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Extended  $p_{3/2}$  Neutron Orbital and the  $N = 32$  Shell Closure in  $^{52}\text{Ca}$ 

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The one-neutron knockout from  $^{52}\text{Ca}$  in inverse kinematics onto a proton target was performed at  $\sim 230$  MeV/nucleon combined with prompt  $\gamma$  spectroscopy. Exclusive quasifree scattering cross sections to bound states in  $^{51}\text{Ca}$  and the momentum distributions corresponding to the removal of  $1f_{7/2}$  and  $2p_{3/2}$  neutrons were measured. The cross sections, interpreted within the distorted-wave impulse approximation reaction framework, are consistent with a shell closure at the neutron number  $N = 32$ , found as strong as at  $N = 28$  and  $N = 34$  in Ca isotopes from the same observables. The analysis of the momentum distributions leads to a difference of the root-mean-square radii of the neutron  $1f_{7/2}$  and  $2p_{3/2}$  orbitals of 0.61(23) fm, in agreement with the modified-shell-model prediction of 0.7 fm suggesting that the large root-mean-square radius of the  $2p_{3/2}$  orbital in neutron-rich Ca isotopes is responsible for the unexpected linear increase of the charge radius with the neutron number.

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Atomic nuclei can be described as neutrons and protons bound in a self-induced attractive mean field [1]. In the shell-model picture, they occupy discrete energy levels, grouped into shells, while interacting with each other via nuclear residual interactions. Particularly stable configurations appear for full shells, associated to the so-called magic numbers of nucleons. The relative energies of single-particle orbitals are dynamic over the nuclear chart, driven by the monopole part of the residual interaction [2,3]. Far from stability the shell closures can disappear or weaken, e.g., at the neutron numbers  $N = 8, 20$ , and  $28$  [4–8], and new magic numbers can emerge. In the neutron-rich  $pf$ -shell nuclei, new shell closures at  $N = 32$  and  $34$  were revealed, corresponding to the filling of the  $2p_{1/2}$  and  $2p_{3/2}$  neutron orbitals, respectively. The  $N = 32$  shell closure in neutron-rich nuclei was claimed from a series of observations relying on first  $2^+$  excitation-energy [9–14], transition-probability [15,16], and mass measurements [17–20], correspondingly the  $N = 34$  shell closure from  $E(2^+)$  [21,22], mass [23], and neutron knockout cross-section [24] measurements. On the other hand, recent measurements along the Ca and K isotopic chains reveal an increase of the charge radii with a slope larger than expected from  $N = 28$  to  $N = 32$  and  $33$ , respectively, and with no local minimum or inflection at  $N = 32$ , which is usually considered as a sign of a neutron shell closure [25–27]. This observation, not quantitatively reproduced by microscopic theories, was interpreted as challenging the doubly closed-shell character of  $^{52}\text{Ca}$ . An erosion of the proton shell closure is not supported by spectroscopic experiments [28,29], while the connection between charge radii evolution and the strength of a neutron shell closure has been recently questioned [30]. As an alternative interpretation, an effective increase in size of shell-model valence  $p$ -wave neutron orbitals influencing the proton radial extension has been proposed to reproduce the observed increase of charge radii of Ca isotopes, while maintaining the doubly magic character of  $^{52}\text{Ca}$  [31]. A sizable difference of 0.7 fm was predicted between the root-mean-square (rms) radius of the  $2p_{3/2}$  and the  $1f_{7/2}$  neutron orbitals, in qualitative agreement with the matter radius trend of  $^{49-51}\text{Ca}$  isotopes extracted from interaction cross sections [32].

In this Letter, we address the neutron shell closure of  $^{52}\text{Ca}$  from direct neutron knockout ( $p, pn$ ) and we provide a first determination of the spatial extension of the  $1f_{7/2}$  and  $2p_{3/2}$  neutron orbitals.

The experiment was performed at the Radioactive Isotope Beam Factory of RIKEN, operated jointly by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. A 240-pnA  $^{70}\text{Zn}$  primary beam at 345 MeV/nucleon impinged on a 10-mm-thick Be target for the production of the secondary cocktail beam. The beam-particle identification was done event by event using the BigRIPS separator [33] via magnetic-rigidity ( $B\rho$ ), energy-loss ( $\Delta E$ ), and time-of-flight (TOF) measurements [34]. The  $^{52}\text{Ca}$  particles were produced with a mean intensity of 4.4 particles per second (2.3% purity).

