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# Pairing forces govern population of doubly magic $^{54}\text{Ca}$ from direct reactions

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Direct proton-knockout reactions of  $^{55}\text{Sc}$  at  $\sim 200$  MeV/nucleon were studied at the RIKEN Radioactive Isotope Beam Factory. Populated states of  $^{54}\text{Ca}$  were investigated through  $\gamma$ -ray and invariant-mass spectroscopy. State energies were calculated from the shell model, employing the GXPFI1Br interaction, and their exclusive cross sections from distorted-wave impulse approximation single-particle estimates factored with the shell model spectroscopic factors. Despite the calculations showing a significant amplitude of excited neutron configurations in the ground-state of  $^{55}\text{Sc}$ , valence proton removals populated predominantly the ground-state of  $^{54}\text{Ca}$ . This counter-intuitive result is attributed to pairing effects leading to a dominance of the ground-state spectroscopic factor. Owing to the ubiquity of the pairing interaction, this argument should be generally applicable to direct knockout reactions from odd-even to even-even nuclei.

Perhaps the most profound of the interactions within the atomic nucleus is that of *pairing*. It is well described by a strongly attractive contact force between two nucleons (protons and neutrons). Notably, it is why, without exception, even-even nuclei have zero total angular momentum and positive parity,  $J^\pi = 0^+$ , ground states. Moreover, it is the origin of odd-even staggering of neutron and proton separation energies ( $S_n$  and  $S_p$ , respectively). Recently, pairing has been shown to have a prominent role in single-nucleon removal cross sections in so-called *neutron-rich exotic nuclei* which have an excess of neutrons compared to their stable counterparts [1]. In this Letter, a further implication of pairing to direct reactions is demonstrated.

Along with pairing, the interaction of a nucleon's intrinsic ( $s$ ) and orbital ( $\ell$ ) angular momenta has far-reaching consequences. In particular, it is necessary for the theoretical reproduction of the canonical nuclear "magic numbers" [2, 3], 2, 8, 20, 28, 50, 82..., which relate to large energy gaps between shells of protons and neutrons. Nuclei with both proton and neutron numbers equalling magic numbers are known as *doubly magic*. A consequence of the pairing interaction, most obvious in doubly magic nuclei, is the existence of excited states based on the promotion of identical nucleon pairs to higher-lying shells into 2-particle-2-hole (2p-2h) states.

A feature of the *tensor force*, which describes meson exchanges between nucleons, is the attraction of unlike nucleons of the same  $\ell$  ( $= s, p, d, f, \dots$ ) with different intrinsic spin directions,  $j_> = \ell + s$  and  $j_< = \ell - s$ , where  $E(j_>) < E(j_<)$  [4]. It implies an evolution of the energies of the spin-orbit generated shells as a function of nucleon number in exotic nuclei [5, 6]. Stable counterparts of neutron-rich nuclei have occupied proton  $j_>$  orbits, lowering the corresponding neutron  $j_<$  orbital energy. Low occupancy of the proton  $j_>$  in the neutron-rich case results in less interaction with the neutron  $j_<$  orbital allowing  $E(j_<)$  to increase. In  $^{54}\text{Ca}$ , this effect, owing to a lack of  $\pi(\text{proton})0f_{7/2}$  occupation, allows for a high-lying  $\nu(\text{neutron})0f_{5/2}$  orbital which creates the non-canonical  $N(\text{neutron number}) = 34$  magic number [7–9]. A direct analogue exists in  $^{24}\text{O}$  where an unoccupied  $\pi 0d_{5/2}$  orbital allows a large, compared even to the nearby  $^{27}\text{Ne}$  [10], gap between  $\nu 0d_{3/2}$  and  $\nu 1s_{1/2}$ , to form, leading to the non-canonical  $N = 16$  magic number [11, 12].

