

Spectroscopy of excited neutron configurations of ^{54}Ca

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Despite its nucleon numbers not coinciding with the traditional nuclear magic numbers, the structure of ^{54}Ca shows signatures of a doubly closed shell nucleus. This article details the structures of neutron-excited states up to beyond the two-neutron emission threshold populated by the $^{55}\text{Ca}(p, pn)$ reaction at ~ 200 MeV/nucleon. Level energies and population cross sections were determined through γ -ray spectroscopy and invariant-mass spectroscopy of ^{54}Ca . Large-scale shell model calculations with protons and neutrons allowed to occupy the sd - pf - sdg orbitals were performed to predict energy levels and spectroscopic factors. Distorted wave impulse approximation calculations provided single-particle knockout cross sections and momentum distributions of the reaction products. The theoretical calculations reproduce the data well. Both theory and experiment are suggestive of a well-preserved shell structure at high excitation energy. Also, inelastic scattering of ^{54}Ca , carried out within the same experiment, validates previously proposed level schemes.

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I. INTRODUCTION

Since its conception, the nuclear shell model has been a foundation upon which the modern understanding of the structure of atomic nuclei has been built. The ingredients of the effective valence-space shell model are the single-particle energies (SPEs) and the residual interaction among nucleons within the considered valence space. Effective single-particle energies (ESPEs) evolve from the underlying nucleon-nucleon (NN) interaction and depend on the orbital occupancies, and are therefore known to migrate across the nuclear chart [1].

Large gaps between the ESPEs are often referred to as shell closures. These shells are typically referred to by the spectroscopic labels of the angular momentum of the nucleons that comprise the shell. The fp -shell comprises the valence neutron shell of ^{48}Ca with the $\nu(\text{neutron})0f_{7/2}$, $\nu 0f_{5/2}$, $\nu 1p_{3/2}$, and $\nu 1p_{1/2}$ orbitals.

In stable nuclei the neutron ESPEs of the $0f_{5/2}$, $1p_{3/2}$, and $1p_{1/2}$ orbitals are closely spaced owing to the tensor-force-driven attraction between the $\pi(\text{proton})0f_{7/2}$ and $\nu 0f_{5/2}$ orbitals [2]. In the neutron-rich Ca isotopes, the absence of $\pi 0f_{7/2}$ occupation leads to a substantial migration of the $\nu 0f_{5/2}$ orbital resulting in large gaps between $\nu 1p_{3/2}$, $\nu 1p_{1/2}$, and $\nu 0f_{5/2}$, leading to the formation of the noncanonical $N = 32$ and 34 shell closures.

The shell closures at $N = 32$ and 34 have been verified through a variety of experimental techniques, including γ -ray spectroscopy [3–5], mass measurements [6,7], reaction studies [8–10], and from β -decay half-lives [11,12]. Conversely, an unclear situation emerges from charge radii measurements of Ca isotopes, where a smooth increase is measured up to $N = 32$, contrary to the expected discontinuity for a shell closure [13]. Explorations above the $N = 34$ shell closure are now being driven by increasing primary beam intensities at existing and newly commissioned radioactive isotope (RI) beam facilities.

Spectroscopy of ^{55}Ca following neutron knockout of ^{56}Ca indicates the latter's two valence neutrons occupy the $\nu 0f_{5/2}$ orbital and the former has an excited state dominated by a hole in the $\nu 1p_{1/2}$ orbital [14]. In the same work, spectroscopy of ^{57}Ca indicates a more collective structure. Deeply bound hole states of ^{55}Ca show a remarkable preservation of shell structure below $N = 34$ consistent with large gaps between

the $\nu 0f_{7/2} - \nu 1p_{3/2}$ and $\nu 1p_{3/2} - \nu 1p_{1/2}$ ESPEs, reflecting the $N = 28$ and $N = 32$ shell gaps, respectively [15]. The energies of the tentatively assigned 2_1^+ states of $^{56,58}\text{Ca}$ were interpreted through shell model calculations using the A3DA-t interaction [16]. It was found that to reproduce the experimental energies, a valence space beyond the $N = 34$ shell closure, which includes at least the $\nu 0g_{9/2}$ orbital nearly degenerate with the $\nu 0f_{5/2}$ is required [16].

