et al. in a study of inclusive momentum distributions following neutron removal on $^{11}$Be [29].}, include absorption (or stripping) and diffractive (or elastic) one-nucleon breakup. An important feature is that the S-matrices describing these processes have been derived from the microscopic interaction of Jeukenne, Lejeune and Mahaux (JLM) [30] within an eikonal approximation employing noneikonal corrections [32,33]. As discussed by Bonaccorso and Carstoiu [31] and Tostevin [5], such microscopic potentials are much better adapted to the intermediate energy range than optical limit [3] or global parameterisations [27]. In addition to the cross sections, the core longitudinal momentum distributions have been computed within this framework, as opposed to the black disk approximation of ref. [7]. A detailed description of the calculations, together with the results obtained for the transverse momentum distributions and with a Ta target, will be presented elsewhere [12].

In terms of structure, overlaps were calculated between the ground state wavefunctions of the projectiles ($J^\pi$) and the core states ($I^\pi_c$) coupled to a valence neutron ($nlj$). The single-particle wavefunctions were defined within a Woods-Saxon potential with fixed geometry ($r_0=1.15$ fm, $a_0=0.5$ fm for $Z=5$ and 6; $r_0=1.2$ fm, $a_0=0.6$ fm for $Z=7$–9) with the depth adjusted to reproduce the effective binding energy ($S_{eff}^n$) which was fixed as the sum of the single-neutron separation energy and the excitation energy of the core state. The cross section to populate a given core final state is then,

$$\sigma(I^\pi_c) = \sum_{nlj} C^2 S(I^\pi_c, nlj) \sigma_{sp}(nlj, S_{eff}^n)$$

(1)

where $C^2 S$ is the spectroscopic factor for the removed neutron with respect to the core state and $\sigma_{sp}$ is the cross section for removal of the neutron by absorption ($\sigma_{abs}$), diffraction ($\sigma_{diff}$) and Coulomb dissociation (only $\sim 7$ mb in the most favourable cases – $^{14}$B and $^{15}$C [12]). The total inclusive one-neutron removal cross section ($\sigma_{Glauber}^{1n}$) is then the sum over the cross sections to all core states. Similarly, the inclusive core momentum distribution is the sum of all core state momentum distributions, weighted by the corresponding cross sections. Within the framework of the spectator core description used here, excitation of the core in the reaction and final-state interactions are neglected.
The spectroscopic factors employed here have been calculated with the shell model code OXBASH [34] using the WBP interaction [35] within the 1p-2s1d configuration space. Where known, the experimentally established spin-parity assignments and core excitation energies have been used. In all other cases the shell model predictions have been assumed. The resulting cross sections and momentum distributions are displayed in Table 1 and figures 1 and 2. The breakdown of the calculated cross sections over the core states for each nucleus is detailed in ref. [12]; as examples, and to aid in the following discussion, the results are listed for $^{14}$B and $^{15,17}$C in Table 2. As the momentum distributions reflect the orbital angular momentum of the removed neutron, the calculated distributions have been normalised to the peak number of counts to facilitate the comparison (figure 1). For all the nuclei observed, including those with known structure, very good agreement is found between the calculated and measured distributions and cross sections, with the exception of $^{22}$F, where the cross section is underestimated. Consequently, spin-parity assignments, derived from the shell model predictions, have been proposed for $^{15}$B, $^{17}$C, $^{19–21}$N, $^{21,23}$O, $^{23–25}$F (Table 1). In the case of $^{24}$F, a $3^+$ or $1^+$ assignment appears possible based on the present data [12]. The decay study of Reed et al. suggests, however, that the former is the most likely [23], in line with the shell model predictions.

Of particular interest amongst the nuclei investigated here are $^{14}$B and $^{15,17}$C, which, based on the relatively weak binding of the valence neutrons and measurements of the core momentum distributions and one-neutron removal cross sections, have been suggested to be one-neutron halo systems [10,16,17]. As may be seen in figures 1 and 2 and Table 2, the momentum distributions and cross sections for $^{14}$B and $^{15}$C are well reproduced by the present calculations employing the spectroscopic factors derived from the shell model, in which the ground state wavefunctions are predominately a $2s_{1/2}$ valence neutron coupled to the core ($^{13}$B and $^{14}$C) in the ground state, as suggested by decay studies [36] and single neutron-transfer experiments [37]. In the case of $^{17}$C, a spin-parity assignment of $3/2^+$ is favoured, whereby the ground state configuration is predominately a $1d_{5/2}$ valence neutron coupled to the $^{16}$C core $2^+_1$ state. This confirms the suggestion of Bazin et al. [17] and the calculations of Ren et al. [38], and is supported by the recent observation of the 1.76 MeV gamma-rays de-exciting the $2^+_1$ state in $^{16}$C following one-neutron removal on $^{17}$C [39]. Such a structure, with a high $S_n^{eff}$ (2.49 MeV) and a valence neutron angular momentum of $l=2$, excludes the possibility of any halo structure developing as evidenced by measurements of the total reaction cross section [40–43].

Moderate enhancements, however, have been observed in the total reaction cross section measurements for $^{14}$B [40–42]. Together with the ground state structure deduced from the present experiment and refs. [10,17], it seems probable that a spatially extended valence neutron density distribution does occur;
Table 2
Calculated one-neutron removal cross sections for $^{14}$B and $^{15,17}$C.

Although the one-neutron binding energy of nearly 1 MeV will suppress the development of a distribution as large as that found in the more weakly bound one-neutron halo nuclei $^{11}$Be and $^{19}$C. Detailed measurements of the total reaction cross section over a range of energies would thus be of particular interest in mapping out the density distribution of $^{14}$B. In the case of $^{15}$C the situation is unclear, with measurements of the total reaction cross section exhibiting no effect [40,41,43] and small enhancements [42,44]. Despite the predominately $l=0$ character of the valence neutron, the higher neutron binding energy of $^{15}$C ($S_n=1.22$ MeV) should restrict further the spatial extent of the neutron density distribution. Interestingly, very recent measurements of the charge-changing cross sections for the C isotopes exhibit an increase for $^{15}$C [45].
In summary, a systematic investigation of one-neutron removal reactions has been carried out on a series of neutron-rich psd-shell nuclei. The longitudinal momentum distributions and corresponding single-neutron removal cross sections for the core fragments were measured using a high acceptance spectrometer. Extended Glauber model calculations, coupled with spectroscopic factors derived from shell model calculations employing the WBP interaction, reproduce well the momentum distributions and cross sections. On this basis spin-parity assignments have been proposed for $^{15}$B, $^{17}$C, $^{19,21}$N, $^{21,23}$O, $^{23,25}$F. Given the ground state configurations deduced here and measurements of the total reaction cross section, it is suggested that $^{14}$B presents a moderately extended valence neutron density distribution. This does not appear to be the case for $^{17}$C, whilst $^{15}$C exhibits contradictory behaviour.

In more general terms it is concluded that high energy one-nucleon removal reactions represent a powerful spectroscopic tool far from stability. Moreover it has been demonstrated that coupled with a high acceptance, broad range spectrograph, such reactions offer a means to survey structural evolution over a wide range of isospin in a single experiment. The current development of large area, highly segmented, multi-element Ge-arrays [46,47] should further enhance the sensitivity of such studies.

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Fig. 1. Core fragment longitudinal momentum distributions for one-neutron removal on C. The solid lines correspond to the Glauber model calculations (see text for details).
Fig. 2. Measured (solid points and line) and calculated (open points and dotted line) one-neutron removal cross sections.