There is some recent evidence that the removal of the valence proton from the  $\pi 0d_{5/2}$  orbital in  $^{25}\text{F}$  leads to  $\sim 60\%$  population of excited states of  $^{24}\text{O}$  [13]. The explanation for this in Ref. [13] was the induced configuration mixing of the  $^{24}\text{O}$  core neutron states by the lowering of the  $\nu 0d_{3/2}$  energy through an artificially strengthened tensor interaction with the  $\pi 0d_{5/2}$  proton. However, from the point of view of the pairing interaction, the spectroscopic factor to the ground-state would be expected to be large. This can be illustrated in a two-level model of 0p-0h (ground state) and 2p-2h neutron states for  $^{25}\text{F}$  and  $^{24}\text{O}$ . The spectroscopic factor to the ground-state of  $^{24}\text{O}$  following a  $\pi 0d_{3/2}$  proton removal is dependent on the product of amplitudes of the 2p-2h states in  $^{25}\text{F}$  and  $^{24}\text{O}$  which is positive owing to the definite signs of the off-diagonal two-body matrix elements of the pairing interaction [14].

Whether the population patterns from direct proton removal reactions  $^{55}\text{Sc}(p, 2p)$  adhere to the pairing interaction expectation or tensor-driven effects is addressed in this letter. As with  $^{25}\text{F}$ ,  $^{55}\text{Sc}$  has a non-canonical doubly magic core that results from the absence of tensor-driven attraction and a single proton in the orbital that acts to lower the valence neutron energies. In the present work

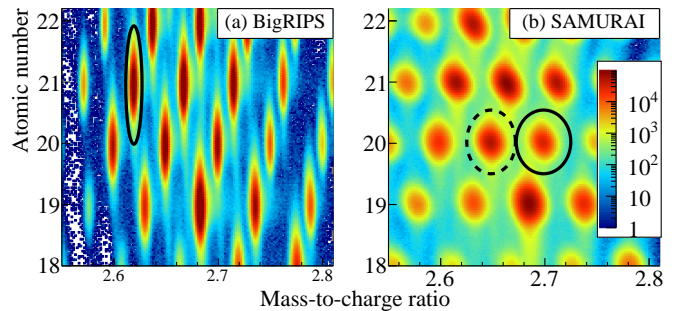


FIG. 1. Identified ions in front of (a) and behind (b) the reaction target. In (a), the ellipse indicates the software gate placed on  $^{55}\text{Sc}$ . In (b), gates applied to select  $^{53}\text{Ca}$  and  $^{54}\text{Ca}$  are shown as dashed and solid ellipses, respectively. The scale is counts per bin and applies to (a) and (b).

and Ref. [13], projectiles were produced under the same conditions and the same reaction is employed at an energy of  $\sim 200$  MeV/nucleon.

The first study of  $^{54}\text{Ca}$  populated through direct reactions is presented. Exclusive cross sections of ground and excited states have been measured as well as  $\ell$  values of removed nucleons that populated them. Only through application of invariant-mass spectroscopy to the heaviest exotic nucleus to date were such measurements possible for the unbound states. Comparisons of the measurements were made to distorted-wave impulse approximation (DWIA) [15, 16] and conventional shell model calculations, the latter employing the GXPf1Br interaction [7] in the full  $sd$ - $pf$ - $gds$  model space. From the comparisons,  $\ell$  values of removed nucleons and tentative  $J^\pi$  assignments to excited states of  $^{54}\text{Ca}$  were determined. The results show predominant ground- and excited-state population of  $^{54}\text{Ca}$  through valence and core proton removals, respectively.

