Structure of $^{12}\text{Be}$: intruder $d$-wave strength at $N=8$

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The breaking of the $N=8$ shell-model magic number in the $^{12}\text{Be}$ ground state has been determined to include significant occupancy of the intruder $d$-wave orbital. This is in marked contrast with all other $N=8$ isotones, both more and less exotic than $^{12}\text{Be}$. The occupancies of the $0h\omega\nu d_{5/2}$ orbital and the $1h\omega\nu d_{5/2}$ intruder orbital were deduced from a measurement of neutron removal from a high-energy $^{12}\text{Be}$ beam leading to bound and unbound states in $^{11}\text{Be}$.

One of the principal aims of present day nuclear structure research is to understand the evolution of shell structure with increasing asymmetry in the neutron-to-proton ratio. In this context the $N=8$ isotonic chain, which spans from $^{28}\text{Si}$ via the doubly magic $N=Z$ $^{16}\text{O}$ to the two-neutron halo system $^{14}\text{Li}$ and the unbound $^{10}\text{He}$, is of considerable interest. Indeed, the $N=8$ shell closure, that is clearly evident close to stability, disappears amongst the lightest of these nuclei. In particular, the halo structure of $^{11}\text{Li}$ is enhanced by a strong $\nu(1s_{1/2})^2$ intruder valence neutron configuration $^{11}$[1]. Similarly, recent experiments $^{2,3}$ have confirmed earlier work $^{4}$ in which it was concluded that the $^{12}\text{Be}$ ground state is formed from both the “normal” closed shell $\nu(0p_{1/2})^2$ valence configuration and the intruder $\nu(1s0d)^2$ configurations. The factors producing these intruder configurations appear to include a reduction in the $p-sd$ shell gap as the drippeline is approached, an increase in the monopole pairing energy and deformation $^{11}$[10]. The deformation is also believed to be related to the tendency towards alpha-particle clustering $^{11}$[11] in the Be isotopes.

Whereas high-energy single-neutron removal (or “knockout”) from $^{12}\text{Be}$ has provided direct evidence for configuration mixing involving the $\nu(1s_{1/2})^2$ and $\nu(0p_{1/2})^2$ valence neutron configurations in the ground-state $^{11}$[12], model predictions indicate that a substantial $\nu(0d_{5/2})^2$ admixture ($\sim 30$-$50\%$) should also be present $^{13}$[13]. In the experiment of Navin et al., $^{11}\text{Be}$ core fragments in either the $J^e = 1^+\,^2$ ground state or the bound $320 \text{ keV} 1/2^+$ excited state were detected $^{11}$[14]. These states have large overlaps with the pure single-particle states $\nu(1s_{1/2})$ and $\nu(0p_{1/2})$ respectively $^{11}$[16]. The measurement of ref. $^{11}$[8] was, however, not sensitive to the $\nu(0d_{5/2})^2$ component as the removal of a $0d_{5/2}$ neutron leaves $^{11}\text{Be}$ in the $\nu(0d_{5/2})$ single-particle state (Ex = 1.78 MeV, $\Gamma = 100 \text{ keV}$) $^{11}$[16] $^{18}$, which is unbound to neutron emission and decays to $^{10}\text{Be}(g.s.)+n$. It is thus necessary to design an experiment to detect both the $^{12}\text{Be}$ fragment and the neutron and then to reconstruct their relative decay energy from the measured momenta. This was the approach adopted in the present work. Further, to assist comparisons with theory and the earlier work, the ability to detect $^{11}\text{Be}$ in the first excited state (via the 320 keV gamma-ray) was included.

