ONE-NEUTRON KNOCKOUT ON ^{11}Be: SPECTROSCOPIC FACTORS TO INDIVIDUAL FINAL STATES OF ^{10}Be

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In this work, published as [1], we have applied a technique based on knockout reactions [2] to study the wave function of the one-neutron halo nucleus ^{11}Be. In the reaction ^{9}Be(^{11}Be,^{10}Be+γ)X at 60 MeV/u, the experimental cross sections to individual final levels in ^{10}Be were determined. These were compared with a calculation combining spectroscopic factors from the shell model with l-dependent single-particle cross sections obtained in an eikonal model. The measurement demonstrated the dominant $1s$ single-particle character of the ^{11}Be ground state and indicated a theoretically expected small contribution of $0d$ admixture in the wave function. After correction for the approximately 22% intensity to excited levels, a clean and precise distribution of parallel momentum for knockout from the $1s$ halo wave function was obtained for the first time. It is slightly broader than the calculated distribution and also shows an asymmetry that cannot be accounted for in the eikonal calculation. We have recently shown (J.A. Tostevin *et al.*, to be published) that these effects are caused by energy conservation in the diffractive breakup channel.

1 INTRODUCTION

Weakly bound atomic nuclei show the interesting property that the wave function of the valence particle can quantum-mechanically penetrate far beyond the range of the nuclear force. Generally, these nuclei are described by a cluster model with a well defined core surrounded by a large diffuse valence wavefunction[3]. The paradigm for the single-neutron halo is the ground state of the nucleus ^{11}Be, which is known to be a $\frac{1}{2}^{+}$ intruder from the sd shell. The standard halo picture of this nucleus has been an inert ^{10}Be core and a $1s$ valence neutron. The first evidence for an unusual spatial extension of its neutron single-particle wavefunction came from lifetime measurements for the ^{11}Be $\frac{1}{2}^{-}$ 320 keV state by Millener *et al.* [4]. One direct reflection of the halo structure is the narrow distribution of the parallel momentum measured by Kelley *et al.* [5] for the ^{10}Be core in inclusive one neutron removal reactions with a light target. The momentum spectrum can be linked in a simple way to the linear momentum content of the halo wave function beyond the nuclear surface [6, 7] in the assumed core-halo cluster model. The important question is the extent to which the inert core/halo model is correct. If in fact the ^{11}Be wavefunction has a significant contribution of excited ^{10}Be states, then the simple picture of halo nuclei is called into question. In the present paper, a comprehensive study of the structure of ^{11}Be is carried out by using a high energy nucleon knockout reaction [2] in order to answer this question.

Table 1: Partial cross sections in mb to the final states I^{π} observed in ^{10}Be. Theoretical single-particle cross sections in the eikonal model are given separately for knockout and diffractive breakup. The sum multiplied by the spectroscopic factor is compared with the experimental values.

I^{π}	l	S	σ_{sp}^{knock}	σ_{sp}^{diff}	σ^{other}	σ^{theo}	σ^{exp}
0^+	0	0.74	125	98	$10^{a)}$	172	203(31)
2^+	2	0.18	36	14	$11^{b)}$	17	16(4)
1^-	1	0.69	25	9		23	17(4)
2^-	1	0.58	25	9		20	23(6)
Σ						224	259(39)

$^{a)}$ Coulomb dissociation, $^{b)}$ Rotational excitation; spectroscopic factor is that of the 0^+ state (see text).

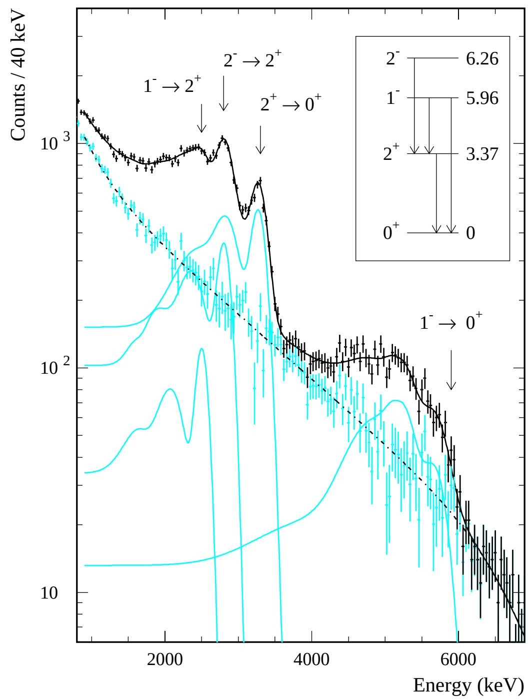

Figure 1: Doppler-corrected energy spectrum measured with the NaI array in coincidence with ^{10}Be fragments. The solid curve is a fit to the experimental spectrum (black error bars) and contains the sum of the simulated response functions (grey curves) for the four γ energies indicated by arrows and a backgound parametrization (dash-dotted curve). The experimental spectrum after subtraction of the simulations for the four γ lines is shown by the grey error bars. The absolute γ energies in MeV and intensities (% after correction for acceptance) for the observed transitions are 2.59 (2.4), 2.89 (9.1), 3.37 (17.6), and 5.96 (4.2).