Experimental investigations were conducted at the Radioactive Isotope Beam Factory, operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. A 240 pA beam of  $^{70}\text{Zn}^{30+}$  was accelerated to 345 MeV/nucleon and secondary beams of isotopes produced from its fragmentation on a 10-mm-thick  $^9\text{Be}$  target situated at the entrance of BigRIPS [18], a two-stage fragment separator. Constituents of the secondary beams were selected and separated up until the 3<sup>rd</sup> focal plane of BigRIPS by their magnetic rigidity ( $B\rho$ ) through two dipole magnets and energy loss ( $\Delta E$ ) through an Al wedge-shaped degrader situated between the dipole magnets. The time-of-flight (TOF),  $B\rho$ , and  $\Delta E$  were recorded for each ion between the 3<sup>rd</sup> and 7<sup>th</sup> focal planes. These measurements were combined to provide unambiguous particle identification (PID) of the ions' mass-to-charge ratio and atomic number [19], shown in Fig. 1(a). Following identification, the secondary beams were transported to the MINOS device [20], a 151(1)-mm-long liquid hydrogen ( $\text{LH}_2$ ) target

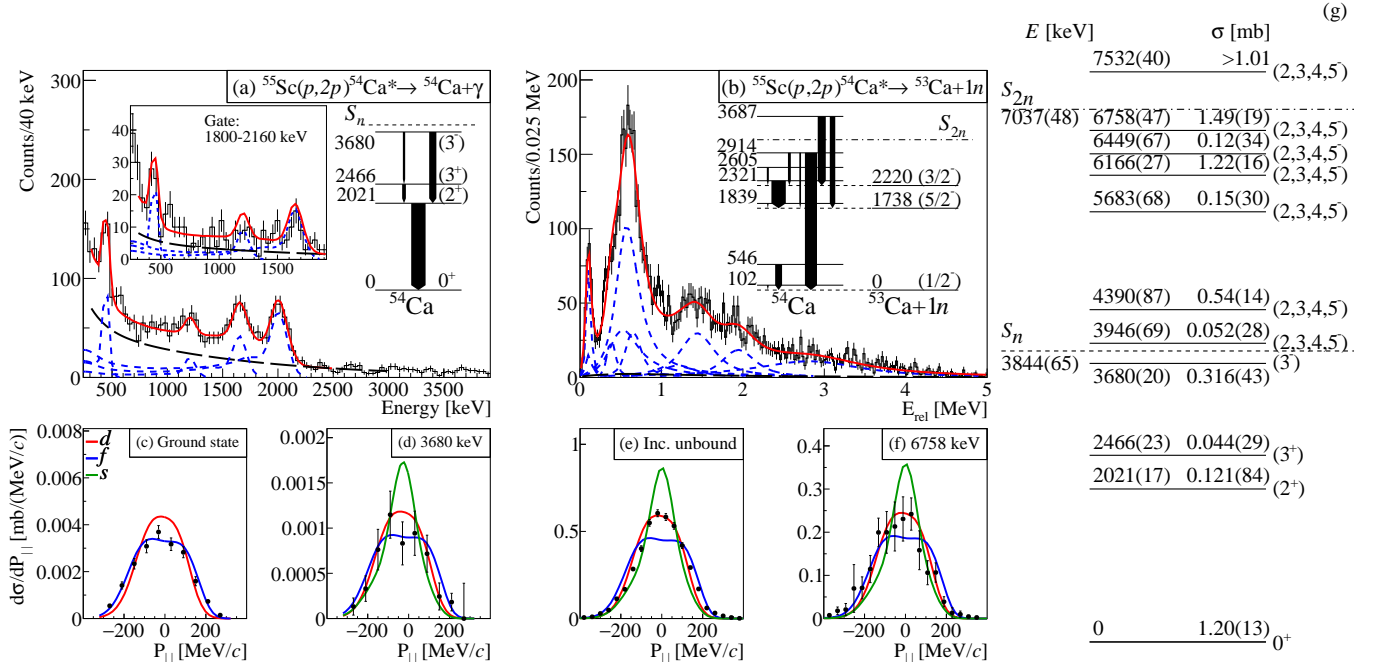


FIG. 2. (a) Doppler-corrected  $\gamma$ -ray spectrum of the  $^{55}\text{Sc}(p, 2p)^{54}\text{Ca}^* \rightarrow ^{54}\text{Ca} + \gamma$  reaction. The total fit function (red line) comprises simulated response functions of DALI2<sup>+</sup> (blue short-dashed lines) and a double-exponential background (black long-dashed line). The inset spectrum is that in coincidence with the 2021-keV transition, where the blue dashed lines are intensity-fixed responses assuming the shown level scheme. Arrow widths on the level scheme represent relative  $\gamma$ -ray intensities. (b) Relative energy spectrum of  $^{55}\text{Sc}(p, 2p)^{54}\text{Ca}^* \rightarrow ^{53}\text{Ca} + 1n$ . The total fit function (red line) is the sum of the simulated responses of NeuLAND+NEBULA and beam-line detectors (blue short-dashed lines), and a non-resonant background (black long-dashed line). Inset is the decay scheme to  $^{53}\text{Ca}$ , level energies are with respect to the  $^{53}\text{Ca}$  ground-state energy and arrow widths are relative decay strengths. (c-f) PMDs of residual  $^{54}\text{Ca}$  (c,d) and  $^{53}\text{Ca} + 1n$  (e,f) following  $^{55}\text{Sc}(p, 2p)$  reactions in coincidence with various states. “Inc. unbound” infers the inclusive PMD for unbound states, otherwise labels of (c-f) correspond to (g), which shows the energies, cross sections, and  $J^\pi$  assignments of observed states. Data points in (c-f) are observed and solid curves are predicted by the DWIA for the  $d$ -,  $f$ -, and  $s$ -wave proton removals normalized to experimental cross sections. Where appropriate,  $S_n$  and  $S_{2n}$  [17] values are indicated.

surrounded by a time projection chamber (TPC) situated at the focal plane designated “F13” which is  $\sim 40$  m downstream of the 7<sup>th</sup> focal plane. Surrounding MINOS was the DALI2<sup>+</sup> array of 226 NaI(Tl) crystals [21, 22] for the high-efficiency detection ( $\sim 23\%$  for a 2 MeV  $\gamma$  ray emitted at  $\beta_{\text{ion}} \approx 0.6$ ) of  $\gamma$  rays emitted by excited states populated by secondary reactions. Behind MINOS, reaction residues were identified, as shown in Fig. 1(b), with the SAMURAI spectrometer by their  $B\rho$  through a single dipole magnet, TOF from the target to a hodoscope, and energy loss in the hodoscope [23]. Reaction vertices in the LH<sub>2</sub> target were identified with a precision of  $\sim 2$  mm ( $\sigma$ ) by tracking incoming fragments with beam-line detectors and tracking protons ejected from the target with the surrounding TPC [24]. Fragment velocities at the reaction vertex were reconstructed using the vertex position and velocity measured in SAMURAI. Beam-velocity neutron-detection was realised with NEBULA [23, 25], comprising two assemblies of 60 vertically-aligned  $12 \times 12 \times 180$  cm<sup>3</sup> detectors arranged in a  $2 \times 30$  configuration, and NeuLAND [26], one assembly of  $400 \times 5 \times 5 \times 250$  cm<sup>3</sup> detectors arranged in alternating vertically- and horizontally-aligned planes of 50 detectors. The center of NeuLAND was 11.8 m from the center of the LH<sub>2</sub> target, and the two NEBULA assemblies were at 14.4 and 15.3 m. Neutron energies were calculated from their velocities which were derived from their TOFs and flight paths.

