DIRECT EVIDENCE FOR THE DISAPPEARANCE OF THE $\mathrm{N} = 8$ SHELL GAP IN ^{12}Be

A. Navin[a], D.W. Anthony[b], T. Aumann[c], T. Baumann, D. Bazin, Y. Blumenfeld[d], B.A. Brown, T. Glasmacher, P.G. Hansen, R.W. Ibbotson, P.A. Lofy[b], V. Maddalena, K. Miller, T. Nakamura[e], B.V. Pritychenko, B.M. Sherrill, E. Spears, M. Steiner, J.A. Tostevin[f], J. Yurkon and A. Wagner

In this work [1] we have studied the partial cross sections and corresponding momentum distributions in the one-neutron knockout reaction (^{12}Be,^{11}Be+γ) on a ^{9}Be target at 78 MeV/u. Dividing the experimental cross sections by the theoretical single-particle knockout cross sections, we obtain the absolute spectroscopic factors for the only two bound states of ^{11}Be to be 0.42±0.06 $(1/2^{+})$ and 0.37±0.06 $(1/2^{-})$, where the errors are experimental only. Owing to the difference in binding of the two single-particle orbits in the initial and final states, the cross sections are reduced by shakeoff. To take this effect into account, we divide by the spectroscopic factors by theoretically calculated mismatch factors of 0.79 and 0.83, respectively. This leads to a more basic quantity denoted S*, which represents directly the shell-model parentage. Calculations with the Warburton-Brown Hamiltonian leads to dominant configurations in the space $(0s)^{4}$-$(0p)^{n}$-$(1s,0d)^{m}$. We find that the magic shell gap has disappeared in the neutron-rich ^{12}Be and that the last neutron pair is to two thirds in the $(1s^{2}$+$0d^{2})$ intruder configuration.

1 INTRODUCTION

Magic numbers in neutron-rich nuclei near the drip line are predicted [2] to be very different from those observed near the valley of stability. Because of the relatively small configuration space in the region of the neutron number $N = 8$, the interpretation of the breakdown should be simpler there than for the heavier nuclei. In this letter, we report a study of single-neutron knockout reactions of the $N = 8$ neutron-rich nucleus ^{12}Be leading to the $1/2^{+}$ ground state and the $1/2^{-}$ excited state of ^{11}Be. The resulting spectroscopic factors provide the first direct demonstration of the breakdown of the shell closure for ^{12}Be, which turns out to have a wave function dominated by deformation and pairing and with major contributions from s, d intruder states. Our result also may cast new light on the $N = 8$ neighbor, ^{11}Li. This two-neutron halo nucleus is usually viewed as a case apart with properties dominated by its low binding energy, but we surmise on theoretical grounds that it will, from the point of view of nuclear structure, resemble ^{12}Be.

The structure of ^{12}Be is not given unambiguously as a consequence of the systematics of the neighboring nuclei. The nearest even-even nucleus with 8 neutrons, ^{14}C, is very magic although the 1/2^{+} state in ^{13}C is only at 3 MeV. This would point to a very pure $0p^{2}$ configuration for ^{12}Be. On the other hand, the isotope ^{11}Be with $N = 7$ is the classic example of an intruder configuration. It has a 1/2^{+} ground state while the normal 0*p*-shell configuration of 1/2^{-} appears at 320 keV. The interpretation of this level inversion is far from trivial, but it can be understood in the framework of shell-model configuration mixing involving a combination of shell-quenching, quadrupole-deformation and pairing-energy effects [3, 4, 5].

Indirect evidence had already suggested that intruder states would play an important role in ^{12}Be; see the work of Barker [6] and also the recent analysis by Sherr and Fortune [7] based on analogue displacement energies and reaction data. The configuration mixing and interaction used in a shell-model which reproduces the ^{11}Be spectrum predicts that the energies of the lowest $(0p)^{8}$ and $(0p)^{6}$-$(1s,0d)^{2}$, J$^{\pi}$=0^{+} configurations in ^{12}Be are degenerate [8]. Other studies such as of the ^{10}Be(t,p) reaction[9] and of the quenching of the Gamow-Teller transitions [10] lead to conclusions similar to those of Barker. An alternative description of the structure of ^{12}Be is provided by core-particle models such as the three-body model of [11], which also predicts a significant $(1s,0d)^{2}$ ground-state admixture when a ^{10}Be(2^{+}) core configuration is included.