Experimental capabilities preclude, for now, measurement of nuclear structure of $A > 58$ Ca isotopes, with the discovery of ^{59}Ca and ^{60}Ca being made with only nine and two counts, respectively [17]. Novel theoretical extrapolations based on different Hamiltonians, however, are able to predict properties of these isotopes. A notable friction between the predictions lies in the magic nature of ^{60}Ca , for example, the A3DA-m and LNPS interactions predict a nonmagic character [16,18,19], while the novel data-driven UFP-CA interaction predicts a magic character [20]. Experimentally, the indicators of magicity in ^{60}Ca are sparse, with the spectroscopy of its so-far closest isotone, ^{62}Ti , and isotope, ^{58}Ca , showing no evidence of an $N = 40$ shell closure [16,21].

The present work is motivated by the expansion of spectroscopic information of ^{54}Ca and to further interrogate its magic nature. To this end, results from two reaction channels are presented, the quasifree neutron knockout from ^{55}Ca into the ground and excited states of ^{54}Ca , and the inelastic scattering of ^{54}Ca . The former provides a detailed view of neutron-hole states up to beyond the two-neutron emission threshold, complementing the proton-hole states measured in Ref. [22], and the latter providing confirmation of the γ -ray decays proposed in Refs. [4,22].

Spectroscopy of bound and unbound states was performed through γ -ray and invariant-mass measurements, respectively. Experimental results are compared to shell model calculations employing the GXPF1Br effective interaction tailored to ^{54}Ca [4], which provide excited state energies and spectroscopic factors between ^{55}Ca and ^{54}Ca . Calculations employing the distorted-wave impulse approximation (DWIA) reaction model provided parallel momentum distributions (PMDs) and single-particle cross sections [23]. The former providing spin constraints of populated states when compared to experimental PMDs, and the latter, when multiplied with spectroscopic factors, give predicted exclusive reaction cross sections.

II. EXPERIMENTAL DETAILS

The experiment was performed at the Radioactive Isotope Beam Factory (RIBF), RIKEN, operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. A series of coupled cyclotrons [24] accelerated a primary beam of ^{70}Zn of intensity 240 pA to an energy of 345 MeV/nucleon. This beam was fragmented upon its collision with ^9Be nuclei, which formed a rotating target wheel situated at the entrance of the BigRIPS fragment separator [25]. The cocktail of fragments was separated based on their magnetic rigidity ($B\rho$) and energy loss through a wedge-shaped degrader at a dispersive focal plane. Selected isotopes were identified on an event-by-event basis according to the prescription in Ref. [26] resulting in clear separation of atomic number (Z) and mass-to-charge ratio (A/Q). Following their secondary reactions on a thick liquid-hydrogen (LH_2) target, ejectile nuclei were identified, again, according to their A/Q and Z , in the SAMURAI spectrometer and associated detector equipment [27]. The resultant particle-identification plots from both BigRIPS and SAMURAI are shown in Fig. 1 of Ref. [22]. In the secondary beam, an average of 0.8 ions of ^{55}Ca per second were detected.

Neutron-knockout and inelastic-scattering reactions were made on a LH_2 target of thickness 150(1) mm, which was surrounded by a time-projection chamber (TPC) to detect recoil protons from quasifree scattering reactions. The reaction position, for neutron knockout, within the target was constrained with a precision of around 2 mm (σ) through locating where the recoiling proton's trajectory intersected with the ion's trajectory, which was determined by beamline detectors. This LH_2 -TPC assembly was collectively known as MINOS [28], and had about 70% proton-detection efficiency for (p , pn) reactions. While also capable of detecting inelastically scattered protons from the target, the detection efficiency is difficult to characterize, but is of the order of 10%.

Decays of particle-bound states were inferred through measurement of their decay via γ -ray emission detected by the DALI2⁺ array of 226 NaI(Tl) detectors [29,30]. An add back algorithm was implemented to counteract Compton scattering of γ rays between crystals, where energies recorded in detectors within 15 cm of the one with the largest energy deposition were summed. An energy calibration of the array was performed using well-characterized ^{88}Y , ^{60}Co , ^{133}Ba , and ^{137}Cs γ -ray sources. The calibration measurements were also used to verify a GEANT4 [31] simulation which was used to create the detector response functions of the γ rays emitted from ions of interest, which traveled at around $0.6c$. Simulated full-energy peak efficiencies for in-flight sources of 0.5 and 2 MeV, with add back applied, were 46% and 23%, respectively. For stationary source measurements, the relative agreement of efficiency with the simulation was $\sim 5\%$.