A secondry beam of $^{12}\text{Be}$ ($\sim 5000 \text{ pps}$) was prepared using the LISE3 spectrometer at GANIL and the reaction of a 63 MeV/nucleon $^{18}\text{O}$ beam on $^{9}\text{Be}$. The average $^{12}\text{Be}$ beam energy was 39.3 MeV/nucleon at the centre of the carbon secondary reaction target (183 mg/cm$^2$). The beam purity was 95% with the remaining 5% being $^{9}\text{He}$ and $^{15}\text{B}$. Owing to the poor emittance of the secondary beam, the spot size on target was $\sim 10$ mm diameter and the incident ions were tracked event-by-event using two position-sensitive drift chambers located upstream of the carbon target. The point of impact was thus determined to within $\pm 1$ mm at the target. The measured time-of-flight through the LISE spectrometer allowed the $^{12}\text{Be}$ ions to be selected uniquely event-by-event from the rest of the beam particles and also provided a measure of the energy with a resolution of 1.6% (FWHM).

All charged particles emerging from the carbon target close to zero degrees, including the unreacted beam, were recorded in a telescope subtending $\pm 9^\circ$ in the horizontal and vertical planes. This was composed of two $50 \times 50$ mm$^2$ $500 \mu$m thick silicon strip detectors to measure the energy loss ($\Delta E_{1,2}$), followed by a $4 \times 4$ array of 16 CsI stopping detectors ($E$) 25 mm thick $^{19}$. The telescope array was calibrated using “cocktail” beams containing all relevant isotopes of Be, with several spectrometer settings to span the energies of interest. Using $\Delta E_{1,2}$...
and $E$, all observed isotopes of H, He, Li, Be and B were clearly resolved. The silicon detectors also provided vertical and horizontal position measurements, which were combined with the drift chamber data to determine the scattering angle with a resolution 0.7° (FWHM).

Coincident $\gamma$-rays were recorded using 4 NaI detectors mounted around the target at angles of $\pm45°$ and $\pm110°$ to the beam, with a total absolute photopeak efficiency of 3.5% for detection of Doppler-shifted 320 keV $\gamma$-rays.

Neutrons were detected using the DEMON array of 91 liquid scintillator modules located between 2.4 m and 6.3 m downstream of the carbon target and spanning angles out to 32°. The neutrons were distinguished from $\gamma$-rays using standard pulse-shape discrimination and their energies ($E_n$) were derived via the time-of-flight with a resolution $\sim5%$. Neutrons with $E_n \leq 15$ MeV, originating from the target, were excluded in the analysis.

In addition to the measurements with the carbon target, data were also acquired with no target. This determined the background arising from $^{12}$Be beam particles that passed through the target and reacted in the telescope. Such events gave a degraded energy signal and could be misidentified as $^{11}$Be or $^{10}$Be. As in previous experiments, the target-out measurements were made with the beam energy lowered to account for the average energy loss in the target. The background from reactions in the telescope preceded an accurate measurement of the yield to the $^{11}$Be ground state. For the excited states, however, coincident detection of a $\gamma$-ray or neutron reduced substantially the background (down to 50 and 60% of the target-in data for the bound and unbound states respectively).

The background subtracted, Doppler corrected $\gamma$-ray spectrum, measured in coincidence with $^{11}$Be ions in the telescope, is shown in Figure 1. The cross section for production of the $1/2^-$ state in $^{11}$Be (see Table I) was extracted after taking into account the experimentally measured $\gamma$-ray detector efficiencies, attenuation in the target and the relativistic focussing of $\gamma$-rays in the laboratory frame ($\beta \simeq 0.28c$). The cross section measured here at 39.3 MeV/nucleon is compatible with the value measured previously at 78 MeV/nucleon with a Be target, as interpreted below using an eikonal reaction model. The longitudinal momentum distribution of the $^{11}$Be*(1/2$^-$) fragments was also measured, giving a FWHM of 137(21) MeV/c, in agreement with the value $\sim150$ MeV/c estimated from ref. 26.

