Reduced Occupancy of the Deeply Bound $0d_{5/2}$ Neutron State in ^{32}Ar

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The ^{9}Be(^{32}Ar, ^{31}Ar)X reaction, leading to the $\frac{5}{2}^+$ ground state of a nucleus at the proton drip line, has a cross section of 10.4(13) mb at a beam energy of 65.1 MeV/nucleon. This translates into a spectroscopic factor that is only 24(3)% of that predicted by the many-body shell-model theory. We introduce refinements to the eikonal reaction theory used to extract the spectroscopic factor to clarify that this very strong reduction represents an effect of nuclear structure. We suggest that it reflects correlation effects linked to the high neutron separation energy (22.0 MeV) for this state.

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The nuclear shell model pictures deeply bound nucleons as being in fully occupied states. At and above the surface of the Fermi sea, configuration mixing then leads to occupancies that gradually decrease to zero. This picture is modified in an important way by several *correlation* effects that are absent from or are described only approximately by effective-interaction theories, such as the shell model. These correlations arise from short-range, soft-core, and tensor nucleon-nucleon (NN) interactions and from longer-range couplings involving low-lying and giant resonance collective excitations [1]. They result in the physical nucleon occupancies of deeply bound states being reduced and the strength shifted into states up to quite high energies; see Pandharipande *et al.* [2]. Absolute measurements of nucleon occupancies may therefore quantify these correlation effects. It should be pointed out that nuclear reaction observables probing the spatial behavior of the nucleonic wave functions agree well with the shell model picture. Examples are the characteristic angular distributions of transfer reactions and the longitudinal momentum distributions of the residues in knockout reactions, which identify the orbital angular momentum l of the nucleon states involved.

The main body of evidence on nucleon occupancies has come from studies of the $(e, e'p)$ reaction [2,3]. These have shown that in stable nuclei over a broad mass region, the valence proton states have their occupancies quenched by factors of order 0.6–0.7 relative to the extreme single-particle values. Recently, evidence has emerged that nucleon knockout reactions with heavy ions, at intermediate energies and in inverse kinematics, offer new possibilities for studying these effects by extending measurements to rare radioactive species and to neutron states. In general, the occupancy is not directly observable, but it is reflected in the spectroscopic factor C^2S_j that measures the overlap of the initial and final states with quantum numbers (l, j) [4]. The reduction factor R_s is defined as the ratio of the experimental and theoretical value for the spectroscopic factor, the latter obtained when the valence nucleons are confined to a single major oscillator shell, the sd shell for the cases discussed here. This is consistent with how the reduction factors are defined in the analysis of $(e, e'p)$ reactions on closed-proton-shell nuclei. While the first knockout results for well-bound nuclei [4] were in line with those found elsewhere, the R_s values for the weakly bound protons in ^{8}B and ^{9}C [5] were close to unity, suggesting a marked dependence on the nucleon separation energy. In the present work this hypothesis is examined by measuring R_s for a deeply bound neutron. In doing so we exploit the large asymmetry in the Fermi energies of neutron and proton states in nuclei near the drip lines; see Fig. 1. This is an experimental option that is unique to a rare-isotope accelerator.

The ^{9}Be(^{32}Ar, ^{31}Ar)X reaction leads to the lightest bound argon isotope. The neutron separation energy S_n is not known experimentally, but an accurate estimate of 21.99(5) MeV can be obtained by adding a generalized Coulomb-energy shift, the quantity D_1 of Ref. [7], to the proton separation energy of ^{32}Si, the mirror nucleus. As a test we calculate in the same way S_n for the ^{32,33}Ar pair to be 15.246 MeV, in excellent agreement with the new experimental value of 15.255 MeV [8]. The spin of ^{31}Ar is known to be $\frac{5}{2}^+$ from measurements of the recoil-energy shift in beta-delayed proton emission [9], and this is also the spin of the mirror nucleus ^{31}Al [10]. The proton separation energy of ^{31}Ar can be obtained from the generalized Coulomb-energy shift [7] to be 0.40(6) MeV, so with the lowest excited states in the mirror, ^{31}Al,

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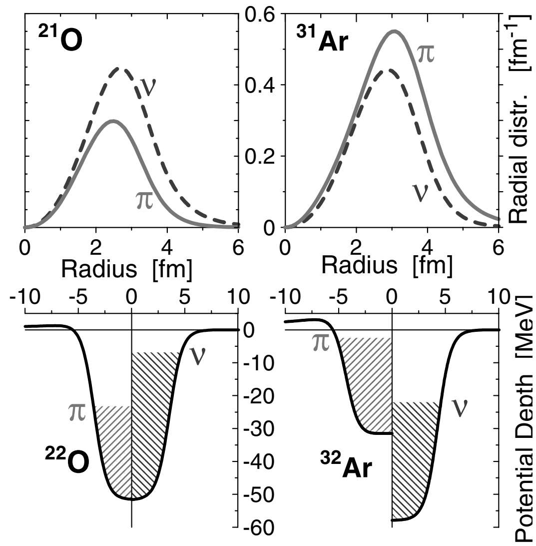