The question of the ground state structure of ^{11}Be is closely related to the theoretical ingredients necessary for understanding the parity inversion occurring in the ^{11}Be ground state [8]. The most important consideration is a particle-rotation admixture $0d_{5/2} \otimes 2^+$ coupled to $\frac{1}{2}^+$. Estimates of the admixed intensity range from 7% [9] to about 40% [10, 11]. Admixtures of different valence orbits to the ^{11}Be ground state wave function can be quantified in terms of spectroscopic factors. A spectroscopic factor of 1 implies one valence nucleon in a given single-particle state coupled to a given state of the ^{10}Be core. The theoretical spectroscopic factors S of Table 1 were calculated with $0\hbar\omega$ (0^+ and 2^+) and $1\hbar\omega$ ($\frac{1}{2}^+$, 1^- and 2^-) wavefunctions obtained with the WBP interactions of Warburton and Brown [12]. (The results with the WBT interaction were similar.)

Up to now, the experimental situation has been unclear. The DWBA analysis of the ^{10}Be$(d,p)^{11}$Be reaction of Refs. [13, 14] give spectroscopic factors $S(0^+)$ of 0.73(6) and 0.77 respectively, while a recent reanalysis with a more detailed reaction model[15] favors a value as low as 0.4. This is a potentially very significant result that calls into question the simple halo picture of ^{11}Be. However, such a low $S(0^+)$ is difficult to reconcile with the large Coulomb breakup cross sections observed by Anne *et al.* [16] and by Nakamura *et al.* [17]. A new experiment based on differential angular distributions in the $p(^{11}\text{Be},^{10}\text{Be})d$ reaction was reported by Fortier *et al.* [18], who concluded the ^{11}Be ground state contains a 16% admixture of excited states. Their result, however, is sensitive to the coupling of the $0d$ orbit and the deformed ^{10}Be core. Another indication of the ^{11}Be ground state structure comes from the recent measurement of the ^{11}Be ground state magnetic moment [19]. This measurement implies essentially no $0d$ state admixture, but is sensitive to the quenching assumed for the single particle magnetic moment. The quenching of the magnetic moment could be significantly different than for a well bound nucleon, and the conclusions of this paper are at odds with the transfer reaction analysis [15, 18].

2 EXPERIMENT

In the present experiment a radioactive beam of ^{11}Be was produced at the National Superconducting Cyclotron Laboratory (NSCL) in fragmentation reactions of an 80 MeV/u primary ^{18}O beam with a 790 mg/cm^2 thick Be target. After selection in the A1200 fragment separator [20], the secondary beam of 60 MeV/u (mid-target energy) was directed onto a 228 mg/cm^2 ^{9}Be reaction target surrounded by a position-sensitive NaI array [21]. This array detected the γ rays emitted by excited fragments, while the emerging ^{10}Be fragments were measured and identified by the S800 spectrometer [22, 23], operated in the dispersion-matched mode. The resulting resolution including a contribution from the finite target thickness was 13 MeV/c FWHM, much narrower than the distributions discussed in the present work. The momentum acceptance of the spectrograph was 6% and its angular acceptances were $\pm 3.5^\circ$ and $\pm 5^\circ$. This meant that the detection efficiency for the narrow distribution corresponding to the ground state was essentially 100% while that for the $0p, 0d$ excited levels was 0.73(6) and 0.59(8), respectively, determined as described later in this letter.