Doppler-corrected  $\gamma$ -ray spectra following the  $^{55}\text{Sc}(p, 2p)$  reaction, Fig. 2(a), show  $\gamma$ -ray peaks at 445(16), 1210(30), 1661(17), and 2021(17) keV, consistent with Ref. [7]. Coincidences between the 2021-keV transition and all others were observed, shown inset of Fig. 2(a), with intensities which imply the level scheme shown in Fig. 2(a). In the coincidence spectrum, an excess of counts appears at  $\sim 560$  keV, with a corresponding excess in the singles spectrum. Assuming this takes the form of a  $\gamma$ -ray transition, a fitted value of 561(19) keV is obtained with a 0.04(2) mb cross section. With a significance of just over  $1\sigma$ , it is not considered in the calculation of other partial cross sections. The strength at  $\sim 300$  keV in the coincidence spectrum is



likely Bremsstrahlung background. The parallel momentum distributions (PMDs) of the reaction products in coincidence with their populated state provides information on the  $\ell$ -value of the removed nucleon. PMDs of  $^{54}\text{Ca}$  nuclei in the ground, Fig. 2(c), and  $(3^-)$ , Fig. 2(d), states were measured with a resolution of  $\sim 34$  MeV/c ( $\sigma$ ) which was inferred from unreacted  $^{55}\text{Sc}$  nuclei [27]. The ground-state PMD is consistent with the removal of an  $f$ -wave proton and the  $(3^-)$  PMD has  $\chi^2/\text{degree of freedom}$  for the  $d$  and  $f$  curves of 0.56 and 0.64, respectively, slightly favoring the removal from a  $d$  orbital. The  $f$ -like PMD of the ground-state population supports previous evidence for a  $J^\pi = 7/2^-$   $^{55}\text{Sc}$  ground-state [28] it almost certainly reflects a valence  $\pi 0f_{7/2}$  orbital. Since the  $2_1^+$  state population is dominated by feeding from the  $(3^-)$  state, its PMD only reflects the  $(3_1^-)$  structure, it can be found with the inclusive PMD in Ref. [27]. From these observations and those in Ref. [7], a  $3_1^-$  state with a  $\pi 0f_{7/2}^{-1} 0d_{3/2}^{-1}$  configuration is suggested for the 3680(20) keV level.

Decays of unbound states of  $^{54}\text{Ca}$ , first inferred through inelastic scattering [9], are shown in the relative energy ( $E_{\text{rel}}$ ) spectrum of  $^{53}\text{Ca}$  and respective emitted neutrons in Fig. 2(b).  $E_{\text{rel}}$  spectra in coincidence with individual states of  $^{53}\text{Ca}$ , so-called exclusive spectra, were used to isolate overlapping peaks and construct the decay scheme shown in Fig. 2(b) [27]. Peaks were fitted with Breit-Wigner distributions [29] folded with experimental responses of the NeuLAND+NEBULA array and beam-line detectors. A low-amplitude background with a shape generated from event-mixing [30, 31] is consistent with a high-statistics study performed with a similar experimental set-up [32]. Transitions strengths at 0.102(21), 0.546(58), and 2.92(12) MeV were identified in coincidence with the  $^{53}\text{Ca}$  ground state, at 0.1013(54), 0.583(13), 1.224(74), and 1.955(45) MeV with the 1738-keV state, and at 0.385(13), 0.672(21), and 1.454(33) MeV with the 2220-keV state. Summing the decay energies with their coincident  $^{53}\text{Ca}$  state energies suggests that the 2.92-, 1.224-, and 0.672-MeV decays depopulate a common state, as do the 1.955- and 1.454-MeV decays. The levels and their cross sections are summarized in Fig. 2(g). An exclusive PMD was extracted for the level strength at 6758 keV, as shown in Fig. 2(f), owing to its  $\sim 3$ -MeV decay being isolated in the  $E_{\text{rel}}$  spectrum of Fig. 2(b), and conforms to a  $d$ -wave proton removal. Other exclusive cross sections do not provide conclusive results. The inclusive PMD for the full  $E_{\text{rel}}$  strength, Fig. 2(e), is consistent with a  $d$ -wave proton removal. Assuming a  $\pi 0d_{3/2}$  proton removal and a  $7/2^-$   $^{55}\text{Sc}$  ground state, as suggested by Fig. 2(c), gives possible  $J^\pi = 2, 3, 4, 5^-$  for the unbound states. Therefore, most observed excited states shown in Fig. 2(g) are likely of  $\pi 0f_{7/2}^{-1} 0d_{3/2}^{-1}$  structure. The relative energy spectrum of  $^{55}\text{Sc}(p, 2p)^{54}\text{Ca}^* \rightarrow ^{52}\text{Ca} + 2n$  has too few statistics for

