PHYSICAL REVIEW C **74**, 021302(R) (2006)

Cross-shell excitation in two-proton knockout: Structure of ^{52}Ca

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(Received 23 March 2006; published 16 August 2006)

The two-proton knockout reaction ^{9}Be(^{54}Ti,^{52}Ca$+\gamma$) has been studied at 72 MeV/nucleon. Besides the strong feeding of the ^{52}Ca ground state, the only other sizeable cross section proceeds to a 3^- level at 3.9 MeV. There is no measurable direct yield to the first excited 2^+ state at 2.6 MeV. The results illustrate the potential of such direct reactions for exploring cross-shell proton excitations in neutron-rich nuclei and confirms the doubly-magic nature of ^{52}Ca.

DOI: 10.1103/PhysRevC.74.021302 PACS number(s): 24.50.+g, 21.60.Cs, 23.20.Lv, 27.40.+z

For decades, the cornerstone of nuclear structure has been the concept of single-particle motion in a well-defined potential leading to shell structure and magic numbers governed by the strength of the mean-field spin-orbit interaction [1]. Recent observations in exotic, neutron-rich nuclei have demonstrated that the sequence and energy spacing of single-particle orbits is not as immutable as once thought: some of the familiar magic numbers disappear and new shell gaps develop [2]. Cross-shell excitations, arising from the promotion of nucleons across shell gaps, probe changes in shell structure. They are, however, not always readily identifiable in nuclear spectra. This Rapid Communication demonstrates that two-proton knockout reactions can examine, selectively, cross-shell *proton* excitations in *neutron*-rich systems.

Single-nucleon knockout reactions with fast radioactive beams are established tools to investigate the properties of halo nuclei [3] and to study beyond mean-field correlations, indicated by the quenching of spectroscopic strengths [4]. Eikonal theory [5] provides a suitable framework for the extraction of quantitative nuclear structure information from such reactions. In contrast, the potential of two-nucleon knockout as a spectroscopic tool has been recognized only recently. Bazin *et al*. [6] have shown that two-proton removal reactions from beams of neutron-rich species at intermediate energies proceed as direct reactions and that partial cross sections to different final states of the residue provide structure information. More recently, such a reaction was used to infer the magicity of the very neutron-rich ^{42}Si nucleus [7].

In the current experiment, sizable cross sections for the ^{9}Be(^{54}Ti,^{52}Ca$+\gamma$)X reaction were found to feed only the ^{52}Ca ground state and a 3^- level with an excitation energy near 4 MeV, bypassing completely the first 2^+ level at 2.6 MeV. These observations can be reproduced qualitatively by calculations which assign the 3^- level to the promotion of protons across the $Z = 20$ shell gap. In addition, the data confirm the presence of a neutron sub-shell closure at $N = 32$, the subject of much recent attention [8–13].

The ^{54}Ti secondary ions were produced by fragmentation of a 130 MeV/nucleon ^{76}Ge beam, delivered by the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory, onto a ^{9}Be fragmentation target. The ions were selected in the A1900 large-acceptance fragment separator [14], which was operated with two settings during different phases of the experiment; 1% momentum acceptance and no momentum restriction, respectively. The secondary beam, with a mid-target energy of 72 MeV/nucleon, interacted with another, 375(4) mg/cm^2 thick, ^{9}Be foil located at the target position of the high-resolution S800 spectrograph [15]. The knockout residues were identified event-by-event from the time of flight between scintillators monitoring the beam, the energy loss measured in an ionization chamber, and the position and angle information provided by the cathode-readout drift counters in the S800 focal plane [15]. The ^{9}Be reaction target was surrounded by SeGA, an array of seventeen 32-fold segmented HPGe detectors [16], arranged in two rings (90° and 37° with respect to the beam axis).

