Evidence Of A $(1d_{5/2})^2$ Component To The ^{12}Be Ground State

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Abstract. Data have been obtained on exclusive single neutron knockout cross sections from ^{12}Be to study its ground state structure. The cross sections for the production of ^{11}Be in its ground state ($1/2^+$) and first excited state (0.32 MeV, $1/2^-$) have previously been measured [1], indicating a strong $(2s_{1/2})^2$ component to the ^{12}Be ground state. In the present experiment, performed at the GANIL laboratory, cross sections for the first (0.32 MeV, $1/2^-$) and second (1.78 MeV, $5/2^+$, *unbound*) excited states in ^{11}Be were measured, which gives information on the admixture of $(1p_{1/2})^2$ and $(1d_{5/2})^2$ components in the ground state of ^{12}Be . A fragmentation beam of ^{12}Be of ~ 10000 pps (95% pure) was incident on a carbon target at 41 MeV/u. The beam particles were tracked onto the target, and their energies were measured event-by-event. The beam-like residues were measured in a position sensitive telescope mounted at zero degrees, and neutrons were measured in the DéMoN array [1]. The $1/2^-$ state of ^{11}Be was identified by measuring coincident 320 keV γ -rays, using four NaI detectors. Full kinematic reconstruction of unbound states in ^{11}Be was performed using coincident neutrons and ^{10}Be ions. Detailed simulations were performed in order to interpret the data, and spectroscopic factors were calculated, using preliminary single particle removal cross sections calculated using a Glauber model.

INTRODUCTION

In stable nuclei, the $N=8$ magic number corresponds to the shell gap between the $v(1p_{1/2})$ and $v(1d_{5/2})$ orbitals. The nuclei ^{16}O and ^{14}C both exhibit "magic" properties, such as a high first excited state energy, and coincide with a sharp discontinuity in neutron separation energy. However, it is well known that the ground state of the 1-neutron halo nucleus ^{11}Be ($S_n = 0.504$ MeV) has $J^\pi = 1/2^+$ [1], whilst the $1/2^-$ state, which a simple spherical shell model would predict to be the ground state, lies 320 keV higher in energy. This level inversion can be understood as the lowering of the $2s_{1/2}$ orbital, relative to $1p_{1/2}$, when tending towards more neutron rich nuclei.

The addition of an eighth neutron, forming the more tightly bound ^{12}Be ($S_n = 3.165$ MeV), does not restore the

shell gap. Direct experimental evidence for this [2] was obtained from data on 1 neutron knockout from ^{12}Be , leading to the only two bound states in ^{11}Be . As the $1/2^+$ ground state in ^{11}Be is predominantly of $\nu(1s_{1/2})$ nature, and the 0.32 MeV state is predominantly of $\nu(1p_{1/2})$ nature, the relative yield to these states gives an indication of the admixture of $\nu(2s_{1/2})^2$ and $\nu(1p_{1/2})^2$ components to the ^{12}Be ground state. Their analysis yielded approximately equal spectroscopic factors for the $1/2^-$ and $1/2^+$ states, indicating the breakdown of the $N=8$ shell closure in ^{12}Be . However, their shell model analysis suggested a significant $\nu(1d_{5/2})^2$ component to the ^{12}Be ground state. Approximately two thirds of the $\nu(1d_{5/2})$ strength lies in the $5/2^+$ state in ^{11}Be [3], which is above neutron decay threshold, and was experimentally unobservable in their work.

The current experiment was designed to measure the cross sections for 1 neutron removal from ^{12}Be leading the unbound $5/2^+$ state in ^{11}Be , in order to attain a measure of the $\nu(1d_{5/2})^2$ component to the ^{12}Be ground state. The cross section to the bound $1/2^-$ state was also measured, as a measure of the $\nu(1p_{1/2})^2$ component, to provide overlap with the results from reference [2]. For experimental reasons, the yield to the $1/2^+$ ground state of ^{11}Be was unobservable.

KNOCKOUT REACTIONS

The single nucleon knockout reaction [4] is particularly suited to the study of single particle structure of systems with relatively loosely bound valence nucleons. It has been widely employed in the study of light neutron-rich isotopes, many of which are well described by a relatively tightly bound core, with one or more loosely bound valence neutrons (e.g. a halo system in the extreme case). Knockout reactions are typically performed with a beam of the nuclei of interest on low Z targets (to minimize Coulomb effects), at high energies (tens of MeV per nucleon, upwards).

