Structure of nuclei beyond the dripline

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Fast beams of exotic nuclei produced in fragmentation reactions were used to study nuclei beyond the drip line, where in particular the structure of unbound $N = 7$ isotopes was explored. An s-wave ground state was established in ^{10}Li and observed for the first time in ^{9}He. A coincidence experiment with γ-rays confirmed that the s-state in ^{10}Li is indeed the ground state. Systematics of proton separation energies can be used to study unbound nuclei beyond the proton dripline.

Introduction

The availability of fast radioactive beams has opened up the possibility for detailed studies of nuclei along and even beyond the drip lines. Although the proton drip line can be reached for many cases with stable beams and fusion evaporation reactions, most recently the study of the most exotic nuclei, for example ^{48}Ni and ^{100}Sn was achieved with fragmentation of fast beams.[1,2] Neutron-rich nuclei cannot be formed with fusion reactions and again the exploration of very neutron-rich nuclei relied predominantly on fast fragmentation reactions. As an example of the new techniques that were developed for nuclear structure studies with fast beams, stripping reactions of fast exotic nuclei will be discussed. The shell inversion of the s- and p-shell, first observed in ^{11}Be,[3] is not a single occurrence but persists also in the lighter $N = 7$ nuclei ^{10}Li and ^{9}He. These nuclei are particle unbound and present a special challenge to study their structure.

Recently it was shown that systematics of neutron separation energies yield important information about the appearance and disappearance of shells. Similarly, proton separation energies can be used to extract information about the structure of nuclei along the proton dripline.

^{10}Li

The determination of the ground state of ^{10}Li has been controversial for quite some time.[4] Several experiments attempted to observe the predicted s-wave ground state which would confirm the level inversion as a general feature of light $N = 7$ isotopes. A recent experiment studied neutron stripping reaction of the radioactive isotopes ^{10,11,12}Be.[5]

Figure 1 shows the relative velocity spectra for the ^{9}Li+n system for the three different projectiles ^{10,11,12}Be. The most striking qualitative result is the almost total absence of ^{9}Li+n events from ^{10}Be, which cannot give rise to ^{9}Li+n in a pure projectile fragmentation process. This proved that the technique, designed to observe projectile fragmentation, discriminates effectively against reaction products, including neutrons, originating in the target. The difference between the ^{11}Be and the ^{12}Be spectra also shows the influence of the initial state, the more bound s state in ^{12}Be leading to a broader distribution. The observation of a single peak around zero relative velocity is due to final state interaction and indicates a low-lying unbound state. Figure 2 shows the ^{10}Li data from the ^{11}Be reaction together with a potential model fit. The scattering length is numerically very large, more negative than -25 fm corresponding to an excitation energy of less than 0.05 MeV for the virtual state. The fact that it is observed in the reaction from ^{11}Be with an s-wave ground state, confirms the previous observations that ^{10}Li has an s-wave ground state.

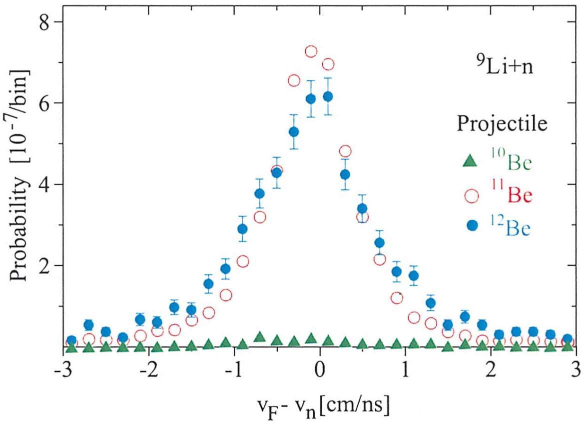

Fig. 1. Velocity difference spectra for the reactions of ^{12,11,10}Be leading to ^{10}Li.

This result was also confirmed in a different measurement of the one proton stripping reaction of ^{11}Be, where the Li isotopes were detected in coincidence with γ-rays.[6] The central peak in the relative velocity spectra could in principle be due to a decay from an excited state in ^{10}Li to the first (and only) bound excited state at 2.7 MeV in ^{9}Li.[7] This state would then decay by γ-ray emission which should be observed in coincidence with the ^{9}Li fragment.

Figure 3 shows the γ-ray spectra in coincidence with ^{9}Li following the one proton stripping reaction from ^{11}Be. The figure also shows γ-rays in coincidence with ^{8}Li which serves as a check of the background. A peak at 2.7 MeV is clearly visible in the γ-ray spectrum in coincidence with the ^{9}Li fragments.