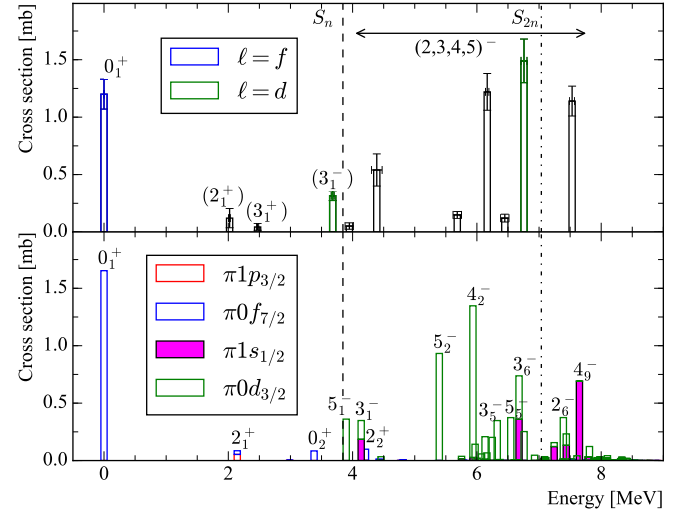


FIG. 3. (Top panel) Below  $S_n$ , the measured cross sections to states from  $\gamma$ -ray spectroscopy are shown. Above  $S_n$ , the population cross sections of the unbound states from invariant mass spectroscopy are shown at the energy centroids of fitted values and likely represent contributions from several states. States with conclusive PMDs are colored accordingly to the  $\ell$ -value of their removed nucleon, otherwise are black. (Bottom panel) Theoretical predictions of state energies and their population cross sections are shown. Contributions to cross sections from proton removals from the different orbitals are indicated. Unlabelled levels have  $J^\pi = 2, 3, 4, 5^-$ .

interpretation.

Figure 2(g) and the upper panel of Fig. 3 summarize measured level energies and population cross sections from this work. Theoretical cross sections and energies are displayed in the lower panel of Fig. 3. Energies were calculated from the conventional shell model using the GXPF1Br interaction in the full  $sd$ - $pf$ - $gds$  model space, including both  $0g_{7/2}$  and  $0g_{9/2}$  orbitals. Cross sections are those of the DWIA single-particle values scaled with spectroscopic factors from the same calculation as used for the energies [27]. Measured cross sections of the  $0_1^+$ , 1.20(13) mb, and  $(2_1^+)$ , 0.121(84) mb, states are reproduced by the calculated, 1.65 mb and 0.086 mb, respectively. Moreover, the measured  $(2_1^+)$  energy is in agreement with theory. Some population of the  $0_2^+$  state is predicted with a cross section consistent with that of the low-significance 561-keV  $\gamma$ -ray candidate, not shown on Fig. 3. To a very good approximation, the predicted  $3_1^+$  at 2.99 MeV has zero cross section, consistent with observation of the  $(3_1^+)$  state at the lower 2.47 MeV. The predicted  $3_1^-$  state is unbound, contrary to observation, however, the measured cross section, 0.316(43) mb, agrees well with the predicted 0.35 mb. It is noteworthy that similar contributions to the  $3_1^-$  state from the  $\pi 1s_{1/2}$ , 0.19 mb, and  $\pi 0d_{3/2}$ , 0.16 mb, orbitals are predicted. The state's experimental PMD shown in Fig. 2(d) does not reflect such a contribution. The inclusive cross