There are two dominant mechanisms for the removal of a nucleon, as indicated in Fig. 1. Diffractive dissociation (elastic breakup) results in the dissociation of the valence nucleon and core via elastic interactions with the target, resulting in both valence nucleon and the core residue continuing at approximately the beam velocity. Stripping comprises interactions in which the valence neutron interacts inelastically with the target, being absorbed or scattered typically at large angles. Experimentally, both mechanisms are defined by the detection of the core-like particle at forward angles; the survival of the core excludes collisions in which the core-target interaction is dominant.

FIGURE 1. Stripping and Diffraction of 1 neutron from ^{12}Be , populating unbound states in ^{11}Be .

The strongly forward focussed projectile residues are typically detected with a high resolution spectrometer. The target may be surrounded by γ ray detectors, to identify the final states of the residues by measuring coincidences between a particular residue and known γ ray transitions from excited states. The cross section to each of the identified states determines spectroscopic factors [5], and the widths of the momentum distributions of the residues are characteristic of the orbital angular momentum ℓ of the removed nucleon, and the separation energy of the valence nucleon (S_n or S_p).

Neutron knockout reactions from light neutron rich nuclei can populate unbound states in the residual which decay by neutron emission. The identification of these states requires the coincident measurement of the core and neutron, and a kinematic reconstruction of the residual; however, the presence of the dipoles of a spectrometer complicates

neutron detection. One solution is to employ a zero degree charged particle telescope, presenting a relatively small mass between target and the neutron detectors (typically $\sim 10\%$ absorption). This results in the entire flux of the beam being incident on the telescope, resulting in a large background in the data. For yield to excited states (where a neutron or γ ray coincidence can be required) this background can be determined by acquiring target-out data, but typically the yield to the ground state of the residual (which presents no possibility of a coincidence measurement) is unobservable.

The reconstruction of the residual from the measurements of the core and breakup neutron results in peaks in the relative energy spectrum corresponding to unbound states populated in the residual, offset by the neutron separation energy. However, it is possible to detect other neutrons in coincidence with the core, such as the diffracted neutrons from the projectile (see Fig. 1), or neutrons from direct breakup into the core + n + n continuum. This leads to an uncorrelated component to the reconstruction data, the effects of which must be understood through simulations.

EXPERIMENTAL DETAILS

The experiment was designed to measure the 1 neutron knockout cross sections from ^{12}Be to the $0.32\text{ MeV } 1/2^-$ and $1.78\text{ MeV } 5/2^+$ states in ^{11}Be , to provide information on the relative admixture of $\nu(1d_{5/2})^2$ and $\nu(1p_{1/2})^2$ components to the ^{12}Be ground state. The fragmentation products of a primary beam of ^{18}O (incident at 63 MeV/A on a rotating beryllium target) were filtered using the LISE3 spectrometer at the GANIL laboratory, France. The spectrometer was tuned to produce a beam of ^{12}Be particles at 41 AMeV (95% pure) with a momentum spread of 0.5%, at an intensity 10000 particles per second. The ^{12}Be beam was incident on a secondary target of 183 mg/cm^2 carbon (natural abundance), with a mid-target energy of 39.3 MeV/A .

FIGURE 2. Photograph of the target chamber (a), with the optic axis indicated, where the beam enters from the lower-right hand corner. A representation of the DéMoN array geometry (b) employed in the current experiment is shown, where the beam is incident from the lower-left.

To compensate for the poor spatial definition associated with fragmentation beams, the ^{12}Be beam particles were tracked, event-by-event onto the secondary target using a pair of drift chambers. The position of interaction on the target was reconstructed with a resolution better than 1 mm (FWHM), with angles measured with a resolution of better than 0.5° (FWHM). To account for the energy spread of the incoming beam particles, their energies were measured event-by-event from their time of flight (relative to the cyclotron RF). This measurement also allowed the ^{12}Be ions to be separated uniquely from the beam, which contained $\sim 5\%$ contaminants (mainly ^{15}B and ^6He). Downstream of the target was mounted a three-stage charged particle telescope, covering $\pm 9^\circ$ degrees in X and Y , comprised of two $500\text{ }\mu\text{m}$ thick silicon detectors, and a close packed array of 16 CsI detectors (in a 4×4 arrangement). The $5\text{ cm} \times 5\text{ cm}$ silicon detectors were divided into 16 resistive strips, which were orthogonally oriented such that measurement of position (better than 1 mm resolution) in both X and Y directions obtained.