The ( $p, pn$ ) reaction was measured at the SAMURAI setup [35] using MINOS [36] and DALI2<sup>+</sup> [37]. MINOS was composed of a 151(1) mm liquid-hydrogen target with a density of 73 mg/cm<sup>3</sup> surrounded by a 300-mm-long time projection chamber allowing a reaction vertex reconstruction with a resolution of 5 mm full-width-at-half-maximum (FWHM) [38]. The prompt  $\gamma$  rays from the deexcitation of the  $^{51}\text{Ca}$  fragments were measured with DALI2<sup>+</sup>, a high-efficiency array of 226 NaI(Tl) scintillation detectors surrounding MINOS and covering angles between 15° and 118° with respect to the target center. The response functions of DALI2<sup>+</sup> for  $\gamma$ -ray-source and in-beam measurements were simulated with the GEANT4 toolkit [39]. The relative agreement between the simulated and measured  $\gamma$ -ray-source efficiencies is within 5%. The reaction fragments were analyzed by the large acceptance 2.7-T SAMURAI spectrometer. The fragment-particle identification was done by trajectory reconstruction using two multiwire drift chambers placed upstream and downstream of SAMURAI for the magnetic rigidity information, while the TOF and  $\Delta E$  were provided by a 24 plastic scintillator-bar hodoscope for the fragment velocity and atomic number ( $Z$ ) determination. A particle identification with  $4.8$  ( $7.2$ ) $\sigma$  separation in  $Z$  and  $31$  ( $8.1$ ) $\sigma$  separation in  $A/Q$  was achieved for the beam (fragmentlike) Ca isotopes. The  $^{52}\text{Ca}$  beam particles had a kinetic energy at the reaction

vertex between 190 and 270 MeV/nucleon with a mid-target energy of  $\sim 230$  MeV/nucleon. The  $(p, pn)$  reaction channel was tagged by gating on  $^{52}\text{Ca}$  in BigRIPS, a high-momentum-transfer proton in MINOS, and  $^{51}\text{Ca}$  in SAMURAI, in coincidence. A total of 37 000 such events were recorded. The detection efficiency of MINOS for  $^{52}\text{Ca}(p, pn)^{51}\text{Ca}$  was 65(3)%, obtained from experimental data as in [38]. Two plastic scintillator arrays, the NeuLAND [40] demonstrator and NEBULA [41], were placed after the SAMURAI magnet for neutron detection. The kinematics of the high-momentum transfer  $(p, pn)$  quasifree scattering reaction leads to neutrons recoiling at large scattering angles mainly outside the neutron detectors' acceptance. On the other hand, events of proton inelastic scattering followed by neutron evaporation,  $^{52}\text{Ca}(p, p')^{52}\text{Ca}^* \rightarrow ^{51}\text{Ca} + n$ , [ $S_n(^{52}\text{Ca}) = 6.005(1)$  MeV [42]] could be detected. These events were subtracted after efficiency correction to extract quasifree scattering cross sections. The efficiency correction was applied as a function of the relative energy of  $(^{51}\text{Ca} + n)$  leading to a mean neutron detection efficiency of 32(4)%.

The Doppler-shift corrected  $\gamma$ -ray spectrum obtained from the deexcitation of the  $^{51}\text{Ca}$  reaction residues is shown in Fig. 1. In order to improve the full-energy-peak efficiency, an add-back analysis was performed for hits in detectors located within 12 cm from each other and a  $\gamma$ -particle time window was imposed for increasing the peak-to-total ratio.  $\gamma$ -ray transitions were found at the following energies: 3453(20) keV, 2375(13) keV, 1720(25) keV, 1461(20) keV, and 691(4) keV, with the significance levels of over  $5\sigma$ ,  $3\sigma$ ,  $2.5\sigma$ ,  $3\sigma$ , and  $3\sigma$ , respectively. These energies are in agreement with those found in the literature [43,44]. The level scheme of  $^{51}\text{Ca}$ , consistently obtained from this work and previous studies [43,44], is shown in the inset of Fig. 1. The simulated resolution for a 3.4-MeV  $\gamma$  ray emitted by particles with  $\beta = 0.6$  was 9% (FWHM) with a photopeak efficiency of 19%. The extracted inelastic scattering leading to bound  $^{51}\text{Ca}$  residues,  $^{52}\text{Ca}(p, p')^{52}\text{Ca}^* \rightarrow ^{51}\text{Ca} + n$  (neutron evaporation), corresponds to a cross section of 5.1(2) mb, 8.4% of the total events, predominantly in the population of the states leading to the 1720-keV, 2375-keV, and 1461-keV transitions. The associated  $(p, pn)$  cross sections after subtracting the neutron-evaporation contribution are 30.3(42) mb for populating the ground state, 22.3(24) mb (3453-keV state), 0.6(3) mb (1720-keV state), 0.9(6) mb (3836-keV state), and 0.9(2) mb (4144-keV state). The strong population of the  $3/2^-$  ground state and  $7/2^-$  3453-keV state is consistent with the  $(p_{3/2})^3$  and  $(f_{7/2})^{-1}(p_{3/2})^4$  single-particle configurations, respectively. The direct population of the  $7/2_1^-$ ,  $3/2_1^-$ , and  $(1/2_1^-)$  states corresponds to the neutron knockout off the  $f_{7/2}$ ,  $p_{3/2}$ , and  $p_{1/2}$  orbitals as illustrated in Fig. 1. The cross sections are listed in Table I.