section to bound states was measured to be 1.69(3) mb, close to the predicted 1.83 mb, suggesting little quenching compared to what is expected from such reactions [33]. Above  $S_n$ , it is stressed that whilst the cross sections are indicated at the level energies shown in Fig. 2(g), they are likely distributed across many unresolvable states. Broadly speaking, the location of level strengths are in good agreement with prediction. Between  $S_n$  and  $S_{2n}$  a total level strength of 3.57(30) mb is observed, compared with predicted 5.30, 5.19, 4.87, and 4.75 mb considering the  $dfs$ ,  $ds$ ,  $df$ , and  $d$  contributions, respectively, and subtracting the  $3_1^-$  contribution. Beyond  $S_{2n}$ , within the experimentally sensitive range, 2.12, 2.09, 0.96, and 0.93 mb population strengths are predicted for  $dfs$ ,  $ds$ ,  $df$ , and  $d$  contributions, respectively, compared to a lower limit of  $>1.01$  mb deduced from a 1.14(13) mb strength in the  $1n$  channel. The over-prediction in the range  $S_n < E_{\text{level}} < S_{2n}$  may result from some levels predicted to lie below  $S_{2n}$  in-fact existing beyond it and decaying via  $2n$  emission, since the bound-state decays are well reproduced by the prediction, quenching of spectroscopic factors is unlikely. In addition, it is noted that exclusion of the deeply bound  $\pi 1s_{1/2}$  contribution lowers predicted cross section towards the measured value. As for cross sections of the strengths beyond  $S_{2n}$ , direct comparison to theory is difficult owing to the lack of sensitivity to the  $2n$  decay channel. If the bold assumption is made that the levels observed in the  $^{53}\text{Ca}+1n$   $E_{\text{rel}}$  spectra only decay via  $1n$  emission, excluding the  $\pi 1s_{1/2}$  contribution brings the predicted value to agreement with observation. Proton removal from  $\pi 0d_{3/2}$  dominates the excited states, reflected by the inclusive PMD. Whilst a strong population of the  $4_9^-$  state following  $\pi 1s_{1/2}$  proton removal is predicted it is not observed clearly in any PMD, possibly due to the influence of states populated by  $\pi 0d_{3/2}$  proton removal.

Negligible population of excited states of  $^{54}\text{Ca}$  originates from the proton removal from  $\pi 0f_{7/2}$  in  $^{55}\text{Sc}$ . All excited states are consistent with population from core-proton removals, predominantly from  $\pi 0d_{3/2}$ , and potentially  $\pi 1s_{1/2}$ . These findings are contrary to the analogous case of  $^{25}\text{F}(p, 2p)$  [13], in which valence proton removals preferentially populated excited states of  $^{24}\text{O}$ .

The shell model calculations result in  $0p-0h$  (closed  $N = 34$  shell) contributions of the  $^{55}\text{Sc}$  and  $^{54}\text{Ca}$  ground-state wavefunctions as 64.2% and 89.4%, respectively. The remainder of the contributions are dominated by  $2p-2h$  configurations. Despite this erosion of the  $N = 34$  closure in  $^{55}\text{Sc}$ , which is supported by experiment [34], the spectroscopic factors ( $C^2S$ ) show removal from  $\pi 0f_{7/2}$  mostly populates the ground-state of  $^{54}\text{Ca}$ , as observed experimentally. This can be understood through a simple two-level system of both  $^{55}\text{Sc}$  and  $^{54}\text{Ca}$ . Assuming each