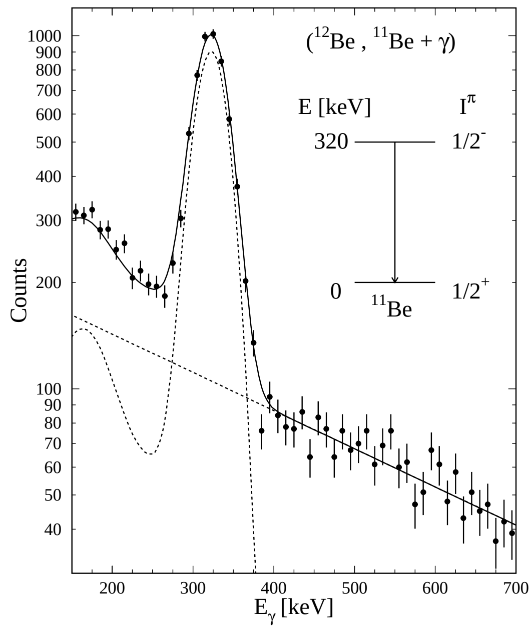

Figure 1: Measured gamma-ray spectrum in the projectile rest frame in coincidence with ^{11}Be residues. The full-drawn line is the result of a fit using a simulated line shape of the 320 keV gamma ray and an exponential background, both shown as dashed lines.

2 EXPERIMENT

The most direct way to measure the ground-state structure of ^{12}Be is to determine the spectroscopic factors for the removal of a neutron [8]. For example, the neutron closed-shell configuration $(0p)^8$ would give spectroscopic factors of zero and about two for the knockout reactions to the 1/2+ and 1/2- states, respectively. The experiment, based on the technique used in our recent experiment on ^{11}Be [12], see also [13, 14], involved the measurement of the partial cross sections and momentum distributions for the two final states of the residue formed in the one-nucleon knockout reaction ^{9}Be(^{12}Be,^{11}Be+γ)X. Secondary beams produced at the NSCL at Michigan State University from the fragmentation of a 100 MeV/u ^{15}N primary beam on a ^{9}Be target were mass- and momentum- analyzed using the A1200 fragment separator. A beam of ^{12}Be at 78 MeV/u with an intensity of 2×10^3 particles/s and a momentum spread of 0.5% was transmitted to the high-acceptance S800 spectrograph [15] operated in a dispersion-matched mode. The projectile residues were detected and identified at the focal plane of the spectrograph using time of flight and the energy deposited in an ion chamber and two plastic scintillators. The longitudinal momentum distribution of the ^{11}Be fragments was reconstructed from the measured positions at the focal plane[15, 16]. The measured inclusive one-neutron removal cross section, based on the ratio of the number of projectile residue to incident beam particles and on the target thickness, is 49.5 $\pm$ 4.5) mb.

The ^{12}Be beam was incident on a 151 mg/cm^2 ^{9}Be target which was surrounded by an array of 38 NaI(Tl) position-sensitive γ-ray detectors[17]. The position information from the array was used to correct for the Doppler effect by converting event by event the registered gamma energy to the the projectile rest frame. The resulting γ-ray spectrum is shown in Fig. 1, where the 320 keV ray identifies the formation of the 1/2$^-$ state. This procedure generates a detector response different from what would be obtained with a stationary source. We have constructed this response by using the code GEANT [18] to create simulated events, which were adjusted to the known energy resolution and subsequently analyzed in the same way as the real data. The resulting line shape is shown in Fig. 1. It corresponds to a photopeak detection efficiency of 33% with a relative accuracy of 5%. The reliability of this approach has been confirmed in a number of measurements with radioactive sources.

