The dominance of the $\nu(0d_{5/2})^2$ configuration in the $N = 8$ shell in ^{12}Be from the breakup reaction on a proton target at intermediate energy

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ABSTRACT

The momentum distribution of ^{11}Be fragments produced by the breakup of ^{12}Be interacting with a proton target at 700.5 MeV/u energy has been measured at GSI Darmstadt. To obtain the structure information on the anomaly of the $N = 8$ neutron shell, the momentum distribution of ^{11}Be fragments from the one-neutron knockout ^{12}Be(p, pn) reaction, measured in inverse kinematics, has been analysed in the distorted wave impulse approximation (DWIA) based on a quasi-free scattering scenario. The DWIA analysis shows a surprisingly strong contribution of the neutron $0d_{5/2}$ orbital in ^{12}Be to the transverse momentum distribution of the ^{11}Be fragments. The single-neutron $0d_{5/2}$ spectroscopic factor deduced from the present knock-out data is 1.39(10), which is significantly larger than that deduced recently from data of ^{12}Be breakup on a carbon target. This result provides a strong experimental evidence for the dominance of the neutron $\nu(0d_{5/2})^2$ configuration in the ground state of ^{12}Be.

The anomaly of the neutron $N = 8$ shell has been known since many years, for example, from the abnormal spin-parity of the ^{11}Be ground state. The systematic change from the conventional sp shell for neutrons in carbon isotopes to a mixture of $0p_{1/2}$, $1s_{1/2}$ and $0d_{5/2}$ shells in the neutron rich Be isotopes was discussed already 20 years ago by Tanihata [1]. The recent studies have been focused on the disappearance of the $N = 8$ shell closure when the $1s_{1/2}$ orbital is shifted below the $0d_{5/2}$ orbital, giving rise to the formation of neutron halos [2]. While the extended sizes of the halo nuclei can be accurately deduced from the measured interaction (or reaction) cross section [3,4], or from the angular distribution of intermediate energy proton elastic scattering in inverse kinematics [5–11], the shell structure of the unstable neutron-rich nuclei has been studied mainly based on the analysis of momentum distributions of fragments from breakup reactions [12–14].