Based on the position information obtained with the NaI array [21], the γ energies in coincidence with ^{10}Be fragments could be transformed back to the projectile center-of-mass system on an event-by-event basis. The resulting spectrum, shown in Fig. 1, is interpreted as originating from the four γ transitions [24] indicated by arrows and shown in the simplified level scheme in the inset. Two other levels with spin and parity 2^+ and 0^+ are known near 6 MeV and would not be resolvable by our techniques. If, contrary to expectations [12], they are populated, then their contributions would be added to the cross sections for the 1^- and 2^- levels, respectively. The response functions corresponding to the individual γ rays were generated with the Monte Carlo code GEANT [25] in a simulation procedure that took into account both the Doppler shift and the distortion of the shapes caused by the back transformation. The experimental efficiencies measured with calibrated radioactive sources agreed with the simulations to within 5%. The calculated line shapes together with an assumed smooth background arising from neutrons and debris from the target give the excellent fit to the measured spectrum shown in Fig. 1, with a χ^2 per degree of freedom of 1.1. The smooth distribution of the residues indicates that no γ lines with statistically significant intensity have been missed. As a further check, the background spectrum was compared with the reactions (^{16}C,^{15}C) and (^{12}Be,^{11}Be), which have no γ rays above 740 and 320 keV, respectively. The agreement was found to be quantitative. Errors arising from a possible anisotropic distribution of the reaction gamma rays are expected to be small because of the large angular coverage of the array, approximately 60° to 150° in the center-of-mass system. All this reassures us that the absolute gamma branching ratios in coincidence with projectile residues intensities are reliable to better than 10%. ¿From the absolute intensities partial cross sections, given in Table 1, were obtained after correcting for the spectrometer acceptance. The error in the cross sections include a common 15% scale error.

3 COMPARISON WITH THEORY

The nature of the ^{10}Be states is well understood. It is seen from Table 1 that only 78% of the inclusive fragment spectrum corresponds to neutron removal to the ground state. About one third of the intensity of the strongest γ ray (3.37 MeV) corresponds to direct feeding of the 2^+ level. It is this part that carries information about the $0d_{5/2} \otimes 2^+$ admixture in the ^{11}Be ground state. The two excited states with negative parity have the dominant structure $1s_{1/2} \otimes ^9\mathrm{Be}(\frac{3}{2}^-)$, and are excited by the removal of a neutron from a $p_{3/2}$ core state, while the halo s-wave neutron acts as a spectator. We now compare these four cross sections with the theoretical expectations.

The theoretical cross section for a given ^{10}Be core final state, and removed nucleon j value, is assumed to be a product of a spectroscopic factor S and a single-particle cross section [2, 26]. The latter is the sum of terms corresponding to knockout (often referred to as stripping) and diffraction dissociation. These were calculated within a spectator-core eikonal three-body model [26] similar to that used in [27] with the same parameters.

The results of the calculations are given in Table 1. These show an expected reduction in the single-particle cross sections for higher l values and higher binding energies, since the reactions take place at the nuclear surface and depend sensitively on the tail of the neutron wavefunction. This surface dominance justifies

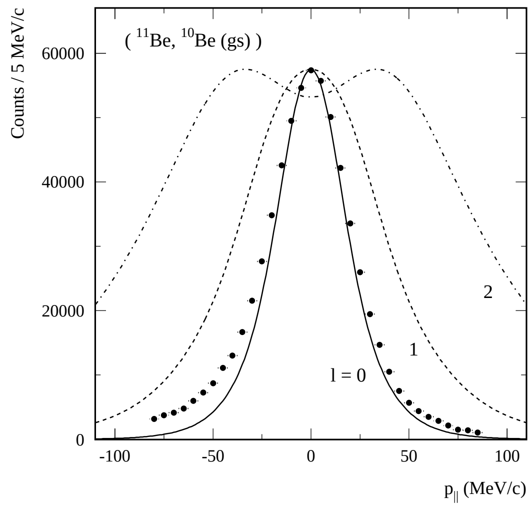

Figure 2: $p_{||}$ distribution of the ^{10}Be fragments in the rest frame of the projectile. Only the contribution leading to the ground state of ^{10}Be is shown. The curves are eikonal calculations assuming a knockout reaction from s, p and d states. Recent work (to be published) has shown that the deviations from experiment can be understood in a theory that takes into account energy conservation in the diffractive breakup process

our use of the optical limit in the 50-100 MeV/u region. Although the potential is highly attractive and absorptive in the nuclear interior, comparison with calculations using S_n derived from the microscopic nucleon optical potential of Jeukenne *et al.* [28] confirm that the optical limit S_n performs well in the critical surface region. The same conclusions pertain for analogous experiments and analyses with phosphorus and carbon isotopes [2, 29]. Details of these theoretical model comparisons, and also those using phenomenological potentials, will be presented elsewhere.

Table 1 shows that the agreement is good in the present case. The most important conclusion is that the cross sections to the two lowest levels support the Warburton-Brown [12] spectroscopic factors, thus corroborating a dominant s-wave single-particle configuration for the ground state.