Knockout from deeply bound orbitals resulted in excitations beyond the neutron emission threshold. In these cases, the excitation energy of the populated state was reconstructed following the invariant-mass spectroscopy of the residual nucleus and the emitted neutron(s), in the present case, $^{53}\text{Ca} + n$ ($^{52}\text{Ca} + 2n$). The summed relative energy of the $^{53}\text{Ca} + n$ ($^{52}\text{Ca} + 2n$) system and the (two) neutron-separation energy,

$S_n = 3844(65)$ keV ($S_{2n} = 7037(48)$ keV) [6], gave the energy of the excited state. The energy of ^{53}Ca (^{52}Ca) ions were derived from their velocity reconstructed from their measured $B\rho$ value through the SAMURAI dipole magnet and calculated back to the reaction position reconstructed by MINOS, taking into account the energy loss in the target and beam-line detectors. Momenta of neutrons were measured from their time of flight and interaction positions between the MINOS target and the neutron wall situated ~ 11 m downstream and comprising the NeuLAND demonstrator [32], with 400 plastic scintillator bars of $5 \times 5 \times 250 \text{ cm}^3$ spread over eight layers, and NEBULA [27,33], with 120 $12 \times 12 \times 180 \text{ cm}^3$ scintillators. Measured timing and energy resolutions of detector components were incorporated into a GEANT4 simulation, which propagated position uncertainties, in order to generate realistic neutron-plus-fragment responses.

III. THEORETICAL MODELS

The results of the experiment are interpreted through comparison with the DWIA reaction model and nuclear shell model calculations employing the GXPFI1Br interaction Hamiltonian for the pf -shell part.

The GXPFI1 family of effective interactions has a rich history in describing the pf -shell region, including predicting the magic character of ^{54}Ca [34,35]. In the present work, shell model calculations were carried out on the basis of the GXPFI1Br interaction. To describe unnatural-parity states, the valence shell was extended to the sd - pf - sdg shell, in which 1 $\hbar\omega$ excitation was allowed. The pf -shell interaction was taken from GXPFI1Br; see Refs. [4,36] for more details of the interaction. The calculations were performed using the KSHELL computer code [37].

To model the quasifree scattering of the target proton with the projectile-bound nucleon an implementation of the DWIA is employed [23]. Inputs to the DWIA calculations are the NN effective interactions, nucleus-nucleon optical potentials, and the single-particle wave functions of the bound nucleon orbitals, which are the same as those described in Ref. [9]. The single-particle cross sections and the PMDs of the ejectile, which reflect the angular momentum of the removed nucleon, were calculated using the PIKOE code [38].

IV. RESULTS

The proton-knockout channel of Ref. [22] probed the negative-parity proton-hole states built mostly from the $(\pi 0f_{7/2})^1(\pi 0d_{3/2})^{-1}$ configuration. In the present work, positive-parity states formed from a particle in the $\nu 0f_{5/2}$ orbital and holes in the $\nu 1p_{1/2}$, $\nu 1p_{3/2}$, or $\nu 0f_{7/2}$ orbitals are populated through neutron-knockout reactions on ^{55}Ca . Moreover, the inelastic scattering channel has been investigated. The inelastic scattering reaction has a higher cross section and less background associated with recoiling protons as compared to the (p , $2p$) reaction reported in Ref. [22], thus providing reliable γ -ray coincidence data to verify the level schemes so far proposed.