FIG. 1. The two lower diagrams show the Woods-Saxon potentials for the valence nucleons of ^{22}O and ^{32}Ar. Note the large asymmetry in the Fermi energies for these nuclei near the neutron and proton drip lines. The top diagrams show the corresponding radial number distributions of the residues (normalized to the number of nucleons divided by 4π) obtained in a Hartree-Fock calculation with the Skyrme X (SKX) interaction [6].

at 0.95 and 1.61 MeV [11], the $\frac{5}{2}^+$ ground state must be the only bound state in ^{31}Ar. Calculations with the universal *sd*-shell (USD) effective interaction [12,13] give 0 MeV ($\frac{5}{2}^+$), 0.94 MeV ($\frac{1}{2}^+$) and 1.74 MeV ($\frac{3}{2}^+$), and C^2S_j of 4.12, 0.37, and 0.08, respectively.

Since the dominant knockout strength will populate the only bound state, an accurate determination of the reduction can be obtained from the inclusive reaction cross section. A secondary beam of ^{32}Ar was produced in fragmentation of a ^{36}Ar primary beam of 150 MeV/nucleon from the Coupled-Cyclotron Facility of the National Superconducting Cyclotron Laboratory (NSCL). Following the 1034 mg/cm^2 primary ^{9}Be fragmentation target, the beam was purified in the A1900 large-acceptance fragment separator [14]. The secondary beam with an average midtarget energy of 65.1 MeV/nucleon interacted with 188(4) mg/cm^2 of ^{9}Be located at the target position of the high-resolution S800 spectrograph [15]. The identification of the reaction products after the secondary target was performed using the focal-plane detector system [16] of the magnetic spectrograph in conjunction with scintillators along the beam line. The intensity of ^{32}Ar projectiles on target was approximately 140 s^{-1}. The knockout residues were identified on an event-by-event basis from the time of flight between scintillators monitoring the beam, the energy loss in the ionization chamber, and the position and angle information provided by the position-sensitive cathode readout drift counters in the S800 focal plane [16].

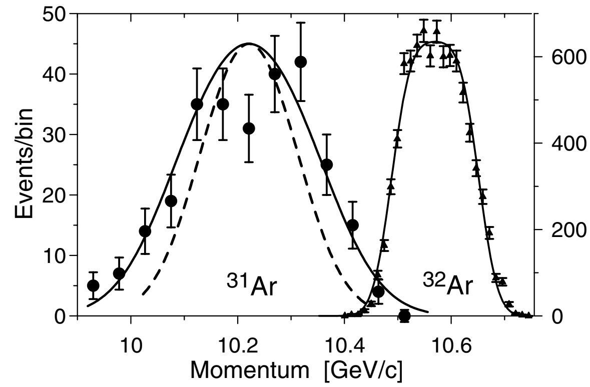

FIG. 2. Longitudinal momentum distribution for the unreacted projectile beam ^{32}Ar fitted with a rectangular distribution folded with a Gaussian resolution function. The distribution of the ^{31}Ar residues (left) is compared with theoretical calculations for $l = 0$ (dashed line) and $l = 2$ (solid line).

The parallel-momentum distributions shown in Fig. 2 were obtained with the ion-optics code COSY [17]. The data were corrected for acceptance, those data points with the correction exceeding a factor of 1.5 being rejected. The theoretical momentum distributions were calculated in a black-disk model [18,19] and folded with the measured response function. These clearly identify the reaction as an $l = 2$ knockout confirming the $\frac{5}{2}^+$ assignment. The experimental cross section $\sigma_{\rm exp} =$ 10.4(13) mb emerges from the number of residues relative to incoming projectiles and the density of the ^{9}Be reaction target. Uncertainties arise from the software gates used for particle identification (10%), the correction for the momentum acceptance of the S800 spectrograph (2.5%), and the purity and stability of the incoming beam (5%) and have been added in quadrature to the statistical error. The empirical reduction factor R_s is defined by the expression [19]

$$\sigma_{\rm exp} = R_s\left(\frac{A}{A-1}\right)^2 C^2S_j\,\sigma_{\rm sp}, \qquad (1)$$

where the A-dependent term is a center-of-mass correction valid for the sd shell and C^2S_j (= 4.12) is the shell-model spectroscopic factor. The single-particle (unit) cross section $\sigma_{\rm sp}$, corresponding to a normalized single-nucleon wave function [20,21], is calculated as outlined in the following to be 9.89 mb. Thus we obtain $R_s = 0.24(3)$, a surprisingly low value. It is clearly important to examine the calculation of the unit cross section carefully.