An inclusive cross section for two-proton knockout to all final states was derived from the yield of detected ^{52}Ca residues and the number of incoming ^{54}Ti projectiles, taking into account the density of the secondary ^{9}Be target. To minimize effects arising from acceptance limitations in the S800 spectrograph, only data with the momentum acceptance of the A1900 fragment separator reduced to 1% were used to deduce the cross section. Systematic uncertainties accounting for particle identification (6%), stability and purity of the beam (5%), and the momentum acceptance of the spectrograph (4%) were added to the statistical uncertainty in quadrature.

Figure 1 presents the inclusive parallel-momentum distribution for all two-proton knockout events from ^{54}Ti to ^{52}Ca, together with that of the unreacted ^{54}Ti projectiles

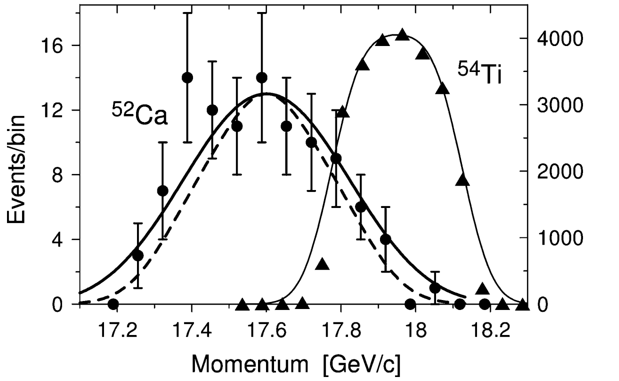

FIG. 1. Longitudinal momentum distribution of the ^{52}Ca knockout residues and the unreacted ^{54}Ti projectiles (momentum acceptance of the A1900 restricted to 1%). The ^{52}Ca data are compared to a calculated shape given by the convolution of the separate distributions for two uncorrelated protons removed from the $f_{7/2}$ orbit (dashed line) and to the same curve, but folded with the momentum profile of the ^{54}Ti beam (solid line).

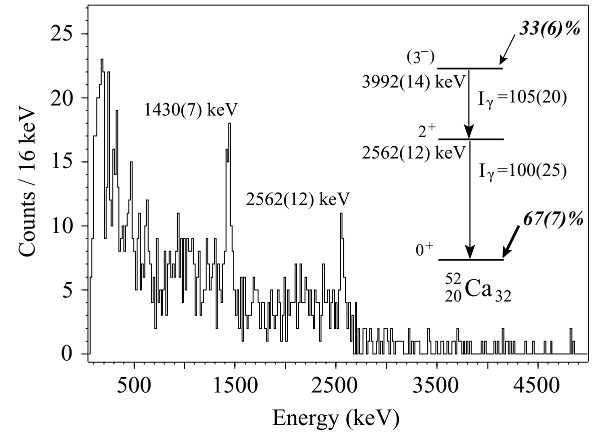

FIG. 2. γ-ray spectrum (2.75% detection efficiency at 1 MeV) in coincidence with the ^{52}Ca knockout residues. The two γ-ray transitions establish the cascade shown in the inset. The arrows indicate the feeding profile by the reaction [$\sigma(3^-) = 0.11(3)$ mb and $\sigma(0^+) = 0.21(3)$ mb]. For this part of the experiment, the A1900 fragment separator was operated without momentum restriction.

passing through the target. As discussed below, ~70% of the two-proton knockout cross section feeds the ^{52}Ca ground state directly, making it worthwhile to consider these inclusive data first. The ^{52}Ca momentum distribution of Fig. 1 is fairly narrow and centered close to the beam velocity. As argued in Ref. [6], this observation is consistent with the reaction mechanism being direct in nature. The magnitude of the inclusive cross section, $\sigma_{\rm inc} = 0.32(4)$ mb, is of the same order as that reported in Ref. [7] for two-proton knockout to ^{42}Si (0.12(3) mb). It is also significantly smaller than that observed for the ^{9}Be(^{28}Mg,^{26}Ne) reaction [6], for example. To first order, this indicates that the number of valence protons available for the process must be small [6].