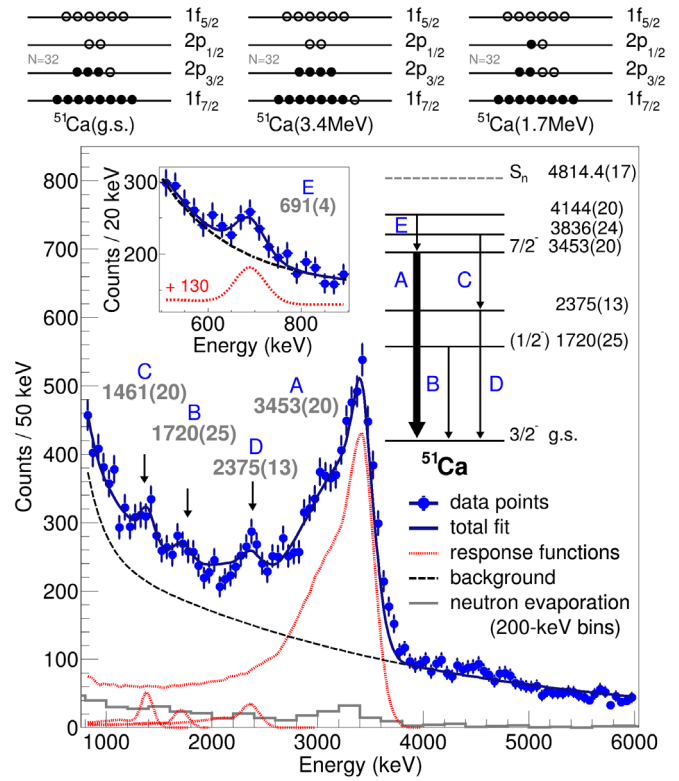


FIG. 1. Top: single-particle neutron configurations of  $^{51}\text{Ca}$  corresponding to the ground state, 3.4 MeV, and 1.7 MeV excited states, from left to right. Bottom: the  $\gamma$ -ray decay spectrum of  $^{51}\text{Ca}$  via the  $(p, pn)$  reaction after Doppler-shift and add-back correction (blue circles), including the neutron-evaporation contribution (gray line). The experimental  $\gamma$  spectrum is fitted (dark-blue line) with the simulated response functions (dotted red line) and a double-exponential background (dashed black line). The left-hand-side inset shows the low-energy region of the spectrum containing the transition at 691(4) keV, where the response function is shifted vertically (+130) for visualization. The level and decay scheme of  $^{51}\text{Ca}$  is summarized on the right.

The parallel and perpendicular momentum distributions (PMDs) of the  $^{51}\text{Ca}$  fragments relative to the beam were determined using the measured velocities and reconstructed angles at the reaction vertex. The differential PMDs  $d\sigma/dP_{\parallel}$  and  $d\sigma/dP_{\perp}$  to individual final states were constructed gating on each bin of the inclusive momentum and fitting the corresponding partial  $\gamma$ -ray spectra the same way as described for the total  $\gamma$ -ray spectrum. In this way the PMDs for the  $7/2^-$  state were obtained, while the ground-state PMDs are the difference between the total and the excited-state PMDs. The other non-ground-state components were found negligible. The neutron-evaporation events were subtracted from all PMDs. The experimental PMDs are shown in Fig. 2.

The theoretical momentum distributions were calculated within the distorted-wave impulse approximation (DWIA) formalism [45–49]. The folding potential (FP) [50] with the Melbourne  $G$ -matrix interaction [51] was used for

TABLE I. Experimental excitation energies ( $E_{\text{ex}}^{\text{exp}}$ ) with associated spin-parity assignment ( $J^\pi$ ) and the experimental cross sections ( $\sigma_{-1n}^{\text{th}}$ ) using  $r_0 = 1.21(5)$  fm,  $1.35(10)$  fm, and  $1.27$  fm (default) for the neutron knockout from  $f_{7/2}$ ,  $p_{3/2}$ , and  $p_{1/2}$  orbitals, respectively, together with the SM prediction for the excitation energies of  $^{51}\text{Ca}$  ( $E_{\text{ex}}^{\text{SM}}$ ) and  $\text{C}^2\text{S}_{\text{SM}}$ . The theoretical cross sections  $\sigma_{-1n}^{\text{th}}$  are calculated using the shell model  $\text{C}^2\text{S}_{\text{SM}}$  and the DWIA single-particle cross section values,  $\sigma_{\text{sp}}^{\text{DWIA}}$ . The ratio of experimental and theoretical single-particle cross sections normalized to  $(2J+1)$  is given in the last column.