The simple and accurate description of knockout cross sections in eikonal theory is linked to the surface dominance of the reaction mechanism, which eliminates the need to specify the motion of fast nucleons in the nuclear interior. The strength of the interactions is defined from the experimental NN cross sections [20]. However, only about 4% of the single-particle wave function is sampled in the reaction, an estimate based on the ratio of the stripping cross section to the 284 mb reaction cross section of a free neutron. This leads us to consider the assumed density distribution of the residue and the neutron-residue relative-motion wave function. A consistent description is obtained from self-consistent Hartree-Fock (HF) calculations based on a Skyrme parametrization, which offers quantitative agreement with experiment for parameters related to nuclear size. We use the recent SKX parameter set [6], determined from a large set of data on spherical nuclei, including nuclei far from stability, and which accounts for the binding-energy differences of mirror nuclei [22], interaction cross sections [23], and nuclear charge distributions [24]. This agreement suggests that the theory will also give a good description of individual single-particle states. Because of the sensitivity of the σ_{sp} to the nucleon separation energy S_n, the central potential of the HF calculation is scaled (by a number near unity) to reproduce S_n for the state required, ensuring the correct large-distance asymptotic behavior of the wave function.

Understanding these sensitivities is simplified by the observation [19] that the key variable is the root-mean-squared (rms) separation R_{sp} of the removed nucleon and the residue in the projectile, while details of the shape of its binding potential are less important. The connection between R_{sp} and the HF radius, which is measured from a fixed center, is

$$R_{sp}^2 = \left(\frac{A}{A-1}\right)\langle r^2\rangle_{HF}. \tag{2}$$

The HF calculation shows that ^{31}Ar has a pronounced proton skin so that the removal of the $0d_{5/2}$ neutron by the neutron-excess target takes place in an environment dominated by protons; see the density distributions in Fig. 1. This effect was included in the calculation of the residue target S matrix in the $[t_{NN}\rho^{(r)}\rho^{(t)}]$ double-folding optical limit of the Glauber multiple scattering theory. We assume a Gaussian form factor for the effective NN interaction t_{NN}. For the ^{9}Be target (t) the neutron and proton distributions were, as in previous work [4,5], taken to be

$$\rho_n^{(t)}(r) = (N_t/A_t)\rho_m^{(t)}(r), \qquad \rho_p^{(t)}(r) = (Z_t/A_t)\rho_m^{(t)}(r), \tag{3}$$

with $\rho_m^{(t)}(r)$ the Gaussian target matter density. For the residue (r) we compare two approaches. The first uses the calculated HF neutron and proton densities of the residue, so that the integrand of the optical limit integral becomes

$$t_{NN}\rho^{(r)}\rho^{(t)} \rightarrow \frac{t_{pp}\rho_m^{(t)}}{A_t}[Z_t\rho_p^{(r)} + N_t\rho_n^{(r)}] + \frac{t_{pn}\rho_m^{(t)}}{A_t}[N_t\rho_p^{(r)} + Z_t\rho_n^{(r)}], \tag{4}$$

and where it is assumed that $t_{nn} = t_{pp}$. In the second approach we use only the HF matter density of the residue, $\rho_m^{(r)}(r)$, and assume that the individual neutron and proton densities are approximated as for the target. The two approaches give 9.89 and 9.98 mb. The contribution from diffraction dissociation is 20% of this. Using instead a two-parameter Fermi distribution with the same rms radius $R^{(r)}$ we obtain 9.68 mb. Consequently, the proton skin and even the precise shape of the density distribution are not critical for the unit cross section. The errors arising from the parameters discussed here, expressed in terms of the finite-difference derivatives, are

$$\delta\sigma_{sp}/\sigma_{sp} = 1.1\delta R_{sp} + 0.2\delta a - 1.2\delta R^{(r)} + 0.5\delta R^{(t)}, \tag{5}$$

where the coefficients are in fm^{-1}. The expression shows that a 0.1 fm error on R_{sp} and $R^{(r)}$ translates into an uncertainty of about 15%; the contributions from the target radius $R^{(t)}$ and the bound-state-potential diffuseness a are small.