The ground-state structure of ^{12}Be with $N = 8$ is of high interest from the shell-model point of view. It should be noted that the $\nu(0d_{5/2})^2$ ($J^\pi = 0^+$, $T = 1$) intruder state in ^{12}Be was pointed out as highly possible by Barker [15] some 40 years ago. A more recent microscopic particle-vibration coupling study by Gori et al. [16] shows a quite strong coupling between the valence neutrons and the lowest 2^+ and 3^- excited states of the ^{10}Be core, leading to a dominance of the $\nu(0d_{5/2})^2$ configuration in the ground state of ^{12}Be. So far, ^{12}Be has been studied in several experiments, and quite interesting are the measurements of the ^{12}Be breakup on a ^{9}Be target by Navin et al. [17], and on a ^{12}C target by Pain et al. [18]. In the first experiment, the observation of ^{12}Be fragmentation followed by the γ-emission from the bound states of ^{11}Be has shown that the $1s_{1/2}$ neutron shell is mixed with the $0p_{1/2}$ shell in the ground state of ^{12}Be. In the second experiment, the γ rays following the neutron emission from the (unbound) 1.78 MeV ($d_{5/2}$) and 2.69 MeV ($p_{3/2}^-$) excited states of ^{11}Be fragments [18] have been observed, which show a strong mixing of the neutron p and sd shells in the ground state of ^{12}Be.
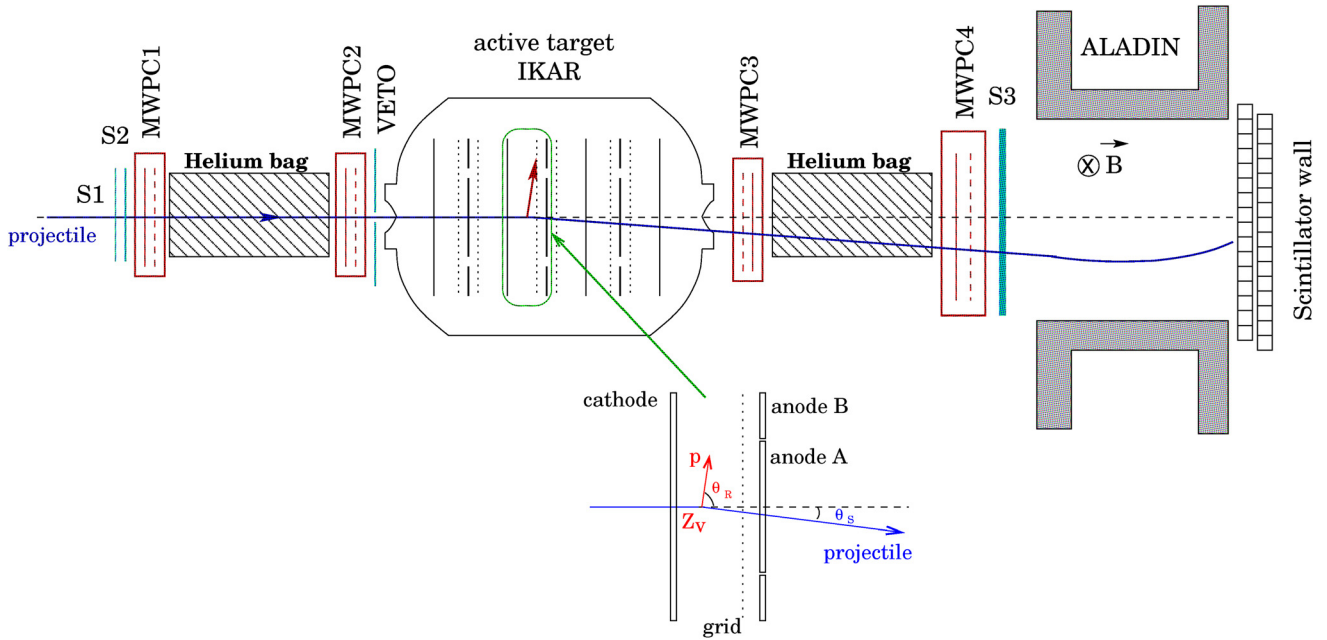
Fig. 1. Schematic view of the experimental setup. The main part is the IKAR ionization chamber serving as an active target, consisting of six identical modules [7,9,21]. One module is zoomed as seen in the bottom inset. Details are explained in the text.

The present work presents the momentum distributions of ^{11}Be fragments produced in the one-nucleon knockout ^{12}Be$(p, pn)^{11}$Be reaction measured at GSI Darmstadt in inverse kinematics at an energy of 700.5 MeV/nucleon. The transverse momentum distribution of the ^{11}Be fragments was analyzed in the distorted wave impulse approximation (DWIA), using the quasi-free scattering (QFS) assumption for the single nucleon knockout reaction [19]. Evidence for a strong dominance of the $\nu(0d_{5/2})^2$ configuration in the ground state of ^{12}Be was found from the present DWIA analysis.

A primary ^{18}O beam, produced from the MEVVA (MEtal Vapour Vacuum Arc) source, was accelerated to the energy of 750 MeV/u by the UNILAC (UNiversal Linear ACelerator) and the heavy-ion synchrotron (SIS) at GSI Darmstadt. The beam was further focused on an 8 g/cm^2 beryllium production target at the entrance of the FRagment Separator (FRS) [20]. The beryllium ions produced by the fragmentation of ^{18}O nuclei were separated by the FRS according to their magnetic rigidity and nuclear charge. At the entrance of the secondary target IKAR [7,9,21], the secondary ^{12}Be beam energy was 700.5 MeV/u with 1.1% FWHM. Its intensity was about 6000 ions/s, and the contamination from other isotopes was approximately 1%. The time projection ionization chamber IKAR [7, 9,21], which was filled with hydrogen gas and operated at 10 bar pressure, served simultaneously as a gas target and a recoil proton detector.