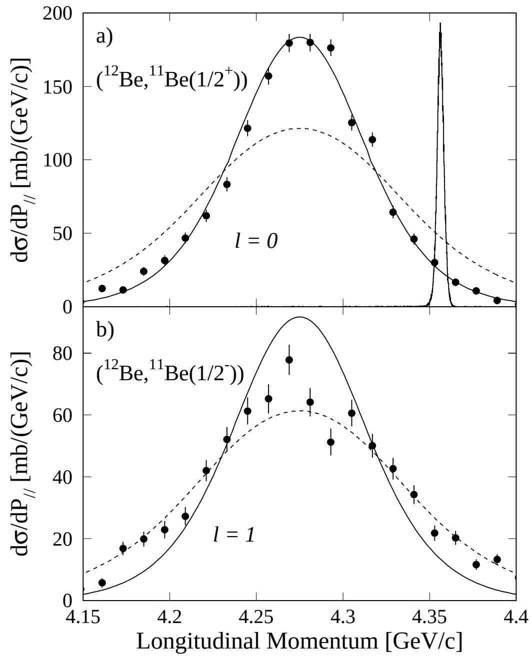

Figure 2: Measured longitudinal momentum distributions in the laboratory frame for ^{11}Be residues in the ground state (a) and excited state (b) after one-neutron removal reactions of ^{12}Be. The solid(dashed) curves are calculations [12] for l=0,1 neutron removal, normalized to the measured cross section. The errors shown are only statistical. The narrow line in (a) illustrates the line profile of the spectrograph for the incident ^{12}Be beam, re-scaled for display purposes.

A 3% attenuation of the 320 keV γ ray in the target material was also taken into account.

The background visible at higher energies in Fig. 1 is attributed to reactions of neutrons, gamma rays and charged particles from the target with the detectors and surrounding materials. It is quite similar to the one deduced in [12] and is for our purposes well represented by a single exponential. The fit to the range 150-700 keV shown in the figure leads to an absolute intensity to the excited state of 35.4$\pm$4.5%. An adjustment with a linear background component and the range restricted to the photopeak and just above (250-500 keV) increases this by 1.4% (absolute) but gives a poorer fit in the region 150-250 keV. The possible systematic error arising from the background is reflected in the error limit. As the ground state is the only other bound state in ^{11}Be, the absolute branch to this is just the complement, 64.6$\mp$4.5%. Combining the absolute branching ratios with the inclusive cross section given above, we obtain the partial cross sections given in Table 1. The gamma coincidences allow the separation of the measured inclusive longitudinal momentum distribution into the constituent distributions for the 1/2$^-$ and 1/2$^+$ states as shown in Fig. 2. Here, the momentum distribution for the 1/2$^-$ state was obtained by gating on the 320 keV γ ray and subtracting from this the contribution from the background. The complement is then the momentum distribution to the 1/2$^+$ ground state, shown in the upper part of Fig. 2. The theoretical momentum distributions are also shown in Fig. 2. They were calculated as in [12] and confirm the known s- and p-wave assignments.

3 DERIVATION OF THE SPECTROSCOPIC FACTORS

The fact that the ground state of ^{11}Be accounts for approximately two thirds of the cross section is direct proof of a significant occupancy of the $1s_{1/2}$ state in ^{12}Be, and hence of the breakdown of the N=8 shell closure. We now discuss this finding more quantitatively in terms of our theoretical model with parameters as used in an experiment on ^{11}Be [12]. In this, each partial cross section is calculated as the product of a single-particle removal cross section (σ_{sp}) and a spectroscopic factor (S) [13, 14]. Our confidence in the method has been bolstered by a recent application to the neutron-rich carbon isotopes [19]. In this we obtained spectroscopic factors that within the experimental errors of 20% agreed with theory for the case of neutron knockout from ^{15}C, which is well understood.

The $0d_{5/2}$ component of the ^{12}Be ground state is unobservable in our experiment since knockout from this orbit leads to the unbound 5/2$^+$ resonance in ^{11}Be, which decays by neutrons. Thus the absolute spectroscopic factors are essential for obtaining indirect information on the $0d_{5/2}$ component, and we now discuss the single-particle cross sections σ_{sp} to the ^{11}Be(j^π) final states in more detail. The spectator core model of Refs. [13, 14] leads to contributions from the removal of the neutron due to the target absorption (stripping) and diffraction dissociation (elastic breakup) mechanisms. The essential ingredients are the interactions of the residue and the removed neutron with the target, which enter through their elastic S-matrices, and the bound state wave function of the removed nucleon.