Kinematic reconstruction of unbound states in $^{11}$Be was performed from the measured momenta of coincident $^{10}$Be ions and neutrons. The procedure was verified by reconstructing the well known ground state resonance of $^7$He from $^9$Be + $n$ coincidences. The relative energy ($E_{rel}$) spectrum for $^{10}$Be + $n$, after background subtraction, is shown in Figure 2. This has been corrected for the intrinsic efficiency of the DEMON detectors but not for the geometrical acceptance. A peak is clearly evident at $\sim1.3$ MeV, corresponding to the decay of the 1.78 MeV (5/2$^+$) state in $^{11}$Be. There is also another peak apparent near 2.2 MeV, corresponding to decay of the 2.69 MeV (3/2$^-$) state. The very narrow peak near threshold is compatible with decay from a state at $\sim4.0$ MeV in $^{11}$Be to the first 2$^+$ state in $^{10}$Be at 3.37 MeV. The ground state branch of this decay corresponds to the peak at $E_{rel}$ $\sim3.5$ MeV; its inclusion improves the fit, but the magnitude of neither peak is well defined by the data for this $\sim4.0$ MeV state. However, good candidates exist for such a state in $^{11}$Be.

The detection efficiency for neutrons from $^{11}$Be* decay is determined in part by their laboratory angular distribution, which in turn depends on the decay energy to $^{10}$Be + $n$ and also the spread in momentum induced by the initial neutron removal from $^{12}$Be. Detailed simulations were performed, including the effects of the geometric acceptance of the neutron detector array, the energy and angular straggling of charged particles, the energy loss in the target, and the divergence and energy spread of the beam. The effects of the telescope resolution and efficiency were also included, along with the absorption of neutrons by the telescope (a 10% effect). The momentum spread arising from the neutron removal was determined from the measured angular distribution of neutrons from the very low energy decay of $^{11}$Be*(4.0 MeV) to $^{10}$Be*(2$^+$, 3.37 MeV) + $n$ (cf. Figure 2), where the neutron momentum distribution was dominated by that of the $^{11}$Be* before decay. The detection of a fast neutron ($E_n > 15$ MeV) from the breakup of $^{12}$Be, measured in coincidence with a $^{10}$Be from the subsequent decay of $^{11}$Be* was also simulated.

Simulations were performed for the decay of the unbound states in $^{11}$Be below 4 MeV (isotropically in the
angular distribution $d\sigma$ of neutrons diffracted from $^{12}$Be is clearly visible at $E_{rel} \approx 1.3$ MeV ($S_0 = 0.50$ MeV). The resolution in $E_{rel}$ varies as $a_0E^{1/2}$ (where $a_0$ is a constant), and at 1 MeV is $\sim 400$ keV (FWHM). The upper panel depicts the simulated array efficiency.

$^{11}$Be rest frame, including the decay from the $\sim 4$ MeV state to the $2^+$ state in $^{10}$Be, and also the detection of neutrons diffracted from $^{12}$Be in coincidence with a $^{10}$Be core. The simulated events were analyzed in the same manner as the experimental data. The resulting $E_{rel}$ line-shapes (Fig. 2) were least-squares fitted to the experimental distribution and, using the detection efficiency determined from the simulations (Fig. 2, upper panel) the cross sections for the different states were determined. As a consistency check, the $^{11}$Be transverse momentum distribution (from $^{10}$Be+n), and the neutron angular distribution $\frac{d\sigma}{d\Omega}$ in coincidence with $^{10}$Be were reconstructed from the simulated events, and in both cases the agreement with experiment was very good. The simulated “hit” efficiency for neutrons was checked and agreed with the value determined by fitting and integrating $\frac{d\sigma}{d\Omega}$ to within 1%.

The cross section extracted for the production of the 1.78 MeV 5/2$^+$ state is included in Table I along with that for the 2.69 MeV 3/2$^-$ state and the bound 1/2$^-$ state. The estimated uncertainties include contributions from statistical fitting plus uncertainties in the efficiency corrections, target thickness and background subtrac-

tion. The cross section for diffractive breakup to produce a bound $^{13}$Be (either 1/2$^+$ or 1/2$^-$) and a fast neutron was also extracted and was $46 \pm 10$ mb.

