Particle Unstable Light Nuclei

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Abstract. Exotic nuclei produced in fragmentation reactions can be used to study nuclei beyond the drip lines. The level structure of these nuclei yields information about disappearing, shifting and emerging shells along the driplines. Light nuclei beyond the neutron dripline (for example $^9\text{He}$, $^{10}\text{Li}$, and $^{13}\text{Be}$) and the proton dripline (for example $^{11}\text{N}$ and $^{15}\text{F}$) are used to establish the vanishing of the $N = 8$ and $Z = 8$ shell closures close to the neutron and proton dripline, respectively.

INTRODUCTION

The availability of fast radioactive beams has opened up the possibility for detailed studies of nuclei along and even beyond the drip lines. The extreme short lifetimes (up to $\sim 10^{-21}$s) of these nuclei make it difficult and for heavy nuclei essentially impossible to study with traditional methods. The strong forward focusing of the reaction products following the production via stripping or transfer reactions from fast radioactive beams allows the detection of these fragments with large efficiency. From the angle and energy determination the invariant mass of these unbound nuclei can be reconstructed. The structure of these nuclei can help to follow systematic trends even beyond particle stable nuclei.

It has been known for a long time that single particle separation energies are valuable tools to extract systematic trends over the chart of nuclei [1]. These separation energies typically increase monotonically with increasing $Z$ (or $N$) for a given $N$ ($Z$). However, just beyond a shell closure there is a dramatic drop in separation energy.

Recently these systematic studies for the neutron separation energies were extended towards the neutron dripline [2]. The disappearance of the characteristic drop of the separation energy towards the neutron dripline across the $N = 20$ shell clearly confirmed the disappearance of this shell. At the same time the separation energy exhibited a reduction for $N = 16$ very close the dripline, thus indicating the emergence of a new shell. In the present work the evolution of the $N = 8$ and $Z = 8$ shells towards and beyond the driplines is studied.

$N = 8$ SHELL

The first indication of the disappearance of the $N = 8$ shell closure was the observation of the shell inversion of the s- and p-shell in $^{11}\text{Be}$ [3]. Bohr and Mottelson demonstrated this disappearance in a plot of the single neutron separation energies [1]. The emergence or disappearance of a shell closure in such a plot is most obvious when other systematic trends like pairing are separated. Thus, in order to study the $N = 8$ shell the one neutron separation energy is plotted only for odd neutron nuclei below and above $N = 8$. In addition, the odd and even $Z$ nuclei are plotted separately. Figure 1 shows the chart of nuclei for the light mass region around $N = 8$. The short-dashed lines indicate the odd-$N$ even-$Z$ nuclei crossing the $N = 8$ line, and the long-dashed lines indicate the odd-$N$ odd-$Z$ nuclei across the $N = 8$ line. The corresponding single neutron separation energies are shown in Figure 2 for the even-$Z$ (top) and the odd-$Z$ (bottom) nuclei. The black circles show the known separation energies of particle-bound nuclei. The $^{11}\text{Be}$ to $^{15}\text{C}$ ($N = 7$, $N = 9$, top) crossing is the only one showing the disappearance of the $N = 8$ shell. In order to determine if this is an anomaly or if it persists for other neutron rich nuclei, it is necessary to extend the systematics to unbound nuclei.
The squares in Figure 2 represent $^{13}\text{Be}$ ($N = 9$, top), $^9\text{He}$ ($N = 7$, top) and $^{10}\text{Li}$ ($N = 7$, bottom). In all three cases the ground-state corresponds to s-wave resonances, which were analyzed in terms of the scattering lengths. Due to the experimental resolution only a lower limit of the scattering length can be extracted. For $^{10}\text{Li}$ the scattering length is more negative than -25 fm corresponding to an excitation energy of less than 50 keV for the virtual state [4]. $^{13}\text{Be}$ [5] and $^9\text{He}$ [6] have scattering lengths of < -10 fm or excitation energies of < 200 keV. The experiments on $^9\text{He}$ and $^{10}\text{Li}$ confirmed the predictions that the level inversion observed in $^{11}\text{Be}$ is not an isolated occurrence but continues to exist in the lightest nuclei of the $N = 7$ isotope chain. It is thus not surprising that the single neutron separation energy systematics also confirms the disappearance of the $N = 8$ shell for these isotopes.

**Z = 8 SHELL**

Similar to the single neutron separation energy systematics, single proton separation energies can be used to study proton shell structures. Figure 3 shows the relevant part of the chart of nuclei for the $Z = 8$ shell. Only the odd-$Z$, even-$N$ nuclei below and above the $Z = 8$ shell are indicated. In contrast to the $N = 8$ shell the separation energies of particle unbound nuclei ($^9\text{He}$ and $^9\text{Li}$) have to be included already for nuclei very close to the line of stability. Figure 4 shows the corresponding single proton separation energies. The $Z = 8$ shell closure indicated by the vertical line is clearly visible as a sharp drop between two adjacent nuclei ($^{11}\text{N}$, $Z = 7$ and $^{17}\text{F}$, $Z = 9$) close to stability. Even for nuclei beyond the dripline ($^{15}\text{N}$ and $^{15}\text{F}$) the discontinuity seems to be still present which would indicate the continuation of the $Z = 8$ shell.

However, $^{11}\text{N}$ is the mirror of $^{11}\text{Be}$ where the level inversion of the $p_{1/2}$ and the $s_{1/2}$ shows the break-down of the $N = 8$ shell. The mass of $^{11}\text{N}$ has recently been
measured by several groups [7-9] and the same level inversion as in $^{11}$Be has been determined for the Z = 8 shell. Thus, the increase in proton separation should not be present. A potential explanation is the large uncertainty of the mass of $^{15}$F which is unbound by 1.48(13) MeV [10]. Based on the presence of the level inversion in $^{11}$N and the single proton separation energy systematics, $^{15}$F has been predicted to be less unbound with a separation energy of ~1 MeV [11]. The open circle in Figure 4 indicates the predicted proton separation energy of $^{15}$F. A recent measurement of the mass of $^{15}$F seems to confirm this prediction [12]. However, if the original mass measurement of $^{15}$F is confirmed it seems to support the largest value for the mass of $^{11}$N [9].

CONCLUSIONS

Systematics of neutron and proton separation energies can be powerful tools to study the nuclear structure at and even beyond the driplines. It can be used to predict masses and separation energies of nuclei beyond the neutron and proton driplines.

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REFERENCES