$0h$  ( $\phi_{0p0h}$ ) and  $2p-2h$  ( $\phi_{2p2h}$ ) configurations,

$$\begin{aligned}\Psi(^{55}\text{Sc}) &= \alpha_{0p0h}\phi_{0p0h}(^{55}\text{Sc}) + \alpha_{2p2h}\phi_{2p2h}(^{55}\text{Sc}), \\ \Psi(^{54}\text{Ca}) &= \beta_{0p0h}\phi_{0p0h}(^{54}\text{Ca}) + \beta_{2p2h}\phi_{2p2h}(^{54}\text{Ca}),\end{aligned}$$

where  $\alpha$  and  $\beta$  are real numbers satisfying  $\alpha_{0p0h}^2 + \alpha_{2p2h}^2 = 1$  and  $\beta_{0p0h}^2 + \beta_{2p2h}^2 = 1$ . With vanishing overlaps of  $\phi_{0p0h}$  and  $\phi_{2p2h}$ , the spectroscopic factor to the ground state of  $^{54}\text{Ca}$  can be expressed as,

$$C^2S_{\text{g.s.}} = (\alpha_{0p0h}\beta_{0p0h} + \alpha_{2p2h}\beta_{2p2h})^2. \quad (1)$$

Since pairing forces have a definite sign in their off-diagonal two-body matrix elements, the amplitudes  $\alpha_{2p2h}$  and  $\beta_{2p2h}$  take on the same sign [14]. Therefore,  $\alpha_{2p2h}\beta_{2p2h} > 0$  leading to a large  $C^2S_{\text{g.s.}}$  following the removal of a valence proton. With  $\alpha_{0p0h} = 0.642$ ,  $\beta_{0p0h} = 0.894$ ,  $\alpha_{2p2h} = \sqrt{1 - \alpha_{0p0h}^2}$ , and  $\beta_{2p2h} = \sqrt{1 - \beta_{0p0h}^2}$ , Eq. 1 yields  $C^2S_{\text{g.s.}} = 0.907$ , and from the full calculation, including all other contributions,  $C^2S_{\text{g.s.}} = 0.828$  for the proton removal from  $\pi 0f_{7/2}$ . For the singly-occupied  $\pi 0f_{7/2}$  orbital,  $\sum C^2S \approx 1$ , leaving little remaining spectroscopic strength available to excited states. Therefore, despite the tensor-induced configuration mixing of the  $^{54}\text{Ca}$  core of  $^{55}\text{Sc}$ , conditions resulting from the pairing force lead to dominant ground-state population following valence proton removal.

In conclusion, the ground and excited states of the non-canonical doubly magic  $^{54}\text{Ca}$  have been populated through direct proton-knockout reactions on a  $\text{LH}_2$  target from  $^{55}\text{Sc}$ . Orbital angular momenta of removed protons were inferred through PMDs of reaction residues. The level scheme of  $^{54}\text{Ca}$  [7] was expanded to beyond the  $S_{2n}$  threshold through  $\gamma$ -ray and invariant-mass spectroscopy. The latter being for the first time applied to such a heavy neutron-rich system. All observed excited states populated through the  $^{55}\text{Sc}(p, 2p)$  reaction were attributed to removal of protons from the  $^{54}\text{Ca}$  core. Valence-proton removals populated predominantly the ground-state of  $^{54}\text{Ca}$  despite significant neutron-excitation amplitudes in the ground-state configuration of  $^{55}\text{Sc}$ . The reasoning behind this was the constructive effects from the pairing interaction on the ground state spectroscopic factor, exhausting the strength available to excited states. Considering the ubiquity of the pairing interaction, it is interesting this effect is seemingly overridden by tensor forces in the  $^{25}\text{F}(p, 2p)$  case [13]. It is noteworthy that the experiment carried out in Ref. [13] did not have beam-velocity neutron-detection capability. An experiment similar to the one reported here would enable the population of individual unbound states of  $^{24}\text{O}$  to be quantitatively studied, leading to a more robust comparison to the predicted spectroscopic factors. With such information, the interplay of the tensor and pairing interactions in direct reactions could be consolidated.

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