The neutron-skin nucleus ^{22}O, also with 14 neutrons, offers an interesting comparison. The theoretical spectroscopic factor to the $\frac{5}{2}^+$ ground state of ^{21}O is 5.22, larger than in the ^{32}Ar case because ^{22}O is essentially a doubly magic structure. Theory suggests that this branch accounts for 92% of the cross section, the rest going to two states below the neutron threshold of approximately 3.8 MeV. Therefore, it is meaningful to deduce R_s from the inclusive one-neutron knockout cross section. Two measurements on a ^{12}C target [25] give 120(14) mb at 51 MeV/nucleon and 70(9) mb at 938 MeV/nucleon. The theoretical cross sections for this neutron-skin nucleus, of 139 and 116 mb, lead to an average value of R_s of 0.70(6), well above the result for ^{32}Ar with the same number of neutrons but ten protons more.

The systematics in Fig. 3 suggests that the reduction factor R_s is strongly correlated with the nucleon separation energy, in turn linked to the nuclear symmetry energy. This raises the interesting question of spectroscopic factors in very asymmetric nuclear matter. A

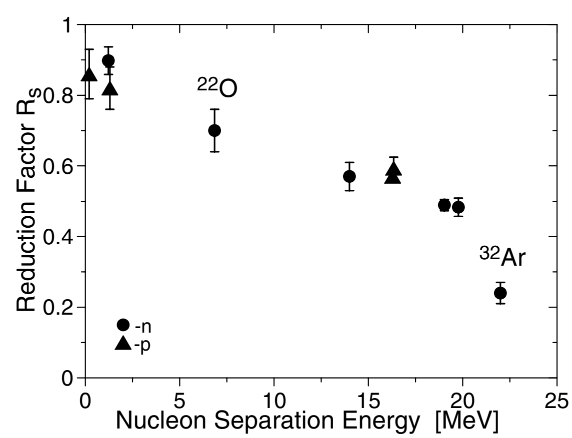

FIG. 3. Measured reduction factors R_s as a function of nucleon separation energy. The points, taken from the left, use data from ^{8}B, ^{9}C, ^{15}C, ^{57}Ni, ^{12}C, and ^{16}O [4,5,26]. The labeled $N = 14$ nuclei are discussed in the present Letter.

transparent but qualitative measure of the importance of (hard-core) short-range NN correlations was suggested by Birse and Clement [27]. They find a reduction of the spectroscopic factor proportional to

$$\delta_s = C \int R_{t_z}^2(r)\left[\frac{1}{2}\rho_{t_z}^{(r)}(r) + \rho_{-t_z}^{(r)}(r)\right] r^2 dr, \qquad (6)$$

expressing the overlap between the density of the nucleon, with isospin projection t_z, and the neutron and proton densities. The factor 1/2 reflects that the Pauli principle favors the neutron-proton interaction. The parameter δ_s links density and asymmetry effects. With Hartree-Fock densities, we obtain for ^{8}B, ^{15}C, ^{22}O, and ^{32}Ar the relative values 0.19, 0.33, 0.47, and 0.68, respectively, reminiscent of the trend in Fig. 3. However, hard-core contributions may only be part of the large reduction [1,2].

High separation energies are also encountered for deep-hole states in nuclei near stability. For example, the reaction ^{116}Sn$(d, t)^{115}$Sn [28] revealed broad giant-resonance-like distributions near 6 MeV excitation energy, corresponding to an effective neutron separation energy of 15 MeV. These resonances had angular distributions characteristic of the $1p_{1/2,3/2}$ and $0g_{9/2}$ states, and the observed strength was 0.2 to 0.3 of the sum-rule value. This reduction is similar to our result for the single final state in ^{31}Ar at the Fermi surface of ^{32}Ar. This strong reduction in strength for deep-hole states in ^{116}Sn was attributed to the coupling of the single-particle states to collective motion [28]. Collective couplings and short-range correlations are clearly both interesting pieces of the ^{32}Ar theoretical puzzle.

Finally, it is important to note that the low occupancy of physical nucleons in the quasiparticle states that make up the description of ^{32}Ar does not seem to be linked to a breakdown of the model for its structure. In fact, all evidence for the $(A, T) = (31, 5/2)$ and $(32, 2)$ nuclei supports the assumption that these are good sd-shell nuclei. The spins, energy spectra, and beta decay properties of the mirror nuclei ^{31}Al and ^{32}Si are well accounted for [11,29]. The Gamow-Teller beta decay of ^{32}Ar has been studied with high resolution [30] and both the distribution of the beta strength (up to 8 MeV excitation energy) and the renormalization of the axial-vector coupling constant are in line with with theoretical calculations.

In summary, the ^{9}Be(^{32}Ar, ^{31}Ar)X reaction with a neutron separation energy of 22.0 MeV leads to a nucleus situated at the proton drip line with only one bound state. The empirical reduction factor R_s is unexpectedly small, which may be linked to the very asymmetric nuclear matter in ^{31}Ar. Experiments on other deeply bound states can help to clarify the origin of this effect.

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