To proceed further in understanding the momentum distribution, a description of ^{54}Ti as a semi-magic nucleus, with a closed $N = 32$ neutron shell and two $f_{7/2}$ valence protons outside the $Z = 20$ core, has been adopted, in keeping with recent experimental information on the level structure and the $B(E2; 0^+ \rightarrow 2^+_1)$ transition rate of this nucleus [11,13]. Following Ref. [6], the dashed curve for ^{52}Ca in Fig. 1 is the result of calculations where the momentum distributions for the removal of two independent, i.e., uncorrelated, $f_{7/2}$ protons have been convoluted. The solid line results when this distribution is folded with the momentum profile of the unreacted ^{54}Ti projectiles, to account for the momentum spread in the incoming beam and the straggling in the target. The agreement is satisfactory, and the measured momentum distribution consistent with the removal of two $f_{7/2}$ protons being the dominant reaction process.

The γ-ray spectrum measured in coincidence with the ^{52}Ca residues (Fig. 2) displays two transitions with energies of 1430(7) and 2562(13) keV. The latter can be identified with the 2563(1) keV line reported by Huck *et al.* [10], the only prominent line seen in the β decay of ^{52}K to ^{52}Ca, and assigned by these authors as the $2^+ \rightarrow 0^+$ ground-state transition. The observation was confirmed in a more recent β-decay study [17]. At present, this second study is also the only one to report additional transitions in ^{52}Ca. In particular, a 3990 keV state was found, with the second highest feeding in the β-decay process, and with deexcitation towards the 2^+ level via a 1427(1) keV transition. It is tempting to associate this γ ray with the 1430(7) keV line of Fig. 2. In the work of Ref. [17], the 3990 keV state was assigned $J^\pi = 3^-$ as the most likely quantum numbers based on the measured feeding in the β-decay process, the feeding from another level at 5951 keV, and the deexcitation pattern towards the 2^+ state. In addition, the excitation energy of the state at 3990 keV is close to that of the known first 3^- excitation along the even-even Ca isotopic chain illustrated in Fig. 3.

There is no appreciable direct feeding of the 2^+ level in the two-proton knockout process as the 1430(7) and 2562(13) keV lines are measured to have the same relative intensity (see Fig. 2). As is discussed below, this 2^+ state is understood as a neutron particle-hole excitation across the $N = 32$ shell gap, involving the $p_{3/2}$ and $p_{1/2}$ orbitals. *A priori*, such an excitation is not expected to be populated appreciably in the reaction of a ^{54}Ti projectile with two $f_{7/2}$ valence protons and no valence neutrons. The same reasoning leads to the complementary conclusion that the sizable cross section to the

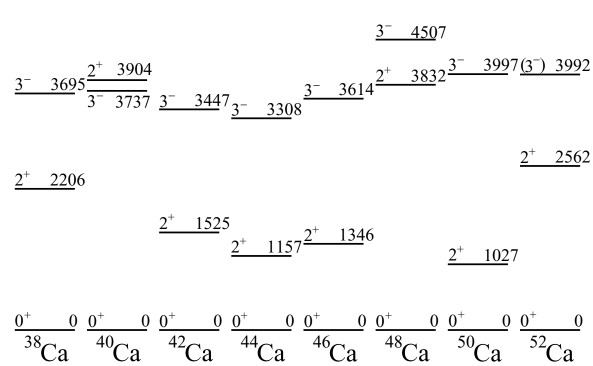

FIG. 3. Systematics of the first 2^+ and 3^- excitations along the even-even Ca isotopic chain (data from Refs. [17–19]).

3392(14) keV state is a direct indication of a proton excitation of 3992(14) keV. Taking account of the closed-shell character of the ^{54}Ti projectile and of the ^{52}Ca residue, this suggests that the two-proton knockout mechanism will be an important tool for exploring cross-shell proton excitations in neutron-rich systems.