Table 1: Spectroscopic factors in the reaction ^{9}Be(^{12}Be,^{11}Be)X. The quantity S_{exp} is obtained by dividing the measured partial cross section by the the single-particle cross section, and assumes a 20% uncertainty in the theory. The quantity S^*_{exp} represents the experimental spectroscopic factor divided by the the mismatch factors of 0.79 (1/2$^+$)and 0.83 (1/2$^-$), see text. S^* should be compared directly with the theoretical spectroscopic factors from the shell model given in the two next columns. The result of the three body calculation (3b) is given in the last column; it should be compared with the spectroscopic factor S_{exp}.

j^π	E (MeV)	σ_{exp} (mb)	σ_{sp} (mb)	S_{exp}	S^*_{exp}	S_{th} WBT	WBT2	3B
1/2$^+$	0	32.0±4.7	75.9	0.42±0.10	0.53±0.13	0.51	0.69	0.7
1/2$^-$	0.32	17.5±2.6	47.2	0.37±0.10	0.45±0.12	0.91	0.58	0.26
5/2$^+$	1.8	-	-	-	-	0.40	0.55	-

The ^{11}Be residues are themselves weakly bound. The correct range and absorption of their interactions, due to breakup of these ^{10}Be+n systems, is calculated from the ^{11}Be(j^π) bound state wave functions and the ^{10}Be- and n-target interactions. The latter are calculated from the particle and target densities using an effective nucleon-nucleon (NN) amplitude [14]. To assess sensitivity to the nucleon-target interaction the breakup was also calculated using the Jeukenne, Lejeunne and Mahaux[20] nucleon optical potential.

The ^{11,12}Be structures enter the calculations through the removed nucleon single-particle overlaps for the $1/2^+$ and $1/2^-$ final states, with separation energies of 3.17 and 3.49 MeV respectively. The overlaps are calculated as single-particle wave functions in Woods-Saxon (WS) potentials with geometries taken (i) with r_0=1.25 fm and a=0.7 fm, typical of WS single-particle states, and (ii) from the three-body (^{10}Be+n+n) calculation of Ref. [11].

The ratio of the calculated σ_{sp} to the two ^{11}Be states (1.60) is insensitive to the formfactors or n-target interactions used. It follows that the relative spectroscopic factors for the two transitions will be well determined by the experiment. The magnitude of each σ_{sp} shows only small sensitivity to the interactions but a greater sensitivity to the assumed formfactor. For example, the total one-nucleon removal cross sections, calculated using the NN interaction and the two wave functions above, are 66.2 and 80.5 mb. The largest sensitivity is to the diffuseness of the nucleon binding potentials. The cross sections and the experimentally derived spectroscopic factors shown in Table 1 use the NN interaction and the Woods-Saxon wave function geometry, as in our study of other nuclei[13, 12, 19]. The leading corrections to these calculations, expected to arise from dynamical coupling between the ^{11}Be core states, have been estimated to lead to a cross section error of less than 1 mb and have been neglected. The comparison with other models and parameter sets suggests a theoretical reaction-model uncertainty on the single-particle cross section of the order of 20%, the same as the experimental uncertainty estimate mentioned above. The errors on the experimental spectroscopic factors given in Table 1 include a 20% theoretical uncertainty.

4 NUCLEAR-STRUCTURE THEORY

We now compare the experimental spectroscopic factors with those obtained from shell-model calculations. We use the WBT Hamiltonian [4] which is appropriate for a model space with active configurations of the type $(0p)^n$-$(1s,0d)^m$. The calculations are done within the full $0s$-$0p$-$(1s,0d)$-$(1p,1f)$ basis in order to remove the spurious states, but the main configurations for this mass region are $(0s)^4$-$(0p)^n$-$(1s,0d)^m$ (elsewhere in this paper we omit the notation $(0s)^4$ which is common to all configurations). low-lying levels for ^{11}Be obtained with the WBT Hamiltonian are 0.0 MeV ($1/2^+$) and 1.52 MeV ($5/2^+$) [$(0p)^6$-$(1s,0d)^1$] and 0.30 MeV ($1/2^-$) [$(0p)^7$], in good agreement with experiment.