A schematic view of the experimental layout is presented in Fig. 1. The proton recoil signal, obtained from the IKAR detector, was coincident with that of the scattered Be particle. The scattering angle θ_s and the vertex point were determined from the coordinates measured by a tracking system consisting of 2 pairs of 2-dimensional multi-wire proportional chambers (MWPC1-MWPC2 and MWPC3-MWPC4), arranged upstream and downstream with respect to IKAR. The scintillators S1 and S2 were used for triggering and beam identification. The beam was identified via the time-of-flight (ToF) between scintillators S1 and S8 (located at the FRS, not shown in Fig. 1) and energy loss measurements in the scintillators S1 and S2, while a circular-aperture scintillator VETO with a 2 cm diameter hole at its center selected the projectiles which en-

tered IKAR within an area of 2 cm in diameter around the central axis. The helium bags were used to reduce the multiple Coulomb scattering of the incoming and outgoing particles. The analysis for the elastic ^{12}Be(p, p) channel was presented in details in Ref. [10]. For the present one-neutron knockout ^{12}Be(p, pn) channel, the difference is the selection of the ^{11}Be fragments which is illustrated in Fig. 2. The residual Be nuclei were identified via a position sensitive scintillator wall placed at the end of the setup (see Fig. 1) after passing through the ALADIN magnet (A Large Acceptance DIpole magNet) which separated the isotopes according to their magnetic rigidity, and the outgoing angle of the residue.

At the high incident energy considered in the present work, the one-neutron knockout from the loosely bound ^{12}Be projectile occurs promptly, inducing almost no perturbation on the other nucleons (adiabatic approximation). The non-participating nucleons in ^{12}Be can be considered as "spectators" [22] which scatter elastically off the p target. Following this idea, the kinematic of the elastic ^{11}Be $+ p$ scattering was used to determine the momentum of the outgoing ^{11}Be fragment (p_{out}), with the scattering angle θ_s determined as discussed above, and the velocity of the incoming ^{11}Be core (with momentum p_{in}) assumed to be equal to that of the ^{12}Be projectile. At very low momentum transfer, the x projection of the fragment's transverse momentum can be calculated as

$$p_x = p_{in}\theta_x^{in} - p_{out}\theta_x, \tag{1}$$

where, $\theta_x^{in}(\theta_x)$ are angle of the incoming (outgoing) particle in the laboratory frame. As the result, the x-component distribution of the ^{11}Be fragment's transverse momentum deduced in such an approximation for the nucleon knockout $p(^{12}$Be, ^{11}Be) reaction at an energy of 700.5 MeV/u is shown in Fig. 3. Its total width (FWHM) after defolding from the momentum resolution is around 248.7(153) MeV/c. The momentum resolution of p_x is determined from the uncertainty of the scattering angle ($\sigma_s \approx 0.61$ mrad) to be about 12.0(12) MeV/c which is less than 5% of the FWHM of the p_x distribution determined for the ^{11}Be fragments. The main contributions to the momentum resolution were due to the position resolution (≈ 2 mm) of the MWPCs and the multiple Coulomb scat-
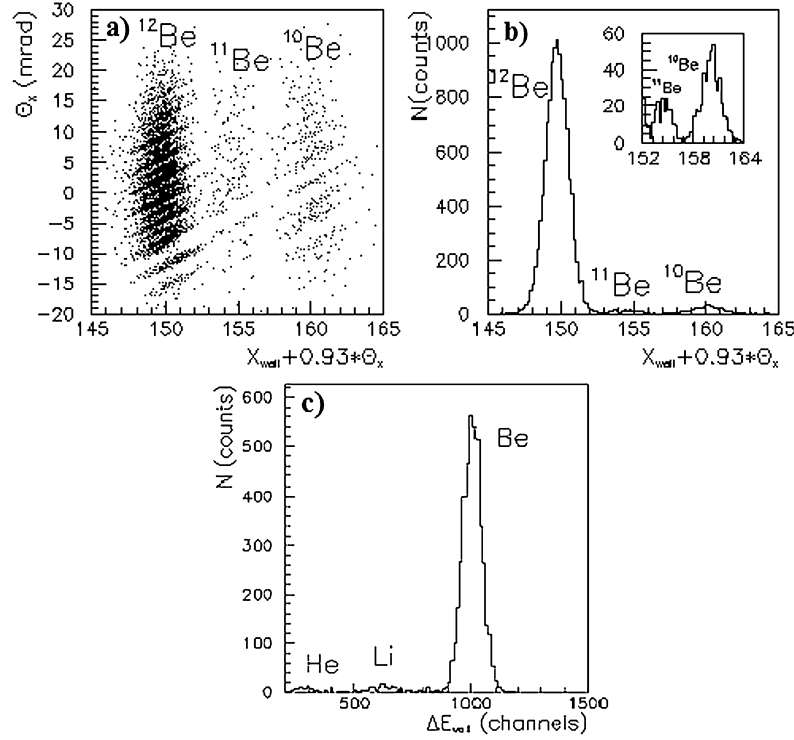
Fig. 2. Identification of the ^{11}Be fragments. Panel a) presents the correlation between the outgoing angle of the residue in the x-plane (θ_x) and $X_{\text{wall}} + 0.93\,\theta_x$, where X_{wall} is the position on the scintillator wall behind the ALADIN magnet. Panel b) shows the projection of the plot in panel a) on the x-axis. The inset is a zoom-in to illustrate the ^{10,11}Be peaks. The stripe structure in panel a) is caused by the segmentation of the scintillator detector. Panel c) shows the energy loss spectrum of the scintillator wall. A selection on the Be bump was applied to make sure the nuclear charge of the Be residues. Panel a) is a rotation of Fig. 4.b in Ref. [10], see this reference for more details.