Clearly, this first principles reasoning requires substantiation by more detailed calculations. While the sudden, direct nature of the two-proton removal reaction was identified in Ref. [6], the associated two-proton structures and reaction mechanism were treated only approximately. A more complete formalism, using eikonal theory and shell-model wave functions, has been developed since for the two-nucleon stripping (inelastic breakup) mechanism [20]. This formalism has now been extended to include a complete calculation of removal events in which one proton is absorbed (stripped) and a second is elastically dissociated (diffracted) by the target. The (smaller) cross section for elastic dissociation of both (strongly-bound) protons is estimated as well. Details will be presented elsewhere [21]. Of relevance here is that, for four test-case *sd*-shell nuclei, the calculated inclusive cross sections overpredict the measured values by a factor of 2 [21], requiring a suppression factor, $R_s(2N) \approx 0.5$, of the shell-model strengths: the analog of the well-documented suppression seen in nucleon and electron-induced single-nucleon knockout reactions [22].

The eikonal S-matrices were calculated from the residue and target one-body matter densities using the optical limit of Glauber's multiple scattering theory [23,24]. A Gaussian nucleon-nucleon (NN) effective interaction was assumed [25] with a range of 0.5 fm and a strength determined, in the usual way, by the free pp and np cross sections and the real-to-imaginary ratios of the forward NN scattering amplitudes [26]. The ^{9}Be density was of Gaussian form with a rms matter radius of 2.36 fm [27]. The density of ^{52}Ca was taken from a spherical Skyrme (SkX) Hartree-Fock (HF) calculation [28], with a rms matter radius of 3.632 fm.

The protons were assumed to occupy *fp*- and *sd*-shell model orbitals with spectroscopic amplitudes obtained using the code OXBASH [29]. Their single-particle wave functions were calculated in Woods-Saxon potential wells with fixed diffuseness ($a = 0.70$ fm) and radius parameters (r_0) adjusted to reproduce the rms radii of the proton single-particle states given by the HF calculation above [4]. The strengths of the binding potentials were adjusted to support bound eigenstates with the physical ground- and excited-state separation energies. The ground-state to ground-state two-proton separation energy for ^{54}Ti was calculated to be $S_{2p} = 27.83$ MeV, in agreement with the measured $S_{2p} = 27.66(71)$ MeV [30].

The nuclear structure input to the cross section calculations was also based on the following additional considerations. While neutron excitations of *fp*-shell nuclei have been the subject of much recent attention and modern effective interactions have been developed that reproduce the data satisfactorily [8,9,11–13], the same cannot yet be said for the proton excitations relevant for the present work. Here, calculations were carried out with the modified WBMB Hamiltonian of Ref. [31], which is able to describe the low-level structure of ^{50}K and the rather unusual characteristics of its β decay to ^{50}Ca. This interaction results in a 0^- ^{50}K ground state and a 2^- excitation at 550 keV. The situation is reversed in ^{52}K, and the 2^- level becomes the ground state while the 0^- excitation is calculated to be located at 2.3 MeV. These ^{52}K ground state I^π quantum numbers agree with the values inferred in the most recent β-decay study [17]. The calculations also account for the observed feeding of ^{52}Ca levels through (i) a first forbidden transition to the 2_1^+ level and (ii) a Gamow Teller (GT) transition to the 3^- state, as well as for the absence of direct feeding of the ground state (first forbidden GT transition).

Besides the ^{52}Ca ground state, the cross section calculations also required proton wave functions for the 3^- level and for positive-parity excitations associated with two holes in the *sd* shell. The WBMB interaction places the negative-parity states ∼3 MeV above the experimental value, illustrating the difficulties with the interaction alluded to above. (Attempts with the interaction of Ref. [32] result in a similar problem). Nevertheless, the negative-parity ^{52}Ca spectrum has a 3^- state as its lowest excitation. The need to consider two particle-two hole excitations in two-proton knockout comes from the observation that, in ^{48}Ca, a 4.28 MeV, 0^+ state with this intrinsic structure (see Fig. 1 in Ref. [28]) lies within 225 keV of the 3^- level. The presence of a similar level in the same energy range in ^{52}Ca cannot be ruled out. Unfortunately, its excitation energy cannot be readily estimated [33], and in this case as well the cross-shell calculations can only be viewed as qualitative.