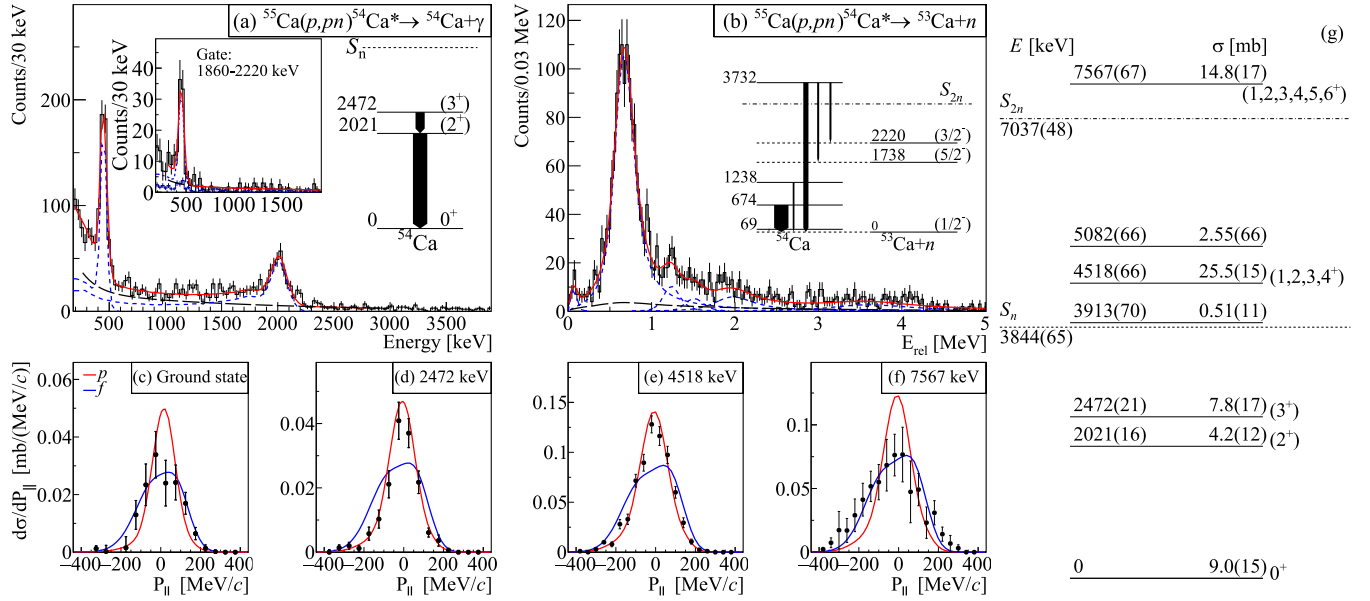


FIG. 1. (a) Doppler-corrected γ -ray spectrum of the $^{55}\text{Ca}(p, pn)^{54}\text{Ca}^* \rightarrow ^{54}\text{Ca} + \gamma$. The total fit function (red line) comprises simulated response functions of DALI2⁺ (blue short-dashed lines) and a double-exponential background (long-dashed line). The inset spectrum is that in coincidence with the 2021-keV transition, where the blue dashed line is the intensity-fixed response assuming the shown level scheme. Arrow widths on the level scheme represent relative γ -ray intensities. (b) Relative energy spectrum of $^{55}\text{Ca}(p, pn)^{54}\text{Ca}^* \rightarrow ^{53}\text{Ca} + n$. 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 nonresonant background (long-dashed line). Inset is the decay scheme to ^{53}Ca , energies are with respect to the ^{53}Ca ground-state energy and arrow widths are relative decay strengths. (c)–(f) Parallel momentum distributions of residual ^{54}Ca (c) and (d) and $^{53}\text{Ca} + n$ (e) and (f) following $^{55}\text{Ca}(p, pn)$ reactions in coincidence with various states. Labels of (c)–(f) correspond to (g), which shows the energies and cross sections of all observed states/strengths. Data points in (c)–(f) are observed and solid curves are predicted by the DWIA for the p - and f -wave neutron removals normalized to experimental cross sections. Where appropriate S_n and S_{2n} [6] values are indicated.

A. $^{55}\text{Ca}(p, pn)$

Figure 1 details the decays of the states populated in the $^{55}\text{Ca}(p, pn)$ reaction. The Doppler-corrected γ -ray spectrum, Fig. 1(a), shows two coincident γ -ray transitions with energies of 2021(16) and 451(14) keV. The energy of the 2021-keV transition is in agreement with previous measurements, 2021(17) keV [22] and 2043(19) keV [4]. The energy of the 451-keV transition is consistent with the 445(16)-keV transition measured in Ref. [22] and similar to a tentatively observed transition at ~ 472 keV in Ref. [4]. The strength of the 451-keV transition in the spectrum coincident with the 2021-keV energy peak is consistent with a direct 451 keV $\rightarrow$ 2021 keV cascade. Their relative γ -ray intensities are $I_\gamma(451) = 65(6)$ and $I_\gamma(2021) = 100(9)$.

