MICHIGAN STATE
UNIVERSITY

National Superconducting Cyclotron Laboratory

**PHYSICS BEYOND THE DRIP LINE
WITH FAST EXOTIC BEAMS**

M. THOENNESSEN

**Proceedings of the International Conference on the
Structure of the Nucleus at the Dawn of the Century, Bologna 2000
May 29-June 3, 2000, Bologna, Italy**

MSUCL-1169 **JULY 2000**

PHYSICS BEYOND THE DRIP LINE WITH FAST EXOTIC BEAMS

M. THOENNESSEN
National Superconducting Cyclotron Laboratory and Department of Physics & Astronomy, Michigan State University, East Lansing, MI 48824 USA
E-mail: thoennessen@nscl.msu.edu

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. In ^{10}Li the observation of an *s*-wave ground state was confirmed. The ground state of ^{9}He was measured for the first time and it has also *s*-wave character.

1 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 ^{100}Sn and ^{48}Ni 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, knockout 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 it is a special challenge to study their structure.

2 ^{10}Li

The determination of the ground state of ^{10}Li has been controversial for quite some time.[4] Several different 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 projectile breakup reactions of the radioactive isotopes ^{10,11,12}Be.[5]

Figure 1 (a) 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

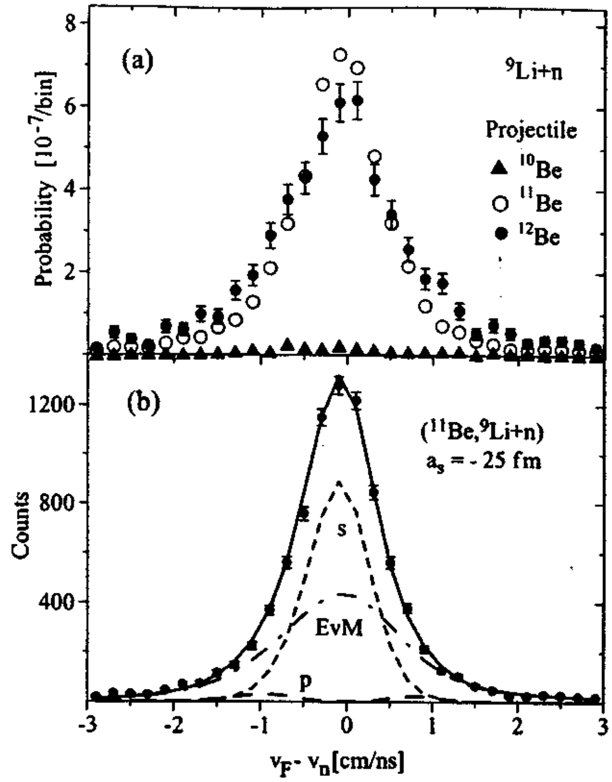

Figure 1. (a): Measured neutron-fragment velocity-difference spectra for ^{10}Li produced with three different projectiles, ^{10,11,12}Be. (b): Velocity difference spectra for the reaction of ^{11}Be leading to ^{10}Li together with a potential model fit. The fit assumed an s-wave component with a scattering length $a_s = -25$, a background from event mixing, and a p-wave resonance at 0.50 MeV (adapted from Ref. 5).

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 1(b) shows the ^{10}Li data from the ^{11}Be reaction together with a