With the WBT Hamiltonian, the energies of the lowest $(0p)^8$ and $(0p)^6$-$(1s,0d)^2$ 0^+ states in ^{12}Be are degenerate to within 50 keV. The spectroscopic factors for these pure configurations leading to the low-lying states in ^{11}Be are S($1/2^-$) = 1.82 for the $(0p)^8$ to $(0p)^7$ transition, and S($1/2^+$) = 1.02 and S($5/2^+$) = 0.81 for the $(0p)^6$-$(1s,0d)^2$ to $(0p)^6$-$(1s,0d)^1$ transitions.

An excited 0^+ state is suggested experimentally to be at 2.730 MeV[9]. In a two-level model this would require an off-diagonal matrix element of about 1.35 MeV, which is much larger than the energy difference between the theoretical unmixed states. Thus the mixed ground state has a 50% admixture of the two configurations. The spectroscopic factors for the mixed ground state are given in Table 1 (WBT) and compared to experiment. (As mentioned above, the $0d_{5/2}$ component is not measured in the present experiment.) The experimental spectroscopic factor for the $1/2^-$ state is smaller than obtained with the WBT two-component model, indicating that the actual ^{12}Be ground-state wave function contains a smaller $(0p)^8$ (neutron closed-shell) component. To match the ratio of the experimental spectroscopic factors an admixture of about 32% $(0p)^8$ and 68% $(0p)^6$-$(1s,0d)^2$ is required, leading to WBT2 results given in Table 1. The $(0p)^6$-$(1s,0d)^2$ configuration has a low-lying 2^+ state with a large B(E2) value of 85 e^2fm^4. Taking the WBT2 solution for the ground state and a pure $(0p)^6$-$(1s,0d)^2$ 2^+ configuration gives B(E2) = 58 e^2fm^4. It would be interesting to measure it in a Coulomb excitation experiment.

When considering the spectroscopic factors, two different types of overlaps need to be taken into account; the shell-model spectroscopic factor and the radial mismatch factor. The shell-model spectroscopic factor takes into account the configuration mixing between the $0p$ and $(1s,0d)$ shells within the WBT basis. The mismatch factor takes into account the reduction from unity in the square of the overlap between the radial wave functions in ^{11}Be and ^{12}Be due to the change in the average potential between these two nuclei. The shell-model calculations already implicitly contain (to some extent) this mismatch factor in its effective Hamiltonian and resulting eigen-energies. But the matrix elements of any operator such as those for single-nucleon knockout and electromagnetic interactions [3] must explicitly account for the the halo nature of the radial wave functions. Using single-particle Woods-Saxon wave functions, we obtain a mismatch factor of 0.79 for the $1s$ state bound by 3.17 MeV in ^{12}Be and by 0.504 MeV in ^{11}Be. For the $0p$ states, bound by 3.49 and 0.18 MeV, we obtain the value 0.83. Since the reduction from unity represents unobserved excitations from the bound states to s and p continuum states, the mismatch factors should multiply the shell-model values of the theoretical spectroscopic factors S_{th} before comparing with experiment. For our application it is, however, more convenient to divide the experimental spectroscopic factor S_{exp} by the mismatch factor to obtain the quantity S^*_{exp} representing the shell-model parentage before the effect of the different binding energies is taken into account. This should compare directly with the theoretical spectroscopic factors denoted WBT and WBT2. (The results for the three-body model should be compared directly with the basic spectroscopic factor S_{exp}.)

Table I provides direct evidence for the occupancy of the $1s_{1/2}$ particle state in the ^{12}Be ground state, and hence for a breakdown of the $N = 8$ shell closure. The effect is stronger than predicted; the experiment suggests that only about 25% of the strength goes to the neutron closed-shell configuration and that almost one half of goes by d-wave knockout to the unbound $5/2^+$ state at 1.78 MeV in ^{11}Be, not directly observed in this experiment. It would be important to design an experiment for ^{12}Be to look for the neutrons from the decay of this low-lying state.