Parallel momentum distributions associated with residual ^{54}Ca nuclei were measured with a resolution (σ) of ~ 38 MeV/ c , as determined by the unreacted ^{55}Ca nuclei. As in Ref. [9], a component of ^{55}Ca inelastic excitation followed by neutron evaporation was accounted for by subtracting contributions to the PMDs in coincidence with beam-velocity neutrons. The experimental PMD in coincidence with the population of the ground-state, Fig. 1(c), is consistent with the removal of an f -wave neutron, according to the comparison with the DWIA calculations, while the (PMD) coincident with the 2472-keV level, Fig. 1(d), supports the removal of a p -wave neutron. Assignment of f - or p -wave neutron removal cannot be made for the 2021-keV level owing to the strong

feeding from the 2472-keV level. These observations provide evidence, in addition to β -decay [39] and γ -ray [14] studies of ^{55}Ca , that the valence-neutron of ^{55}Ca predominantly occupies the $\nu 0f_{5/2}$ orbital. Moreover, the PMDs provide experimental evidence that the bound excited states have a $(\nu 0f_{5/2})^1(1p_{1/2})^{-1}$ structure. A $(\nu 0f_{5/2})^1(1p_{3/2})^{-1}$ configuration, discussed below, is excluded as its associated energies are expected to be higher in energy.

Six decays of unbound states were identified in the relative energy (E_{rel}) spectrum of $^{53}\text{Ca} + n$ following the $^{55}\text{Ca}(p, pn)$ reaction, as shown in Fig. 1(b). Contrary to the unbound states populated in the $^{55}\text{Sc}(p, 2p)$ reaction [22], the relatively low density of strengths to unbound states in the $^{55}\text{Ca}(p, pn)$ reaction allow for fitting the inclusive spectrum, i.e., no condition placed on the populated state of ^{53}Ca , as shown in Fig. 1(b). It shows clearly a narrow peak at $E_{\text{rel}} < 0.1$ MeV, a dominant peak at around 0.7 MeV, a relatively sharp peak at ~ 1.3 MeV, two proximal peaks at 1.5–2 MeV, and then a broad strength from 3 to 5 MeV. The level scheme shown in Fig. 1(b) was derived using coincidences of peaks in the E_{rel} spectrum with excited and ground states of ^{53}Ca , which are given in the Supplemental Material [40]. Parallel momentum distributions in coincidence with the 4518- and 7567-keV strengths, Fig. 1(e) and 1(f), respectively, show their population proceeds via p - and f -wave neutron removals. This suggests the 4518-keV strength was performed from states with J^π in the range 1, 2, 3, 4⁺ from the $\nu(0f_{5/2})^1(1p_{3/2})^{-1}$

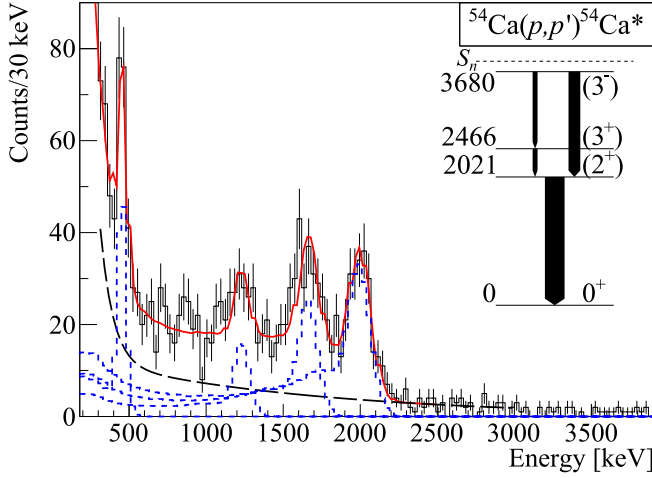


FIG. 2. Spectrum measured in coincidence with the inelastic scattering channel of ^{54}Ca . Lines have the same meaning as Fig. 1(a). The energies of the level scheme are taken from Ref. [22] for ease of comparison.

configuration and the 7567-keV strength having states with J^π in the range 1, 2, 3, 4, 5, 6^+ from the $\nu(0f_{5/2})^{-1}(0f_{7/2})^{-1}$ couplings. Low statistics for the other states do not allow for conclusive assignments from PMDs. Full details of the fitted peaks and the observed $E_{\text{rel}}(^{52}\text{Ca} + 2n)$ spectrum are given in the Supplemental Material [40].