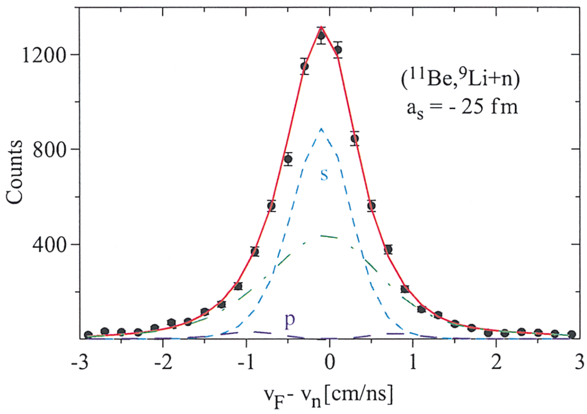

Fig. 2. Velocity difference spectra for the reaction of ^{11}Be leading to ^{10}Li together with a potential model fit. The fit assumed an s-wave component with a scattering length $a_s = -25$ fm, a background, and a p-wave resonance at 0.50 MeV.

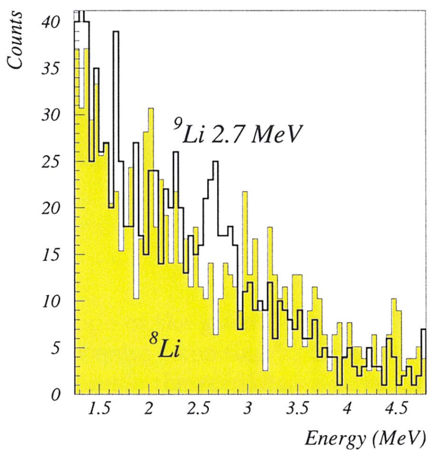

Fig. 3. ^{9}Li-γ coincidence spectrum (black line) showing an excess of γ-rays at 2.7 MeV. The smooth background is determined from ^{8}Li-γ coincidences (yellow area). The two spectra are normalized to the same number of incident particles.

However, it accounts for only $7 \pm 3\%$ of the total population of ^{9}Li. The weak branch to the excited state proves that the low-energy neutrons are emitted in a transition from the lowest state of ^{10}Li to the ground state of ^{9}Li and proves the $l = 0$ assignment.

^{9}He

The experiment measuring the relative velocity of a fragment and a neutron from ^{11}Be has also been used to measure ^{9}He. The spectrum for ^{8}He + n is shown in Fig. 4. Again, a central peak is observed which indicates the presence of a low-energy transition. A final-state interaction characterized by a scattering length of the order of -10 fm (or more negative) was necessary in order to fit the data.[5] This corresponds to an energy of the virtual state of < 0.2 MeV. The initial state was an s state (^{11}Be) which fixes the angular momentum of the observed state to zero. Thus the level inversion of $N = 7$ isotopes continues to exist in this lightest nucleus of this isotone chain.

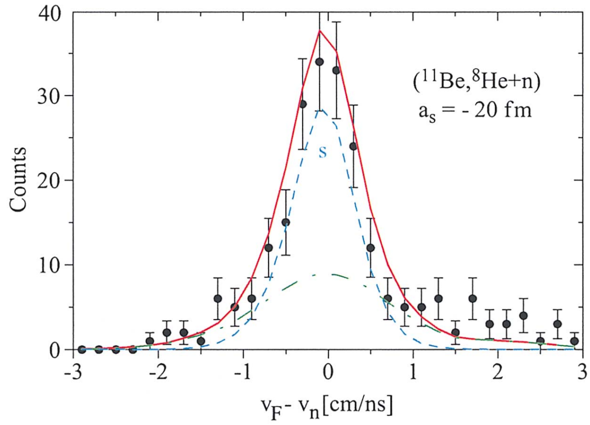

Fig. 4. Velocity difference spectra for the stripping reaction from ^{11}Be leading to ^{9}He. The potential model fit assumes an s-wave component characterized by a scattering length $a_s = -20$ fm.

Shell structures along the driplines

The vanishing of the $N = 8$ and $N = 20$ shells close to the dripline can be observed in the systematics of single neutron separation energies for nuclei with a given isospin as a function of neutron number.[8] At shell closures the neutron separation energy shows a sharp drop between adjacent nuclei. The absence of this sharp decrease indicates the disappearance of a shell. This is the case for nuclei close and beyond the dripline for $N = 8$ and $N = 20$. For neutron-rich $N = 14$ nuclei a new shell develops as documented by the appearance of the characteristic drop in neutron separation energy.[8]

Similarly, proton separation energies can be used to study proton shell structures. Figure 5 (a) shows the single proton separation energies for odd-Z−even-N nuclei with isospin (from top to bottom) 7/2, 5/2, 3/2, 1/2, −1/2, and −3/2. The $Z = 8$ shell closure is clearly visible as a sharp drop between two adjacent nuclei and it is indicated by the vertical line. However, for $T_z = -3/2$ nuclei the discontinuity vanishes which would indicate a disappearance of the $Z = 8$ shell for proton-rich nuclei which are beyond the dripline. The $N = 7$ nucleus is ^{11}N which is unbound by 1.97 MeV according to the latest evaluation of experimental masses.[9] However, the ground state was recently remeasured by several groups[10−12] and it was determined to be less unbound than previously thought. The new mass is included in Fig. 5 (b) which again shows the discontinuity characteristic for the presence of a shell.