The measured neutron removal partial cross sections from $^{12}$Be can be interpreted in terms of spectroscopic factors using a reaction model. The spectroscopic factors listed in Table II are, except for the 1/2$^+$ state, the ratio of the experimental ($\sigma_{exp}$) to the eikonal model partial cross section ($\sigma_{exp}$). For the 1/2$^+$ state, the measurement of diffractive breakup of $^{12}$Be to the two bound $^{11}$Be states has been used, with the 1/2$^-$ contribution being subtracted according to its theoretical diffraction cross section (see Table II and the spectroscopic factor of 0.44$\pm$0.08 found here. Note that the uncertainties quoted for $S_{exp}$ in Table II do not include any contribution arising from the assumptions in the reaction calculation, where for example two-step processes are not included, and it is estimated that this implies an additional uncertainty of up to 20% (which is consistent with ref. 3).

The present reaction analysis follows closely the eikonal model of Refs. 2, 26. The neutron-target S-matrix was computed from the target density and the JLM effective nucleon-nucleon interaction 27. The usual real and imaginary part scale factors ($\lambda_V = 1.0$, $\lambda_W = 0.8$) were applied to the optical potential. The matter densities for $^{12}$C and $^{10}$Be were of harmonic oscillator and Gaussian form, respectively, with rms radii of 2.4 fm and 2.28 fm. For the 1/2$^+$, 1/2$^-$ and 5/2$^+$ (particle) transitions, ($^{10}$Be+n) composite core-target S-matrices were constructed from those of $^{10}$Be and the neutron 26. In the (unbound) 5/2$^+$ case, a separation energy of 0.01 MeV was used to compute the S-matrix. For the 3/2$^-$ (hole) state, a Gaussian (mass 11) core density of rms radius 2.54 fm was used, representative of the size of $^{12}$Be. The removed-nucleon single-particle overlaps were taken as eigenstates of Woods-Saxon potentials, with geometry $r_0=1.25$ fm and $a=0.7$ fm, and with depths adjusted to the physical separation energies for each final state.

Our observation of the 5/2$^+$ state in knockout from $^{12}$Be is the first direct experimental evidence for a significant $d$-wave intruder component in any N=8 isotope. Barker 6 first pointed out that the observed lowering of the 1$s_{1/2}$ and 0$d_{5/2}$ neutron orbitals in $^{11}$Be should lead to strong admixtures of both these orbitals in the ground state of $^{12}$Be and concluded 6, 7 that as little as 20-40% of the $^{12}$Be ground state might comprise the $0h\omega 1/2(0p_{1/2})^2$ configuration. For $^{11}$Li, this model also successfully predicted a strong $1s_{1/2}$ strength admixture in the ground state.

The $(1s0d)^2$ contribution to the $^{12}$Be ground state was deduced in an indirect fashion by Fortune et al. 8 in the light of their measurements of $\tau_{1/2}$ and $E(2^+_1)$ for $^{12}$Be 8, 25. Indeed, according to subsequent psd-space shell model calculations, the $\beta$-decay from the $^{12}$Be ground state is quenched to an extent that places an upper limit of 35% on the $0h\omega$ component of the wavefunction 28.
TABLE I: Cross sections for states in $^{11}$Be produced via neutron removal from $^{12}$Be on a carbon target at 39.3 MeV/nucleon (present work) compared with reaction calculations and previous work at 78 MeV/nucleon on $^{13}$Be. Uncertainties for $\sigma_{exp}$ are experimental only (for comparison, ref. 3 values have been adjusted to remove the assumed 20% theory uncertainty).