Table 1 includes an estimate of the effect of excitation of an assumed deformed ^{10}Be core by the target. Within the eikonal framework [30], using the same interaction and density parameters and an assumed ^{10}Be quadrupole deformation $\beta_2 = 0.67$ [10], the calculated cross section for excitation to the 2^+ core state is 11 mb, which has to be multiplied with the 0^+ state spectroscopic factor. In addition, a small contribution of 7 mb was estimated for the Coulomb breakup, which was added to the ground state cross section (see Table 1).

We now turn to the momentum distributions of the ^{10}Be fragments, from which the angular-momentum assignments are deduced. Since the normalization of the distribution is contained in the absolute cross section, we present the distributions scaled in an arbitrary way to the data. ¿From the coincidences with γ rays it is possible to obtain the distribution corresponding to the ground state by subtracting the components to excited states from the singles spectrum. The result is shown in Fig. 2. The full width at half maximum is 47.5(6) MeV/c (45.7(6) after subtracting quadratically the resolution). The ability to cleanly see the contribution of nucleon removal from the $1s$ state allows us to make a precise comparison of the measured ^{10}Be fragment distribution with calculations. Past experiments [5, 31] had significant contributions from parts of the wavefunction that do not reflect the halo, including the 2^- and 1^- core neutron removal hole states. We compare our result with theoretical momentum distributions calculated in an eikonal model for the knockout process. The distribution for diffractive dissociation is expected to have a similar shape [27]. We follow [7] and calculate the distribution for a given impact parameter as the one-dimensional Wigner transform of the wave function after the reaction. For this we use a black-disc approximation. The cutoff radii were adjusted to reproduce the core-target and neutron-target reaction cross sections for free particles and are 5.28 and 3.12 fm, respectively. The calculated

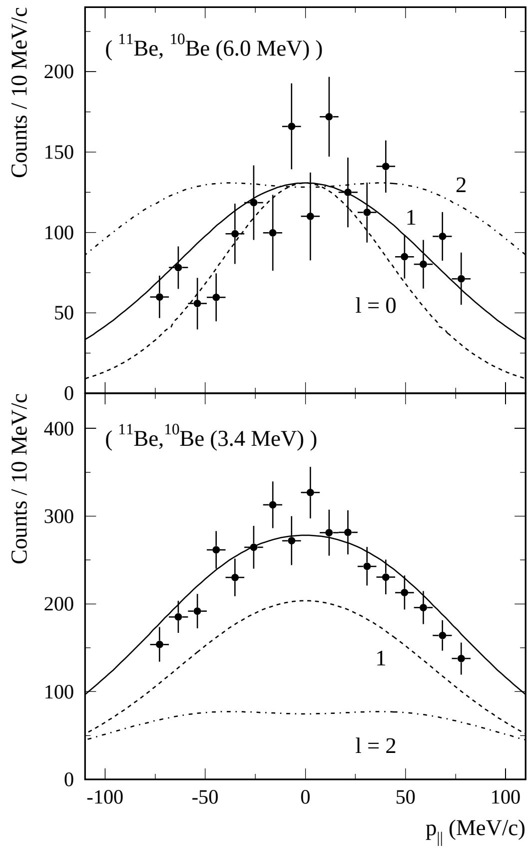

Figure 3: ^{10}Be $p_{||}$ distributions for the excited states. *Upper panel:* in coincidence with 6.0 MeV γ rays, compared with a calculation (solid line) assuming knockout of a neutron from a $p_{3/2}$ core state. *Lower panel:* in coincidence with the 3.4 MeV γ ray, compared with our calculation (solid curve) representing the sum of individual contributions with $l = 2$ (direct feeding, dot-dashed) and with $l = 1$ (dashed).

result for a neutron separation energy of 0.5 MeV and for three values of the angular momentum is shown in Fig. 2. The comparison points to an unambiguous $l = 0$ assignment.

The second calculation, by Bonaccorso and Brink [32], used time-dependent perturbation theory with the interaction represented by optical potentials. The two reaction channels were treated separately, but turned out to give essentially identical shapes and absolute cross sections. The close agreement between the two theoretical differential cross sections suggests that both approaches reflect the same basic physics input: the momentum content of the external part of the single-particle neutron wave function. The experimental data, which have been cleansed of a 22% branch to core excited states, agree well with the two calculations and give for the first time a quantitative check on our understanding of the parallel-momentum distribution of a neutron halo.