tering in material along the flight path of the particle which was estimated to be approximately 0.49 mrad. The total momentum acceptance was determined to be about 1000 MeV/c thus ensuring the full coverage of the fragment's momentum.

The motivation of the present study is focused on the structure information concerning the anomaly of the $N = 8$ neutron shell in the Be isotopes. Therefore, the momentum distribution of the ^{11}Be fragments from the one-neutron knockout ^{12}Be(p, pn) reaction (in inverse kinematics) was carefully studied in the DWIA analysis of the knockout reaction. The DWIA has been well proven as a reliable approach to describe the single-nucleon knockout reaction [19,23,24]. There are three particles emerging in the exit channel of the ^{12}Be(p, pn) reaction, whose exact kinematics cannot be determined by the present experimental setup. Therefore, as discussed above, the ^{11}Be core of the ^{12}Be projectile was assumed to scatter on the proton target elastically during the breakup reaction, and the elastic ^{11}Be + p kinematics was used to determine the momenta of the ^{11}Be fragments. This is in fact the quasi-free scattering (QFS) approximation usually adopted in the DWIA studies of the quasi-elastic scattering at high energies [19].

In such a QFS scenario, the DWIA scattering amplitude for the A(p, pn)B reaction can be determined [19,23] as

$$T_{p,pn} = \sqrt{S(lj)} \langle \chi^{\text{out}}_{\boldsymbol{k}'_p} \chi^{\text{out}}_{\boldsymbol{k}_n} | \tau_{pn}(\boldsymbol{k}'_{pn}, \boldsymbol{k}_{pn}; E) | \chi^{\text{in}}_{\boldsymbol{k}_p} \psi_{jlm} \rangle, \tag{2}$$

where $\chi^{\text{in}}_{\boldsymbol{k}}$ and $\chi^{\text{out}}_{\boldsymbol{k}'}$ are the incoming and outgoing distorted waves of the proton and knockout neutron, $S(lj)$ is the spectroscopic factor of the lj component in the wave function of the valence neutron in A, which is described by the ψ_{jlm} function. τ_{pn} is the proton-neutron scattering matrix that depends on the energy and the relative proton-neutron momenta in the entrance ($\boldsymbol{k}_{pn}$) and exit ($\boldsymbol{k}'_{pn}$) channels.