$E_{\text{ex}}^{\text{exp}}$ (keV)	$J^\pi$	$-1n$	$\sigma_{-1n}^{\text{exp}}$ (mb)	$E_{\text{ex}}^{\text{SM}}$ (keV)	$\text{C}^2\text{S}_{\text{SM}}$	$\sigma_{\text{sp}}^{\text{DWIA}}$ (mb)	$\sigma_{-1n}^{\text{th}}$ (mb)	$\sigma_{-1n}^{\text{exp}}/(2J+1)\sigma_{\text{sp}}^{\text{DWIA}}$
0	$3/2^-$	$p_{3/2}$	30.3(42)	0	3.7	6.5(9)	23.9(32)	1.17(23)
1720(25)	$(1/2^-)$	$p_{1/2}$	0.6(3)	1.620	0.1	4.8	0.5	0.06(3)
3453(20)	$7/2^-$	$f_{7/2}$	22.3(24)	3.927	7.4	3.4(4)	25.0(27)	0.83(12)

incoming and outgoing nucleon scattering waves. The single-particle wave function of the knocked-out neutron was obtained as a bound state in the Bohr-Mottelson potential [52]. The Woods-Saxon one-body potential was used with the radial extension  $r_0 = 1.27$  fm and diffuseness  $a_0 = 0.67$  fm parameters as a starting point, and with the depth of the potential adjusted to match the neutron effective separation energy throughout the study [53]. The nonlocality correction was made to both the scattering and bound-state wave functions by using the Perey factor [54]. The elementary  $p$ - $n$  scattering process was described by the

nucleon-nucleon effective interaction parametrized by Franey and Love [55]; the Möller factor [56] was introduced for treating the Lorentz transformation of the  $p$ - $n$  cross section. The theoretical shapes were folded with the reaction energy profile and the experimental momentum resolution. The momentum profile of the direct  $^{52}\text{Ca}$  beam contained the main information on the experimental momentum resolution of  $49.5$  MeV/ $c$  ( $76.5$  MeV/ $c$ ) for the parallel (perpendicular) component to which an additional degradation of the resolution of  $1.5$  MeV/ $c$  ( $7.5$  MeV/ $c$ ) originating from the vertex position uncertainty inside the target is considered. The momentum profile of the direct  $^{52}\text{Ca}$  beam and the theoretical distributions for  $^{51}\text{Ca}$ , for populating the ground state and the 3453-keV excited state by  $p_{3/2}$  and  $f_{7/2}$  neutron knockout, respectively, are also plotted in Fig. 2.

For the  $(p, pn)$  reaction at  $\sim 230$  MeV/nucleon incident energy, the quasifree scattering approximation is proven to be suitable from the observed kinematics. The PMDs relate to the single-particle wave functions of the knocked-out neutrons, and therefore to their rms radii [57]. We conducted a variation of  $r_0$  and  $a_0$  of the Woods-Saxon potential used for the calculation of the wave function of the knocked-out neutron. It was found that the PMDs are not sensitive to  $a_0$ ; a change of  $a_0$  by 10% (40%), causes a PMDs width variation by less than 1% (4%). Calculations with the Dirac phenomenology potential EDAD1 (Dirac) [58] were also performed to estimate the impact of the choice of potential on the PMDs; in this case, the nonlocality correction to the scattering waves was made by multiplying them by the Darwin factor [46,59] in the Dirac phenomenology. The folding and Dirac potentials lead to almost identical PMDs within 4.5% for all considered  $(r_0, a_0)$  combinations (Fig. 2) and therefore the choice of potential has no significant impact on the PMDs and rms radii study. The momentum distributions and single-particle cross sections were calculated with FP for a range of  $r_0$  values keeping  $a_0 = 0.67$  fm. A  $\chi^2$  criterion was used and a probability analysis assuming a Gaussian probability density function was performed in order to determine the rms radii of the individual orbitals within our framework. Figures 2(c) and 2(d), show the reduced  $\chi^2$  distribution and