The momentum distributions for the excited levels in the rest frame of the projectile are shown in Fig. 3. The data in the upper panel are consistent with the known $p_{3/2}$ core state assignment but better statistical accuracy would be needed to distinguish s and p states. In the lower part of Fig. 3 the corresponding distribution is shown gated on the $2^+ \rightarrow 0^+$ transition. The curve blending the contributions from direct and indirect feeding is seen to be in good agreement with the data. The p-wave and especially the d-wave contributions are very broad, and the acceptance corrections mentioned above were estimated from an extrapolation of the theoretical curves. The corrections for angular acceptance were small.

4 CONCLUDING REMARKS

In summary, a knockout reaction has been used to determine the ground state structure of ^{11}Be. It has been used to answer the question of the nature of the ^{11}Be halo and the admixture of the ^{10}Be excited core to it. In addition, the measurement allowed for the first time an accurate determination of the distribution of longitudinal momentum in the removal of a $1s$ neutron to the ^{10}Be ground state. The distribution agrees reasonably well with recent calculations and confirms the validity of the knockout models for extracting structure information. The partial cross sections connecting to four ^{10}Be states are in good agreement with calculations based on the shell model and eikonal reaction theory and the results lend support to a picture in which the ^{11}Be ground state is dominated by the $1s$ single-particle component with a small $d_{5/2} \otimes 2^+$ admixture.

We are grateful to Henning Esbensen and Angela Bonaccorso for discussions. This work was supported by NSF Grants No. PHY-9528844, No. PHY-9605207 and PHY-9402761.

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References

1. T. Aumann *et al.*, Phys. Rev. Lett. **84**, 35 (2000).
2. A. Navin *et al.*, Phys. Rev. Lett. **81**, 5089 (1998).
3. P.G. Hansen, A.S. Jensen and B. Jonson, Annu. Rev. Nucl. Part. Sci **45**, 591 (1995).
4. D.J. Millener *et al.*, Phys. Rev. C **28**, 497 (1983).
5. J.H. Kelley *et al.*, Phys. Rev. Lett. **74**, 30 (1995).
6. J. Hüfner and M.C. Nemes, Phys. Rev. C **23**, 2538 (1981).
7. P.G. Hansen, Phys. Rev. Lett. **77**, 1016 (1996).
8. H. Sagawa, B.A. Brown and H. Esbensen, Phys. Lett. B **309**, 1 (1993).
9. N. Vinh Mau, Nucl. Phys. A **592**, 33 (1995).
10. F.M. Nunes, I.J. Thompson and R.C. Johnson, Nucl. Phys. A **596**, 171 (1996).
11. T. Suzuki, T. Otsuka and A. Muta, Phys. Lett **B364**, 69 (1995).
12. E.K. Warburton and B.A. Brown, Phys. Rev. C **46**, 923 (1992).
13. D.L. Auton, Nucl. Phys. A **157**, 305 (1970).
14. B. Zwieglinski, W. Benenson and R.G.H. Robertson, Nucl. Phys. A **315**, 124 (1979).
15. N.K. Timofeyuk and R.C. Johnson, Phys. Rev. C **59**, 1545 (1999).
16. R. Anne *et al.*, Nucl. Phys. A **575**, 125 (1994).
17. T. Nakamura *et al.*, Phys. Lett. B **331**, 296 (1994).
18. S. Fortier *et al.*, Phys. Lett. B **461**, 22 (1999).
19. W. Geithner *et al.*, to be published in Phys. Rev. Lett.
20. B.M. Sherrill *et al.*, Nucl. Instr. Meth. B **70**, 298 (1992).
21. H. Scheit *et al.*, Nucl. Instr. Meth. A **422**, 124 (1999).
22. B.M. Sherrill *et al.* (to be published), J.A. Caggiano, PhD Thesis, MSU 1999.
23. J. Yurkon *et al.*, Nucl. Instr. Meth. A **422**, 291 (1999).
24. F. Ajzenberg-Selove, Nucl. Phys. A **490**, 1 (1999).
25. GEANT, Cern Library Long Writeup W5013 (1994).
26. J.A. Tostevin, J. Phys. G **25**, 735 (1998).
27. K. Hencken, G. Bertsch and H. Esbensen, Phys. Rev. C **54**, 3043 (1996).
28. J.-P. Jeukenne, A. Lejeunne and C. Mahaux, Phys. Rev. C **16**, 80 (1977).
29. V. Maddalena *et al.* Phys. Rev. C **63**, 024613 (2001).
30. G. Fäldt and R.J. Glauber, Phys. Rev. C **42**, 395 (1990).
31. F. Negoita *et al.* Phys. Rev. C **59**, 2082 (1999).
32. A. Bonaccorso and D.M. Brink, Phys. Rev. C **58**, 2864 (1998).