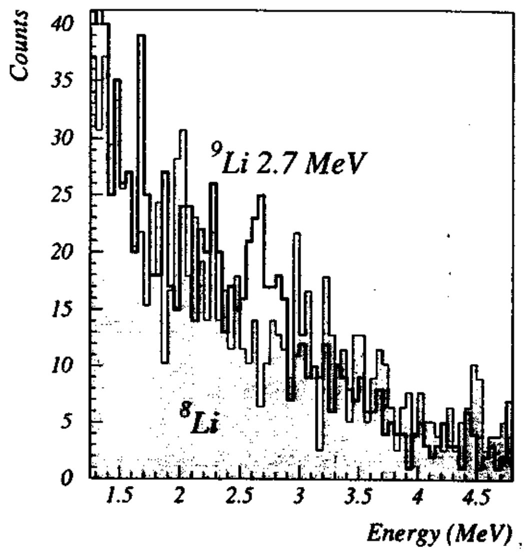

Figure 2. ^{9}Li-γ coincidence spectrum (black line) showing an excess of γ-rays at 2.7 MeV. The smooth background is determined from ^{8}Li-γ coincidences (shaded area). The two spectra are normalized to the same number of incident particles (adapted from Ref. 6).

potential model fit. The extracted scattering length is numerically very large, more negative than -20 fm corresponding to an excitation energy of less than 50 keV 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.

This result was also confirmed in a different measurement of the one proton knockout 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 2 shows the γ-ray spectra in coincidence with ^{9}Li following the one proton knockout 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

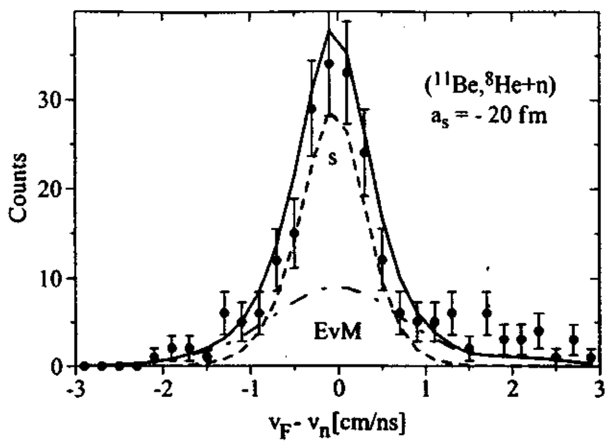

Figure 3. Velocity difference spectra for the knockout reaction from ^{11}Be leading to ^{9}He. The potential model fit assumes an s-wave component characterized by a scattering length of $a_s = -20$ fm, a background from event mixing, and a d-wave resonance at 2.1 MeV (adapted from Ref. 5).

fragments. However, it accounts for only 7±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 confirms the $l = 0$ assignment.

3 ^{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 Figure 3. 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 < 200 keV 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 the lightest nucleus of this isotone chain.

4 Conclusions

Projectile breakup 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 $a_s \leq -20$ fm and $a_s \leq -10$ fm for ^{10}Li and ^{9}He, respectively. In addition, it was shown that in ^{10}Li the observed transition was really a ground state to ground state transition and not a transition between two excited states.

With new more intensive exotic beam facilities coming online in the future these structure studies can be extended to heavier systems.[8]

Acknowledgments

The present work is based on experiments performed at the National Superconducting Cyclotron Laboratory at Michigan State University. The ^{9}He results were the Ph.D. thesis work of L. Chen. Other contributors were T. Aumann, J. R. Beene, B. Blank, B. A. Brown, M. Chartier, F. Deák, A. Galonsky, N. Gan, P. G. Hansen, Y. Higurashi, Á. Horváth, K. Ieki, Y. Iwata, Á. Kiss, J. Kruse, V. Maddalena, H. Schelin, Z. Seres, M. Steiner, J. Stetson, S. Takeuchi, and R. L. Varner. This work was supported by the National Science Foundation under grants PHY-9528844.

References

1. K. Sümmerer *et al.*, Nucl. Phys. **A616**, 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. **C59**, 111 (1999), and references therein.
5. L. Chen *et al.*, submitted to be Phys. Rev. Lett. (2000).
6. M. Chartier *et al.*, submitted to Phys. Lett. B (2000).
7. R. A. Kryger *et al.*, Phys. Rev. **C37** R2439, (1993).
8. *Scientific Opportunities with Fast Fragmentation Beams from the Rare Isotope Acceleartor*, NSCL Report, Michigan State University (2000).