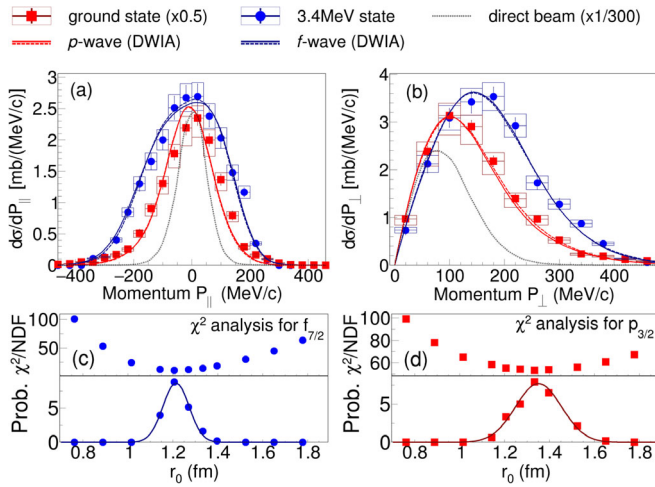


FIG. 2. Experimental parallel (a) and perpendicular (b) momentum distributions of the  $^{52}\text{Ca}$  direct beam (dotted black line),  $^{51}\text{Ca}$  ground-state (red squares), and 3453-keV state (blue circles) population together with the theoretical curves for  $p$ -wave (red) and  $f$ -wave (blue), with a binning of  $40$  MeV/ $c$ . The calculations were performed using a folding potential (solid lines) and the Dirac phenomenology potential (dashed lines) with  $a_0 = 0.67$  fm and the optimal  $r_0$  values:  $1.35$  fm ( $p$  wave) and  $1.21$  fm ( $f$  wave). The statistical errors are marked with crosses and the systematic errors on the absolute normalization with boxes. The (c) and (d) panels show the reduced  $\chi^2$  (upper panels), i.e.,  $\chi^2/\text{NDF}$  (NDF being the number of degrees of freedom), and the probability distribution (lower panels) for the  $f_{7/2}$  and  $p_{3/2}$  orbitals as a function of the parameter  $r_0$ . Study performed for vertex kinetic energies between  $190$  and  $270$  MeV/nucleon. See text for details.

the corresponding probability distribution as function of  $r_0$ . The optimal  $r_0$  and associated  $1\text{-}\sigma$  uncertainty for neutron knockout from the  $p_{3/2}$  and  $f_{7/2}$  orbitals are 1.35(10) fm and 1.21(5) fm, respectively. The deduced  $r_0$  values correspond to the rms radii of the single-particle wave functions of the knocked-out neutron of 4.74(18) fm for  $p_{3/2}$  and 4.13(14) fm for  $f_{7/2}$ . The single-particle wave functions were also obtained from Hartree-Fock-Bogolyubov (HFB) calculations using the HFBRAD [60] code and the SKM Skyrme interaction [61]. The SKM interaction was chosen for its best agreement to experimental data for the proton and matter radii. The rms radii of the single-particle wave function in this case were found at 4.49 fm for the  $p_{3/2}$  orbital and 4.12 fm for the  $f_{7/2}$  orbital, the rms radius of  $f_{7/2}$  being in perfect agreement with the rms radius obtained with the optimal  $r_0$ , while the  $p_{3/2}$  radius is underestimated. The proton, neutron, and matter total density rms radii obtained with HFB calculations with the SKM interaction for  $^{52}\text{Ca}$  are 3.46 fm, 3.74 fm, and 3.63 fm. Experimental data from isotopic shift measurements situate the charge distribution radius at 3.55 fm [25] and thus the proton rms radius at 3.46 fm [32]. The “unexpectedly” large charge radius for  $^{52}\text{Ca}$  found by [25] is explained by [31] proposing a “pronounced halo nature” of the  $p_{3/2}$  and  $p_{1/2}$  orbitals, 0.7 fm larger than the rms radii of the  $f_{5/2}$  and  $f_{7/2}$  orbitals. The rms radii difference between the  $p_{3/2}$  orbital and the  $f_{7/2}$  orbital obtained by the present analysis is 0.61(23) fm, in agreement with this prediction.