At high energies, the distorted waves are determined in the eikonal approximation as

$$\chi^{\text{in}}_{\boldsymbol{k}_p} = S^{(p)}_{\text{in}} \exp(i\alpha \boldsymbol{k}_p \cdot \boldsymbol{r}) \tag{3}$$

$$\chi^{\text{out}}_{\boldsymbol{k}'_p} \chi^{\text{out}}_{\boldsymbol{k}_n} = S^{(p)}_{\text{out}} S^{(n)}_{\text{out}} \exp\left[i(\boldsymbol{k}'_p + \boldsymbol{k}_n) \cdot r\right] \tag{4}$$

where $S^{(p)}_{\text{in}}$ is the pA scattering matrix in the entrance channel, and $S^{(p)}_{\text{out}}$ and $S^{(n)}_{\text{out}}$ are the pB and nB scattering matrices in the exit channel. They are obtained from the (real) nucleon optical potentials given by the folding model, and the corresponding imaginary parts given by the $t\rho\rho$ approach [25]. A recoil correction $\alpha = (A - 1)/A$ due to the center of mass (c.m.) motion is also introduced [19,23]. The single-neutron wave function ψ_{jlm} is generated by the standard method using a Woods–Saxon potential supplemented with a spin-orbit term, whose parameters were adjusted to reproduce the observed neutron separation energy of ^{12}Be. Adopting the free proton-neutron scattering amplitude for τ_{pn}, the DWIA transition amplitude (2) at a given impact parameter b can be written as

$$T_{p,pn} = \sqrt{S(lj)}\,\tau_{pn}(\boldsymbol{k}'_{pn}, \boldsymbol{k}_{pn}; E)$$
$$\times \int d^3r\, S(b, \theta'_p, \theta_n) \exp(-i\boldsymbol{q} \cdot r) \psi_{jlm}(\boldsymbol{r}), \tag{5}$$

where θ'_p and θ_n are the c.m. angles of the outgoing proton and neutron, respectively, and the momentum transfer $\boldsymbol{q} = \boldsymbol{k}'_p + \boldsymbol{k}_n - \alpha \boldsymbol{k}_p$. The total scattering matrix is a product of the nucleon scattering matrices

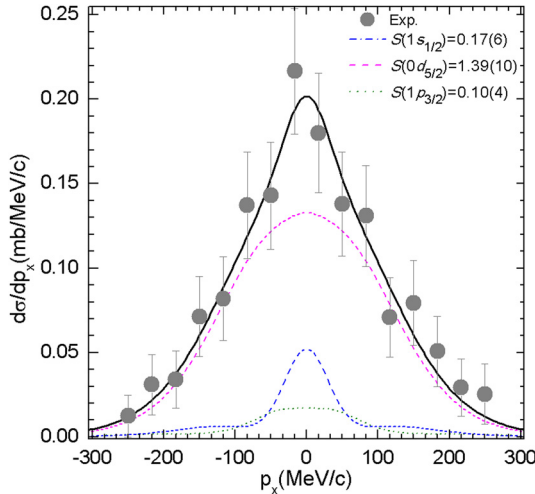$$S(b, \theta'_p, \theta_n) = S_{pA}(E_p, b) S_{p'B}(E'_p, \theta'_p, b) S_{nB}(E_n, \theta_n, b). \tag{6}$$

Fig. 3. The measured transverse momentum distribution of ^{11}Be fragments from the breakup ^{12}Be(p,pn)^{11}Be reaction (solid circles) in comparison with the result of the DWIA calculation (solid line) for the one-neutron knocked out from ^{12}Be, with the spectroscopic factors $S(lj)$ of the single-particle configurations $\nu 1s_{1/2}$, $\nu 0d_{5/2}$ and $\nu 1p_{3/2}$ deduced from the best fit of the calculated momentum distribution to the present data.

Expressing $\mathbf{q}$ explicitly in terms of the transverse ($\mathbf{q}_t$) and longitudinal (q_z) momentum transfers, the transverse momentum distribution of the neutrons knocked out from the single-particle state ψ_{jlm} is obtained (after integrating over q_z) as [19]

$$\frac{d\sigma_{lj}}{d^2 q_t} = \frac{S(lj)d\sigma_{lj}}{2\pi q_t dq_t} = \frac{S(lj)}{2\pi(2j+1)} \sum_m \left\langle \frac{d\sigma_{pn}}{d\Omega} \right\rangle_{q_t} |C_{lm}|^2 \int\limits_{-\infty}^{\infty} dz$$
$$\times \left| \int\limits_0^{\infty} db \langle S(b)\rangle_{q_t} \frac{u_{lj}(r)}{r} J_m(q_t b) P_{lm}(b, z) \right|^2, \quad (7)$$