5 CONCLUDING REMARKS

The present experimental observation of about equal s and p spectroscopic factors is similar to that of Simon *et al.*[21] for ^{11}Li. However, although they also found an approximately equal s and p admixture, their analysis did not include a d admixture. Theory suggests that the shell-model structure of ^{11}Li will be very similar to that of ^{12}Be; both have degenerate $(0p)^n$ and $(0p)^{n-2}$-$(1s,0d)^2$ 0^+ ground-state configurations with the WBT Hamiltonian [8]. The possibility for a significant d-wave contribution in ^{11}Li should be considered in future analyses. Improved shell-model calculations for ^{11}Li and ^{12}Be will require a consideration of complete mixing between all configurations, an expansion of the model space to allow more than two neutrons to be excited out of the $0p$ shell shell, and perhaps also for the neutron continuum. The Hamiltonian which is appropriate for the expanded model space needs to be investigated.

This work was supported by NSF Grants No. PHY-9528844 and No. PHY-9605207.

a: Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, India
b: Department of Chemistry, Michigan State University, East Lansing, Michigan 48824
c: Gesellschaft für Schwerionenforschung, Planckstr.1, 64291 Darmstadt, Germany
d: Institut de Physique Nucleaire IN2P3-CNRS, 91406 Orsay, Cedex, France
e: Department of Physics, University of Tokyo, 7-3-1 Hongo Bunkyo, Tokyo 113-0033, Japan
f: Department of Physics, School of Physical Sciences, University of Surrey, Guildford, Surrey, GU2 5XH, United Kingdom

References

1. A. Navin *et al.*, Phys. Rev. Lett. 85 (2000) 266.
2. J. Dobaczewski *et al.*, Phys. Rev. Lett. **72**, 981 (1994).
3. D. J. Millener, J. W. Olness, E. K. Warburton, and S. S. Hanna, Phys. Rev. C **28**, 497 (1983).
4. E.K. Warburton and B.A. Brown, Phys. Rev. C **46**, 923 (1992).
5. H. Sagawa, B.A. Brown and H. Esbensen, Phys. Lett. B **309**, 1 (1993).
6. F.C. Barker, J. Phys. G **2**, L45 (1976); Phys. Rev. C **59**, 535 (1999).
7. R. Sherr and H.T. Fortune, Phys. Rev. C **60**, 064323 (1999).
8. B.A. Brown, in *Proc. ENAM95*, ed. by M. de Saint Simon and O. Sorlin, Editions Frontieres (1995) p451; B.A. Brown, *International School of Heavy-Ion Physics, 4th Course: Exotic Nuclei*, ed. by R.A. Broglia and P.G. Hansen (World Scientific, Singapore, 1998) p1.
9. H.T. Fortune, G.B. Liu and D.E. Alburger, Phys. Rev. C **50**, 1355 (1994).
10. T. Suzuki and T. Otsuka, Phys. Rev. C **56**, 847 (1997).
11. F.M. Nunes *et al.*, Nucl. Phys. A **609**, 43 (1996).
12. T. Aumann *et al.*, Phys. Rev. Lett. **84**, 35 (2000).
13. A. Navin *et al.*, Phys. Rev. Lett. **81**, 5089 (1998).
14. J.A. Tostevin, J. Phys. G: Nucl. Part. Phys. **25**, 735 (1999).
15. J.A. Caggiano, Ph.D. thesis MSU (1998); B.M. Sherrill *et al.*, to be published.
16. M. Berz *et al.*, Phys. Rev. C **47**, 537 (1993).
17. H. Scheit *et al.*, Nucl. Inst. Meth. **A** 422, 124 (1999).
18. GEANT, Cern Library Long Writeup W5013 (1994).
19. A. Navin *et al.*, in *Experimental Nuclear Physics in Europe*, ed. by B. Rubio *et al.*, CP495 American Institute of Physics (1999) p309; V.M. Maddalena *et al.*, to be published.
20. J.P. Jeukenne, A. Lejeunne and C. Mahaux, Phys. Rev. C **16**, 80 (1977).
21. H. Simon *et al.*, Phys. Rev. Lett. **83**, 496 (1999).