The calculated single-particle cross sections with  $r_0 = 1.27$  fm are 5.8 mb ( $p_{3/2}$ ), 3.8 mb ( $f_{7/2}$ ), and 4.8 mb ( $p_{1/2}$ ). Using the optimum  $r_0$  values obtained in this work, 6.5(9) mb and 3.4(4) mb were found for  $p_{3/2}$  and  $f_{7/2}$  orbitals, respectively. The single-particle cross sections are listed in Table I. Shell-model (SM) calculations were carried out with the pf-shell part of the PFSDG-U [62] interaction assuming a  $^{40}\text{Ca}$  core and a neutron effective charge of  $0.46e$ . The calculations predict the following occupation numbers for  $^{52}\text{Ca}$ : 7.803 ( $f_{7/2}$ ), 3.857 ( $p_{3/2}$ ), 0.142 ( $p_{1/2}$ ), and 0.198 ( $f_{5/2}$ ), corresponding to a neutron shell closure at  $N = 32$ . In comparison, the following occupation numbers are obtained for  $^{48}\text{Ca}$  and  $^{54}\text{Ca}$ : 7.704 and 7.809 ( $f_{7/2}$ ), 0.171 and 3.944 ( $p_{3/2}$ ), 0.023 and 1.861 ( $p_{1/2}$ ), and 0.103 and 0.064 ( $f_{5/2}$ ). The resulting excitation energies and spectroscopic factors to  $^{51}\text{Ca}$  are gathered in Table I.

The occupancies can be tested using neutron knockout cross sections and we use the ratio between the experimental and the single-particle cross sections normalized to  $(2J + 1)$ ,  $R_S = \sigma_{-1n}/(2J + 1)\sigma_{\text{sp}}$  in comparing  $^{52}\text{Ca}$  relative to  $^{48}\text{Ca}$  and  $^{54}\text{Ca}$ , considered as doubly closed-shell neutron-rich Ca isotopes [21–24,63]. For the systematic comparison, the theoretical single-particle cross sections obtained with the best-fit  $r_0$  values are used for  $^{52}\text{Ca}$ . The

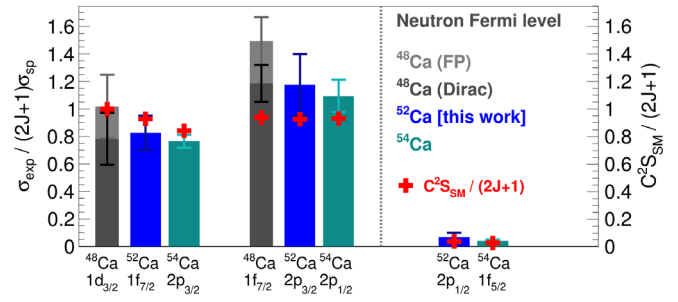


FIG. 3. The ratio of experimental neutron knockout cross sections and theoretical single-particle cross sections normalized to  $(2J + 1)$  for  $^{48,52,54}\text{Ca}$  (gray, blue, and turquoise, respectively) below and above the corresponding shell closures. Experimental data are from [24,64] and this work. The error bars contain experimental cross-section uncertainties. For  $^{52}\text{Ca}$ , theoretical uncertainties from the  $r_0$  sensitivity study are added quadratically.

$^{48}\text{Ca}(p, pn)$  triple-differential cross section (TDX) was studied at 149.5 MeV/nucleon by [64]. The theoretical single-particle TDX for the  $^{48}\text{Ca}(p, pn)$  reaction was calculated both with the FP, as for  $^{52}\text{Ca}$ , and Dirac. At higher reaction energies, as in the present experiment, the difference in cross sections between FP and Dirac are below 5%, but at  $\sim 150$  MeV/nucleon as for  $^{48}\text{Ca}$  from [64], the differences become significant. Dirac is more suitable for the stable  $^{48}\text{Ca}$ . The following values were obtained for the proportionality factors between the experimental and calculated TDX after the normalization to  $(2J + 1)$ , equivalent to  $R_S$ : 1.49(17) (FP) and 1.19(13) (Dirac) for the  $f_{7/2}$  orbital and 1.02(23) (FP) and 0.78(19) (Dirac) for the  $d_{3/2}$  orbital. The ratio between experimental and theoretical cross sections for  $^{54}\text{Ca}$  from [24], reporting on data obtained from the same measurement as the present work, is used for the comparison. The values for  $R_S$  for  $^{48}\text{Ca}$  (with FP and Dirac),  $^{52}\text{Ca}$ , and  $^{54}\text{Ca}$  for the orbitals below and above the neutron Fermi level are plotted in Fig. 3 together with the  $C^2 S_{\text{SM}}$ . The three Ca isotopes exhibit a consistent pattern: a ratio close to unity below the Fermi level and a very small ratio above. The  $N = 32$  shell closure in  $^{52}\text{Ca}$  thus proves to be as strong as  $N = 28$  and  $N = 34$  in Ca isotopes. This finding justifies the use of single-particle wave functions in this work.