B. $^{54}\text{Ca}(p, p')^{54}\text{Ca}$

Figure 2 shows the singles spectrum associated with the $^{54}\text{Ca}(p, p')$ reaction. Energies of the transitions were extracted to be 2010(11), 1669(19), 1234(17), and 445(5) keV, in agreement with previously obtained values. Table I lists the γ -ray energies and intensities observed from four reactions populating bound states of ^{54}Ca : $^{55}\text{Ca}(p, pn)$, $^{55}\text{Sc}(p, 2p)$ [22], $^{54}\text{Ca}(p, p')$, and $^{55}\text{Ca}(p, p')^{55}\text{Ca}^* \rightarrow ^{54}\text{Ca} + n$ [15]. The $^{55}\text{Ca}(p, pn)$ reaction shows no appreciable population of the (3^-) state in ^{54}Ca , as deduced from the nonobservation of the 1210 and 1661 keV transitions. When these transitions are present, their intensity ratios are consistent within uncertainties, as can be verified from Table I. This is in line with the expectation that they depopulate the same state. Coincidences

TABLE I. Comparison of measured γ -ray intensities from different reaction channels. Values from the $^{55}\text{Sc}(p, 2p)$ reaction are taken from Ref. [22] and those in the final column from Ref. [15]. Energy values of γ -ray transitions from Ref. [22] are used.

E_γ [keV]	I_γ			$^{55}\text{Ca}^* \rightarrow ^{54}\text{Ca} + n$
	$(p, 2p)$	(p, p')	(p, pn)	
445	32(4)	25(5)	65(6)	71(18)
1210	14(5)	27(6)		27(18)
1661	46(7)	60(9)		56(23)
2021	100(10)	100(11)	100(9)	100(31)

TABLE II. Excitation energies (E_{level} in MeV) of states in ^{54}Ca along with their spectroscopic factors with ^{55}Ca from the GXPF1Br calculation. The ruled lines represent the locations of S_n and S_{2n} values. Only levels with $\sigma_{\text{th}} > 0.5$ mb are shown, a more complete listing is given in the Supplemental Material [40].

J^π	E_{level}	C^2S				σ_{th} [mb]
		$\nu p_{1/2}$	$\nu p_{3/2}$	$\nu f_{5/2}$	$\nu f_{7/2}$	
0^+	0			0.95		5.14
2^+	2.14	0.78	0.00	0.00	0.00	7.50
3^+	2.99	1.05	0.04	0.01	0.00	10.44
4^+	4.43		0.10	0.07	0.00	1.40
3^+	4.77	0.04	1.03	0.00	0.00	10.65
2^+	4.81	0.00	0.68	0.01	0.00	6.80
4^+	4.81		1.24	0.01	0.02	12.46
1^+	5.38		0.36	0.00	0.00	3.66
1^+	6.46		0.08	0.00	0.00	0.77
4^+	6.47		0.05	0.00	0.01	0.58
2^+	6.63	0.00	0.05	0.00	0.00	0.51
4^+	7.54		0.01	0.00	1.12	4.50
5^+	7.69			0.00	0.85	3.36
5^+	7.73			0.00	0.91	3.57
4^+	7.76		0.02	0.01	0.24	1.12
6^+	8.10				1.97	7.68
3^+	8.13	0.00	0.00	0.00	0.93	3.66
2^+	8.33	0.00	0.00	0.00	0.53	2.08
2^+	8.54	0.00	0.00	0.00	0.22	0.85
1^+	9.81		0.00	0.00	0.33	1.25

supporting the proposed level schemes are presented in the Supplemental Material [40].