| $J^\pi$ | $E_x$ (MeV) | $\sigma_{exp}$ (mb) | $\sigma_{strip}$ (mb) | $\sigma_{diff}$ (mb) | $\sigma_{exp}$ (present work) | $S_{exp}^a$ | $S_{exp}^a$ | WBT2 | WBT2 $^\prime$ | EXC2 |
|---------|-------------|-------------|-------------------|----------------|-----------------------------|----------|----------|--------|-------------|--------|
| 1/2$^+$ | 0.00        | 61.28       | 57.69             | 118.96         | $[0.56 \pm 0.18]^b$          | 0.42     | 0.05     | 0.69   | 0.55        | 0.44   |
| 1/2$^-$ | 0.32        | 32.5 $\pm$ 6.1 | 42.59             | 30.72          | 73.31                       | 0.44     | 0.08     | 0.37   | 0.58        | 0.47   |
| 1/2$^-$ | 1.78        | 30.3 $\pm$ 4.0 | 39.78             | 22.77          | 62.55                       | 0.48     | 0.06     |        | 0.55        | 0.44   |
| 3/2$^-$ | 2.69        | 22.6 $\pm$ 4.1 | 35.47             | 20.87          | 56.35                       | 0.40     | 0.06     |        |             | 0.58   |

$^a$Uncertainties do not include contribution from theoretical model of reaction mechanism, estimated to be ±10-20%.

The $^{12}$O-$^{12}$Be Coulomb energy difference also supports shell breaking of this order.

The magnitude of shell breaking observed in the present work can be quantified by comparing with theory. Table I includes spectroscopic factors (WBT2′) based on the shell model calculations reported in ref. 3, which correspond to a mixing of 32% 0hω (0p$^3$) and 68% 2hω (0p$^0$(1s0d)$^2$) contributions. The sum of these is close to the value 2.0 that would be expected in the simplest picture. These values are scaled by 0.8 to give WBT2′ (which is consistent with other knockout work 31) and this reproduces the present experimental results very well. Also listed for comparison, the EXC2 values from a 3-body model including $^{10}$Be core excitation 31 give good agreement with the present work while reproducing other features of $^{12}$Be.

Recently, Iwasaki et al. inferred the disappearance of the N=8 shell gap in $^{12}$Be from both the deformation length derived from inelastic proton scattering to the 2$^+_1$ state 21, and the low energy and large B(E1;0$^+_1$ → 1$^-$) for the 1$^-_1$ state 14. Their deductions agreed in detail with the psd shell model calculations 13, 23, concluding that the 0p$_{1/2}$ and 1s$_{1/2}$ orbitals are effectively degenerate for $^{12}$Be, just as they are in $^{11}$Be.

Consistent theoretical results are obtained using nuclear field theory 12, which predicts both the presence of large $\nu$(0d$^{5/2}$)$^2$ strength in $^{12}$Be and its absence in $^{11}$Li, in agreement with Barker 7, and with a recent theoretical analysis 32 of $^{11}$Li reaction data 11. It is interesting to note that the early work of Barker 7 also predicted a low-lying 0$^+_2$ state at 2.35 MeV in $^{12}$Be which has only recently been observed, at 2.24 MeV 17.

Thus, the neutron shell breaking observed at N=8 for $^{12}$Be, but not $^{14}$C, is similar to the breaking of N=20 for $^{32}$Mg but not $^{34}$Si. In each case, when the proton $j_>$ orbital is full, the neutrons are magic. When protons are removed, the full $j_<$ orbital for neutrons is no longer magic, the next shell intrudes and deformation results.

In conclusion, one-neutron removal cross sections from $^{12}$Be to the 0.32 MeV (1/2$^-$) and 1.78 MeV (5/2$^+$) states in $^{11}$Be have been measured. From these and eikonal model calculations, spectroscopic factors were deduced. These indicate strong breaking of the N=8 magic number in $^{12}$Be, including a significant d-wave component. This is distinct from other N=8 isotones and is the first direct experimental confirmation of the predictions of a number of structure models.

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