To summarize, the  $(p, pn)$  one-neutron knockout from  $^{52}\text{Ca}$  at  $\sim 230$  MeV/nucleon was measured. Exclusive cross sections to bound final states in  $^{51}\text{Ca}$  and the momentum distributions corresponding to the removal of  $1f_{7/2}$  and  $2p_{3/2}$  neutrons were measured and analyzed within the DWIA framework. A consistent shell structure for  $^{48,52,54}\text{Ca}$  was obtained from the ratio of experimental and single-particle cross sections. The agreement with shell-model predictions places  $^{52}\text{Ca}$  among the doubly magic Ca isotopes. In addition, the measured momentum distributions with high statistics allowed to access the rms radii of

the  $1f_{7/2}$  and  $2p_{3/2}$  neutron orbitals at 4.13(14) fm and 4.74(18) fm, respectively. With this result, the  $p_{3/2}$  neutron single-particle orbital rms radius, 0.61(23) fm larger than  $1f_{7/2}$ , supports the prediction of [31] where the large spatial extension of  $p$  neutron orbitals in neutron-rich Ca isotopes is proposed to be responsible for the linear increase of their charge radii beyond  $^{48}\text{Ca}$ . The present result calls for a systematic extension of the method to several isotopic chains, complementary to ongoing efforts to explore the neutron radial extension in radioactive nuclei [65–69], relevant to the nuclear equation of state and the physics of neutron stars [70–73].

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- [1] M. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (Wiley, New York, 1955).
- [2] T. Otsuka, A. Gade, O. Sorlin, T. Suzuki, and Y. Utsuno, *Rev. Mod. Phys.* **92**, 015002 (2020).
- [3] F. Nowacki, A. Poves, and A. Obertelli, *Prog. Part. Nucl. Phys.* **120**, 103866 (2021).
- [4] B. Bastin, S. Grevy, D. Sohler, O. Sorlin, Z. Dombradi, N. L. Achouri *et al.*, *Phys. Rev. Lett.* **99**, 022503 (2007).
- [5] A. Navin, D. W. Anthony, T. Aumann, T. Baumann, D. Bazin, Y. Blumenfeld *et al.*, *Phys. Rev. Lett.* **85**, 266 (2000).
- [6] C. Thibault, R. Klapisch, C. Rigaud, A. M. Poskanzer, R. Prieels, L. Lessard, and W. Reisdorf, *Phys. Rev. C* **12**, 644 (1975).
- [7] D. Guillemaud-Mueller, C. Detraz, M. Langevin, F. Naulin, M. de Saint-Simon, C. Thibault, F. Touchard, and M. Epherre, *Nucl. Phys.* **A426**, 37 (1984).
- [8] T. Motobayashi, Y. Ikedaa, Y. Ando, K. Ieki, M. Inoue, N. Iwasa *et al.*, *Phys. Lett. B* **346**, 9 (1995).
- [9] D. Steppenbeck, S. Takeuchi, N. Aoi, P. Doornenbal, M. Matsushita, H. Wang *et al.*, *Phys. Rev. Lett.* **114**, 252501 (2015).
- [10] A. Huck, G. Klotz, A. Knipper, C. Miehé, C. Richard-Serre, G. Walter, A. Poves, H. L. Ravn, and G. Marguier, *Phys. Rev. C* **31**, 2226 (1985).
- [11] R. Kanungo, I. Tanihata, A. Ozawa, *Phys. Lett. B* **528**, 58 (2002).
- [12] R. V. F. Janssens, B. Fornal, P. F. Mantica, B. A. Brown, R. Broda, P. Bhattacharyya *et al.*, *Phys. Lett. B* **546**, 55 (2002).
- [13] J. I. Prisciandaro, P. F. Mantica, B. A. Brown, D. W. Anthony, M. W. Cooper, A. Garcia *et al.*, *Phys. Lett. B* **510**, 17 (2001).
- [14] M. L. Cortés, W. Rodriguez, P. Doornenbal, A. Obertelli, J. D. Holt, J. Menéndez *et al.*, *Phys. Rev. C* **102**, 064320 (2020).
- [15] D.-C. Dinca, R. V. F. Janssens, A. Gade, D. Bazin, R. Broda, B. A. Brown *et al.*, *Phys. Rev. C* **71**, 041302(R) (2005).
- [16] A. Bürger, T. R. Saito, H. Grawe, H. Hübel, P. Reiter, J. Gerl *et al.*, *Phys. Lett. B* **622**, 29 (2005).
- [17] F. Wienholtz, D. Beck, K. Blaum, Ch. Borgmann, M. Breitenfeldt, R. B. Cakirli *et al.*, *Nature (London)* **498**, 346 (2013).
- [18] M. Rosenbusch, P. Ascher, D. Atanasov, C. Barbieri, D. Beck, K. Blaum *et al.*, *Phys. Rev. Lett.* **114**, 202501 (2015).
- [19] X. Xu, M. Wang, Y. Zhang, H. Xu, P. Shuai, X. Tu *et al.*, *Chin. Phys. C* **39**, 104001 (2015).
- [20] E. Leistenschneider, M. P. Reiter, S. Ayet San Andres, B. Kootte, J. D. Holt, P. Navratil *et al.*, *Phys. Rev. Lett.* **120**, 062503 (2018).
- [21] D. Steppenbeck, S. Takeuchi, N. Aoi, P. Doornenbal, M. Matsushita, H. Wang *et al.*, *Nature (London)* **502**, 207 (2013).
- [22] H. N. Liu, A. Obertelli, P. Doornenbal, C. A. Bertulani, G. Hagen, J. D. Holt *et al.*, *Phys. Rev. Lett.* **122**, 072502 (2019).
- [23] S. Michimasa, M. Kobayashi, Y. Kiyokawa, S. Ota, D. S. Ahn, H. Baba *et al.*, *Rev. Lett.* **121**, 022506 (2018).
- [24] S. Chen, J. Lee, P. Doornenbal, A. Obertelli, C. Barbieri, Y. Chazono *et al.*, *Phys. Rev. Lett.* **123**, 142501 (2019).
- [25] R. F. Garcia Ruiz, M. L. Bissell, K. Blaum, A. Ekström, N. Frömmgen, G. Hagen *et al.*, *Nat. Phys.* **12**, 594 (2016).
- [26] Á. Koszorús, X. F. Yang, W. G. Jiang, S. J. Novario, S. W. Bai, J. Billowes *et al.*, *Nat. Phys.* **17**, 439 (2021).
- [27] K. Kreim, M. L. Bissell, J. Papuga, K. Blaum, M. De Rydt, R. F. Garcia Ruiz *et al.*, *Phys. Lett. B* **731**, 97 (2014).
- [28] Y. L. Sun, A. Obertelli, P. Doornenbal, C. Barbieri, Y. Chazono, T. Duguet *et al.*, *Phys. Lett. B* **802**, 135215 (2020).
- [29] T. Koiwai, K. Wimmer, P. Doornenbal, A. Obertelli, C. Barbieri, T. Duguet *et al.*, *Phys. Lett. B* **827**, 136953 (2022).