V. DISCUSSION

Table II and the bottom of Fig. 3 present the results from the DWIA and shell model calculations for positive-parity states of ^{54}Ca up to 10 MeV. Exclusive cross sections are the product of the DWIA single-particle cross sections with the shell model spectroscopic factors. Systematic uncertainties in the cross section values given by the DWIA arise through calculation of the single-particle wave functions and treatments of scattering amplitudes, which amount to 15% [23]. In the present work, as in Ref. [15], quenching factors of predicted strengths, as discussed in detail in Ref. [41], are not applied. The DWIA cross sections were calculated between 160 and 280 MeV/nucleon at intervals of 10 MeV/nucleon, these were translated to their corresponding interaction positions in the LH_2 target and averaged over the length of the target according to the measured reaction position distribution.

Figure 3 and Table II, show populated states are predicted to be well isolated in energy corresponding to the $\nu 1p_{1/2}$, $\nu 1p_{3/2}$, $\nu 1f_{5/2}$, and $\nu 0f_{7/2}$ hole states. A similar pattern is observed from experiment, shown in the upper panel of Fig. 3 where it should be noted that the bars for the unbound states can represent the contributions from several calculated states. All calculated energies agree reasonably with observation. The measured cross sections of the 0^+ , 9.0(15) mb, and (2^+) ,

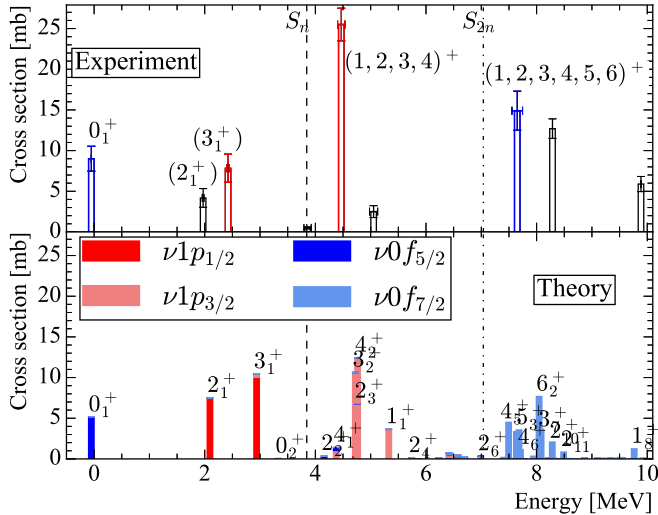


FIG. 3. (Top) Measured cross sections to states of ^{54}Ca from neutron knockout of ^{55}Ca . Bars are drawn at the energy centroids of fitted values and, for the case of the unbound strengths, likely represent contributions from many closely spaced states. Red and blue bars indicate knockout from p and f orbitals, respectively, could be assigned from PMDs, whereas black bars indicate no assignment was possible. (Bottom) Theoretical predictions of state energies and their population cross sections from (p, pn) reactions are shown. The red and blue colored bars indicate contributions predicted from p - and f -orbital knockout, respectively, with the different shades differentiating between the spin-orbit partners.

4.2(12) mb, states show deviations ($\sim 2\sigma$) from the predicted 5.14(77) mb and 7.5(11) mb, respectively, albeit with large uncertainties. The strength to the ground state is underpredicted, while the 2_1^+ cross section is overpredicted. The measured cross section for the (3_1^+) state, 7.8(17) mb, compares more favorably to the predicted 10.4(16) mb with a tension of $\sim 1\sigma$. Studies of other knockout reactions from Ca isotopes from the same experiment, also report an underestimation of ground-state population cross section of $\sim 80\%$ [9,10]. They also report a slight overprediction to excited states, similar to the current work. In the proton knockout from Ca isotopes, there is a better agreement between experiment and theory, with a slight overprediction of cross sections being the general trend [14,42]. In Ref [43], which reports the $^{51}\text{Ar}(p, pn)$ reaction, an underprediction of the reaction cross section of the 0_1^+ is also observed.

The measured cross section of the strength just above S_n is 0.51(11) mb, consistent only considering the contribution of the 2_2^+ state, 0.357(54) mb, but becomes too low when including the 1.40(21) mb of the 4_1^+ state. The dominant strength at ~ 4.5 MeV was measured to have a cross section of 25.5(15) mb, in fair agreement with the predicted summed cross section, 29.9(27) mb, of the predicted 2_3^+ , 3_2^+ , and 4_2^+ states, with cross sections of 6.8(10), 10.7(16), and 12.5(19) mb, respectively. As for the state at about 5 MeV, the measured energy of 5.082(66) MeV and cross section of 2.55(66) mb are in reasonable agreement with predicted the 1_1^+ state, 5.38 MeV and 3.66(55) mb, respectively.