The DéMoN array of ~ 100 neutron detector modules was mounted downstream of the target chamber, as shown in Fig. 2b. The neutron energies were determined from their time of flight, relative to the fast signal from a avalanche

FIGURE 3. Particle Identification in the charged particle telescope. The $E\Delta E$ plot (a) shows loci corresponding to isotopes of H, He, Li, Be and B, with a broad horizontal line due to ^{12}Be particles reacting in the CsI detector, overlapping with the $^{7,9,10,11}\text{Be}$ and lithium loci. The 1-dimensional particle identification parameter (b), gated on a neutron in DeMoN, shows the target-in data (target and telescope induced reactions), the target-out data (telescope induced reactions only) and the background subtracted (target only). The regions corresponding to the relevant isotopes of beryllium are indicated, showing strong coincidences between ^{10}Be and neutrons.

counter (PPAC), mounted upstream of the target. The angle of the neutron was determined from the position of the relevant detector module. Neutrons were distinguished from γ rays using a pulse shape discrimination technique. The target was surrounded by four NaI detectors, in order to detect the 320 keV γ rays, to tag the $1/2^-$ state in ^{11}Be . These detectors were sufficiently compact to be mounted within the target chamber and could be run under vacuum, allowing them to be placed close to the target to achieve a relatively high solid angular coverage.

The $1/2^-$ state was identified by tagging the detected ^{11}Be residues with the 320keV de-excitation γ ray. The $5/2^+$ (unbound) state was identified by the coincident measurement of $^{10}\text{Be} + n$, and performing a kinematic reconstruction of the ^{11}Be excitation energy spectrum.

A consequence of using a zero degree charged particle telescope is that the entire beam flux is incident on these detectors. As the CsI detectors are necessarily significantly thicker than the target, the number of beam particles entering the telescope that undergo nuclear reactions within its volume is significant relative to the number of products of target-induced reactions. This has two linked consequences. Firstly, the effect of these reactions is to produce a CsI signal of typically lower magnitude than that associated with unreacted beam particles. In conjunction with the energy loss associated with the beam particles, this results in the intense horizontal band seen in Fig. 3a, which overlaps with the $^{10,11}\text{Be}$ particles of interest. Secondly, the reactions in the CsI detector are a source of neutrons with approximately the beam velocity. This, coupled to the first effect, can give a neutron of approximately the expected energy, in coincidence with a false identification of a charged particle of interest. This background can be understood and subtracted by measuring its form by acquiring target-out data, with the beam energy lowered to account for the average energy loss in the target, as shown in Fig. 3b. This method requires that specific attention be paid to measuring the number of incident beam particles for target-in and target-out runs, and precise measurement of all relevant detector efficiencies, run by run.

SIMULATIONS

The efficiency for detecting neutrons is dependent on their spread over the array, and there are several contributions to the angular spread of neutrons in the laboratory frame. Due to the asymmetry of the breakup, there is a strong dependence of the length of the neutron's velocity vector (in the ^{11}Be rest frame) on the decay energy, making this the dominant effect on angular spread of the neutrons in the laboratory frame. A smaller effect is the spread momenta

introduced to the ^{11}Be particles via the process of removing a neutron from ^{12}Be .

In order to interpret the experimental data, detailed simulations were performed using a Monte Carlo simulation code [6], for the breakup of states below 4 MeV in ^{12}Be , and for the detection of diffracted neutrons. The simulations included the effects of the acceptance of the neutron array, energy and angular straggling of charged particles, the observed beam divergence and energy spread, and detector acceptances, resolutions and efficiencies. Absorption of neutrons by the CsI array was also included. As input to the the code, momentum distributions of neutrons and beryllium residues were measured. The simulated data were analyzed in the same manner employed for the experimental data. Momentum distributions and neutron angular distributions were reproduced to verify methodological consistency.