However, the ^{11}N is the mirror of ^{11}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 remeasured mass in ^{11}N corresponds to the same level inversion 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 the next $T_z = -3/2$ nucleus ^{15}F which is unbound by 1.48 ± 0.13 MeV.[9] A new and more accurate measurement of the mass of ^{15}F is necessary in order to confirm the prediction from this systematic that ^{15}F should be less unbound.

A reduction of the mass of ^{15}F would also have a large influence on the search for the two-proton decay of ^{16}Ne. With the present mass values ^{16}Ne is marginally (74 ± 133 keV) bound with respect to one proton decay but unbound with respect to

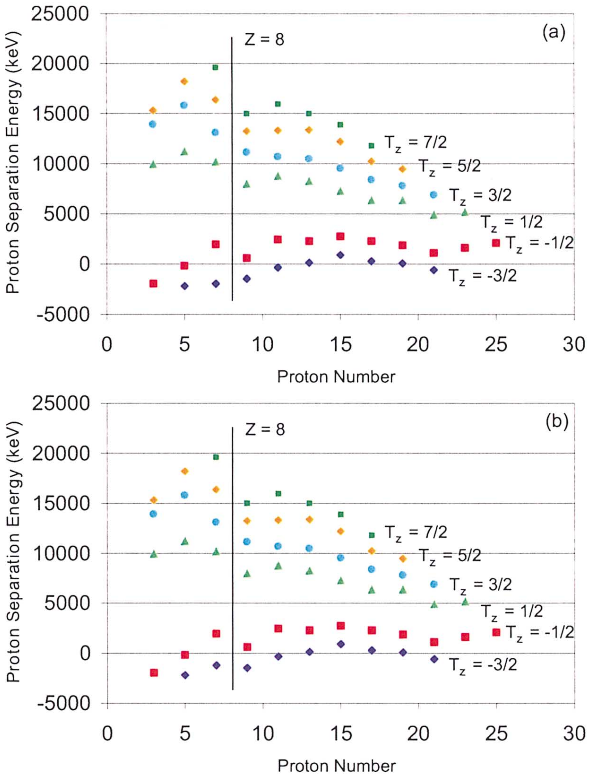

Fig. 5. Proton separation energies for odd-Z−even-N nuclei. The location of the $Z = 8$ shell is indicated by the vertical line.

two proton emission.[9] This scenario is the ideal configuration for the presence of a di-proton decay. Several experiments in neighboring nuclei (^{12}O and ^{19}Mg) have been performed with no indication for ground state di-proton emission.[13,14] The expected reduction of the ^{15}F mass would allow the single proton emission and reduce the probability for a di-proton decay.

Conclusion

Stripping reactions of exotic beams at high energies in coincidence with neutrons and/or γ-rays are powerful tools to study the structure of very neutron rich nuclei along and even beyond the drip line. All light $N = 7$ isotone were shown to exhibit a level inversion of the s- and p-states. These states are particle unbound in ^{10}Li and ^{9}He. The s-states were expressed as scattering lengths of the final state interaction with upper limits of $a_s \leq -10$ fm and $a_s \leq -20$ fm for ^{9}He and ^{10}Li, respectively. In addition, it was confirmed that in ^{10}Li the observed transition was a ground state to ground state transition and not a transition between two excited states by a γ-ray coincidence experiment.

Systematics of neutron and proton separation energies can be powerful tools to study the nuclear structure at and even beyond the driplines. It is predicted that the currently accepted value for the mass of ^{15}F is too large.

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References

1) K. Sümmerer et al.: Nucl. Phys. A **616**, 341c (1997).
2) B. Blank et al.: Phys. Rev. Lett. **84**, 1116 (2000).
3) I. Talmi and I. Unna: Phys. Rev. Lett. **4**, 469 (1960).
4) M. Thoennessen et al.: Phys. Rev. C **59**, 111 (1999) and references therein.
5) L. Chen et al.: Phys. Lett. B **505**, 21 (2001).
6) M. Chartier et al.: Phys. Lett. B **510**, 24 (2001).
7) R. A. Kryger et al.: Phys. Rev. C **37**, R2439 (1993).
8) A. Ozawa et al.: Phys. Rev. Lett. **84**, 5493 (2000).
9) G. Audi et al.: Nucl. Phys. A **624**, 1 (1997).
10) L. Axelsson et al.: Phys. Rev. C **54**, R1511 (1996); K. Markenroth et al.: Phys. Rev. C **62**, 034308 (2000).
11) A. Azhari et al.: Phys. Rev. C **57**, 628 (1998).
12) J. M. Oliviera et al.: Phys. Rev. Lett. **84**, 628 (2000).
13) R. A. Kryger et al.: Phys. Rev. Lett. **74**, 860 (1995).
14) B. Blank et al.: GANIL experiment and private communication (2000).