Beyond S_{2n} , the cross section measured in the one-neutron-emission channel was 14.8(17) mb, approximately half the predicted 25.8(24) mb. Depending on the strategy used to derive the total strength present in the two-neutron-emission channel, detailed in the Supplemental Material [40], values between ~ 18 and 30 mb are obtained. The larger end of this range may reflect the inclusion of more deeply bound knockout states and/or a systematic underprediction of the background. However, the observed strength still reflects a fully occupied $0f_{7/2}$ orbital in ^{55}Ca , which is consistent with $^{54,56}\text{Ca}$ [15]. In ^{50}Ca , with two valence neutrons in the $\nu 1p_{3/2}$ orbital above the $N = 28$ shell closure, approximately half the expected strength from $0f_{7/2}$ removal was observed [44].

To summarize, observed energies and overall population cross sections of states up to 10 MeV broadly agree with predictions from the shell model using the GXPF1Br Hamiltonian and DWIA calculations. The 3_1^+ and 2_1^+ states are experimentally suggested to be populated from neutron knockout reactions which form the $(\nu 0f_{5/2})^1(\nu 1p_{1/2})^{-1}$ configuration. States between S_n and S_{2n} are associated with the $J^\pi = 1, 2, 3, 4^+$ multiplet formed from the $(\nu 0f_{5/2})^1(\nu 1p_{3/2})^{-1}$ configuration. The GXPF1Br predicts closely spaced 2, 3, 4 $^+$ states with an isolated 1^+ state, which appears consistent with observation, see Fig. 3. Beyond S_{2n} , the GXPF1Br predicts strength originating from the removal of the $0f_{7/2}$. Given the PMD of Fig. 1(f), this is reflected in the experimental results for the one-neutron-emission channel.

It is evident from Fig. 3 that the strengths populated from specific nucleon orbitals are well localized. As in Ref. [15], this is indicative of a preservation of shell structure for the very deeply bound orbitals, with the $N = 28$ ($0f_{7/2} - 1p_{3/2}$), 32 ($1p_{3/2} - 1p_{1/2}$), and 34 ($1p_{1/2} - 0f_{5/2}$) shell closures. The energy spacing between these groupings in Fig. 3 are ~ 3 MeV, ~ 2 MeV, and ~ 2 MeV, respectively, which reflect, but are not equivalent to, the ESPEs gaps predicted by the GXPF1Br interaction.

VI. CONCLUSION

The neutron-excited states of ^{54}Ca have been investigated by the direct $^{55}\text{Ca}(p, pn)$ reaction. These data, along with those of Ref. [22] provide a comprehensive survey of the excited states of the noncanonically doubly magic nucleus. Parallel momentum distributions were used to identify the origin of ground and excited states, with the population patterns well reproduced by the combination of shell model calculations using the GXPF1Br interaction and DWIA calculations. In addition, inelastic scattering data were used to solidify the bound state level scheme of ^{54}Ca .

Experimentally supported, if not firmly assigned, spin-parities of newly and previously observed states will provide useful inputs to data-driven interactions such as those in Ref. [20]. Moreover, they will prove valuable benchmarks when judging the predictive powers of *ab initio* theories, such as those presented in Refs. [45–47]. Agreement between the predicted energies and population strengths in both this work and of Ref. [22] with the GXPF1Br interaction, which assumes a robust $N = 34$ shell closure provides a further piece of evidence as to the double magicity of ^{54}Ca .

Notably absent from previous and current spectroscopy of ^{54}Ca is an observation of the 0_2^+ state, which informs on the correlations present in the gds ($N > 34$) shell. Depending on its location, its decay via γ -ray emission may be forbidden, making missing-mass spectroscopy a promising detection method. High-resolution in-beam γ -ray spectroscopy may provide valuable feedback to the lifetimes of states, and therefore transition probabilities between excited states as a further constraint to theoretical predictions.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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