RESULTS AND CONCLUSIONS

The doppler corrected, background subtracted γ ray spectrum, in coincidence with ^{11}Be , is shown in Fig. 4a, accounting for the incident beam flux, target thickness, detector efficiencies, attenuation in the target, and the geometric effects of relativistic focussing of the γ ray spatial distribution in the laboratory frame. The peak at 320 keV, corresponding to ^{11}Be residues formed in the $1/2^-$ state, is evident. This spectrum was fitted, to account for the background beneath the peak (Compton scattered γ rays of higher energy), and a cross section of 33.5(5.6) mb was extracted for the removal of 1 neutron from ^{12}Be at 39.1 MeV/A on a carbon target, leading to the first ($1/2^+$) excited state in ^{11}Be .

FIGURE 4. The background subtracted, Doppler corrected γ -ray spectrum (a) in coincidence with ^{11}Be particles, for ^{12}Be incident on a C target at 41 MeV/A, showing a peak at 320 keV (the only bound excited state in ^{11}Be). The relative energy spectrum (b) of $^{10}\text{Be} + n$, showing evidence for the population of unbound states in the ^{11}Be , along with the simulated response for various states. The peak at ~ 1.3 MeV corresponds to the 1.78 MeV $5/2^+$ state, and the peak near threshold corresponds to a decay from a state ~ 4 MeV to the 3.368 MeV 2^+ state in ^{10}Be .

The lineshapes for each decay, obtained from the simulations were fitted to the experimental $^{10}\text{Be} + n$ relative energy spectrum. The components of the fit are shown in Fig. 4b, along with the experimentally measured spectrum. The "uncorrelated" component was determined by the simulation of the detection of a diffracted neutron in coincidence with a ^{10}Be residue; the form of this component, particularly the fall-off at high energy, is dominated by the array acceptance. Using the incident beam flux, target thickness, detector efficiencies, and the efficiency for the detection of each component (from the simulations), cross sections were calculated for the production of ^{11}Be in the various unbound states listed in Table 1. That the cross section for the production of ^{11}Be in the $5/2^+$ state is of a comparable magnitude to the cross section for the $1/2^-$ state is strong evidence for a significant $(1d_{5/2})^2$ component to the ^{12}Be ground state. These cross sections are preliminary, as further work is being performed to determine more accurately the form of the uncorrelated neutron component. Preliminary calculations of single particle removal cross sections were performed using a Glauber model by J. Tostevin [7], for both stripping and diffraction components. These were used to calculate preliminary spectroscopic factors, as summarized in Table 2.

TABLE 1. Preliminary cross sections for the production of ^{11}Be in its $1/2^-$ bound excited state, and the unbound $5/2^+$ and $3/2^-$ states in ^{11}Be . The errors quoted are statistical only. An additional 20% uncertainty is estimated in the precise form of the uncorrelated component in the $^{10}\text{Be} + n$ E_{rel} spectrum.

J^π of State in ^{11}Be	E_{ex} of State in ^{11}Be (MeV)	E_{ex} of State in ^{10}Be (MeV)	Cross Section (mb)
$1/2^-$	0.32	0	33.5(5.6)
$5/2^+$	1.78	0	22.4(4.4)
$3/2^-$	2.69	0	18.3(5.2)

TABLE 2. Preliminary single particle removal cross sections for stripping (σ_{strip}) and diffraction (σ_{diff}), experimentally measured cross sections σ_{expt} and spectroscopic factors (S). The spectroscopic factors were obtained by dividing σ_{expt} by σ_{Total} , and are compared with those measured previously in the final column.

J^π	σ_{strip} (mb)	σ_{diff} (mb)	σ_{Total} (mb)	σ_{Expt} (mb)	S (present work)	S (MSU [2])
$1/2^+$	61.28	57.69	118.96	-	-	0.42(10)
$1/2^-$	42.59	30.72	73.31	33.5(5.6)	0.46(12)	0.37(10)
$5/2^+$	39.78	22.77	62.55	22.4(4.4)	0.36(10)	-

In conclusion, single neutron knockout cross sections from ^{12}Be , to the $1/2^-$ (bound) and $5/2^+$ (unbound) states in ^{11}Be have been measured at 39.1 MeV on a carbon target. The $1/2^-$ state was tagged by measuring the 320 keV de-excitation γ ray in coincidence with the ^{11}Be . The $5/2^+$ state was reconstructed by the coincident detection of ^{10}Be and neutrons. A significant cross section was measured for the production of the $5/2^+$ state, relative to the $1/2^-$ state, indicating a considerable $(1d_{5/2})^2$ component to the ^{12}Be ground state. Further work is being performed to determine more accurately the form of the uncorrelated neutron component.

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