With the wave functions derived in this manner, the calculated *fp*-shell, two-proton knockout partial cross section to the ^{52}Ca 0^+ ground state is 0.38 mb. Comparison with the measured value, 0.21(3) mb, yields the ratio $R_s(2N) = 0.55(8)$, in agreement with the available *sd*-shell systematics [21]. The direct population of the 2_1^+ state is predicted to be very small as this level corresponds to a neutron excitation: the calculated value of 0.04 mb is well below the detection sensitivity of the present measurements.

In view of the uncertainties discussed above, the knockout cross section calculations to the other excited states were restricted to the simplest shell-model configurations expected. Thus, 3^- states with (i) one-proton hole in the $d_{3/2}$ shell and (ii) one-proton hole in the $s_{1/2}$ state were considered (i.e., the configurations were of the type $\pi((d_{3/2})^{-1} \times (f_{7/2})^{+1})$, for example). Similarly, for the 0^+ states, configurations with (iii) two $d_{3/2}$ proton holes and (iv) two $s_{1/2}$ proton holes were included. The calculated two-proton knockout cross sections (taking $R_s(2N) = 0.55$) are 0.13, 0.19, 0.09 and 0.09 mb, respectively. As the physical lowest 3^- state is expected to correspond to a linear combination of configurations (i) and (ii), their sum, 0.32 mb, can be used as a upper limit of the two-proton knockout cross section, assuming coherent superposition. A similar upper limit to the 0_2^+ level is then 0.18 mb.

An interpretation of the experimental results is, therefore, that the 3990 keV level can be associated with the 3^- state seen in ^{52}K β decay, and that the two-proton knockout cross section of 0.11(3) mb is several times weaker than the maximum allowed by the 3^- calculation. The absence of any other notable strength in the experimental spectrum then suggests that the 0_2^+ state lies above the neutron threshold of 4.7(7) MeV. In addition, it is worth noting that the two-proton knockout cross sections summed over all one- and two-proton hole states in the *sd*-shell are 1.93 and 9.51 mb, respectively. Most of these strengths proceed towards levels above the neutron separation energy and lead to states in lighter Ca isotopes that cannot be discerned by the experiment.

In summary, the present work has demonstrated that two-proton knockout reactions represent an important tool in the arsenal of experimental techniques aimed at the study of neutron-rich nuclei. The specific ^{9}Be(^{54}Ti,^{52}Ca+γ)X reaction investigated here was instrumental in identifying a proton cross-shell excitation in an exotic nucleus with large neutron excess. In addition, the data provided confirmation of the $N = 32$ subshell closure in ^{54}Ti. Finally, the reduction of the spectroscopic strength, verified thus far only for *sd*-shell nuclei ($R_s(2N) \approx 0.5$) was found to apply to this *fp*-shell nucleus as well.

This work was supported by the National Science Foundation under Grant Nos. PHY-0110253, PHY-9875122, and PHY-0244453, by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. W31-109-ENG-38, the UK Engineering and Physical Sciences Research Council (grant EP/D003628) and by Polish Scientific Committee Grant No. 1P03B 059 29.

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[33] An estimate of this 0_2^+ excitation energy can be obtained from binding energies (BE) through [2BE(^{52}Ca)-BE(^{54}Ti)-BE(^{50}Ar)]+4$\bar{V}$ with the residual proton-neutron interaction $\bar{V} = -0.75$ MeV derived from this expression for the 0_2^+ level in ^{48}Ca. Unfortunately, the BE values of the neutron-rich nuclei involved are not known with the required accuracy.