where $\left\langle \frac{d\sigma_{pn}}{d\Omega} \right\rangle$ and $\langle S(b)\rangle$ are averaged over the energies of the outgoing proton and neutron (at the given transverse momentum q_t), the later also averaged over the scattering angles of the protons. $u_{lj}(r)$ is the radial part of the single-particle wave function $\psi_{jlm}(\mathbf{r})$; $J_m(q_t b)$ and $P_{lm}(b, z)$ are the cylindrical Bessel function and Legendre polynomials, respectively, and

$$C_{lm} = \sqrt{\frac{2l+1}{4}} \sqrt{\frac{(l-m)!}{(l+m)!}}.$$

To compare with the experimental momentum distribution, we need to reduce the distribution (7) to that along the x-component of $\mathbf{q}_t$. Inserting $q_t = \sqrt{p_x^2 + p_y^2}$, we obtain [26] the inclusive momentum distribution of the one-neutron knockout ^{12}Be(p, pn)^{11}Be reaction as

$$\frac{d\sigma}{dp_x} = \sum_{lj} S(lj)\frac{d\sigma_{lj}}{dp_x} = \sum_{lj} S(lj) \int\limits_0^{\infty} dp_y \frac{d\sigma_{lj}}{d^2 q_t}(p_x, p_y). \quad (8)$$

The measured transverse momentum distribution of ^{11}Be fragments ejected from the one-neutron knockout ^{12}Be(p, pn)^{11}Be reaction was subjected to the DWIA analysis (7)–(8), with the spectroscopic factors $S(lj)$ of the single-particle configurations $\nu 1s_{1/2}$, $\nu 0d_{5/2}$ and $\nu 1p_{3/2}$ of the valence neutron in ^{12}Be adjusted independently as free parameters of the best DWIA fit of the calculated momentum distribution (8) to the measured data. From

the comparison of the best-fit DWIA result with the data in Fig. 3 one can see the dominant contribution from the $\nu 0d_{5/2}$ configuration of the valence neutron in ^{12}Be. The obtained spectroscopic factors $S(lj)$ of the single-particle configurations $\nu 1s_{1/2}$, $\nu 0d_{5/2}$ and $\nu 1p_{3/2}$ are 0.17 ± 0.06, 1.39 ± 0.10, and 0.10 ± 0.04, respectively. The contribution of the $\nu 0p_{1/2}$ component was found to be negligible by the present DWIA analysis. The uncertainties in the deduced spectroscopic factors were based on the statistical errors as well as the uncertainty in the absolute normalization of the measured cross sections.

The present result provides an important evidence for the dominance of the $(\nu 0d_{5/2})^2$ configuration in the ground state of ^{12}Be, with the spectroscopic factor $S(\nu d_{5/2}) \approx 1.39$ which is significantly larger than that reported in Ref. [18] ($S(\nu d_{5/2}) \approx 0.48$). The dominance of the d-wave in the ground state of ^{12}Be was also shown by a recent microscopic particle-vibration coupling study by Gori et al. [16] as due to a strong coupling between the valence neutron and the 2^+ and 3^- excitations of the ^{10}Be core. At the relatively high energy of 700.5 MeV/u, the ^{11}Be fragment produced in the present ^{12}Be(p, pn)^{11}Be knockout reaction could well populate the known $1/2^-$, $5/2^+$ and $3/2^-$ excited states seen in the ^{12}Be breakup reaction on a carbon target [18]. With the small spectroscopic factors found for the $\nu 1s_{1/2}$ and $\nu 1p_{3/2}$ configurations, such a strong preference of the neutron knockout channel to the $5/2^+$ excitation of ^{11}Be found in the present work poses a challenge for the future experimental and theoretical structure studies of the neutron rich Be isotopes.

In conclusion, the transverse momentum distribution of ^{11}Be fragments ejected from the one-neutron knockout ^{12}Be(p, pn)^{11}Be reaction has been measured at an energy around 700 MeV/nucleon. A dominance of the d-wave in the ground state of ^{12}Be was found from the DWIA analysis of the present neutron knockout data. This result provides a clear evidence for the intruder $\nu 0d_{5/2}$ level in the single-particle scheme that breaks the magicity of the $N = 8$ shell in the Be isotopes.

Acknowledgements

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