- [30] F. Sommer, K. Konig, D. M. Rossi, N. Everett, D. Garand, R. P. deGroote *et al.*, *Phys. Rev. Lett.* **129**, 132501 (2022).
- [31] J. Bonnard, S. M. Lenzi, and A. P. Zuker, *Phys. Rev. Lett.* **116**, 212501 (2016).
- [32] M. Tanaka, M. Takechi, A. Homma, M. Fukuda, D. Nishimura, T. Suzuki *et al.*, *Phys. Rev. Lett.* **124**, 102501 (2020).
- [33] T. Kubo, D. Kameda, H. Suzuki, N. Fukuda, H. Takeda, Y. Yanagisawa *et al.*, *Prog. Theor. Exp. Phys.* **2012**, 03C003 (2012).
- [34] N. Fukuda, T. Kubo, T. Ohnishi, N. Inabe, H. Takeda, D. Kameda, and H. Suzuki, *Nucl. Instrum. Methods Phys. Res., Sect. B* **317**, 323 (2013).
- [35] T. Kobayashi *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. B* **317**, 294 (2013).
- [36] A. Obertelli, A. Delbart, S. Anvar, L. Audirac, G. Authelet, H. Baba *et al.*, *Eur. Phys. J. A* **50**, 8 (2014).
- [37] S. Takeuchi, T. Motobayashi, Y. Togano, M. Matsushita, N. Aoi, K. Demichi, H. Hasegawa, and H. Murakami, *Nucl. Instrum. Methods Phys. Res., Sect. A* **763**, 596 (2014).
- [38] C. Santamaria, A. Obertelli, S. Ota, M. Sasano, E. Takada, L. Audirac *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **905**, 138 (2018).
- [39] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [40] K. Boretzky, I. Gašparić, M. Heil, J. Mayer, A. Heinz, C. Caesar *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1014**, 165701 (2021).
- [41] T. Nakamura and Y. Kondo, *Nucl. Instrum. Methods Phys. Res., Sect. B* **376**, 156 (2016).
- [42] M. Wang, W. J. Huang, F. G. Kondev, G. Audi, S. Naimi, *Chin. Phys. C* **45**, 030003 (2021).
- [43] M. Rejmund, S. Bhattacharyya, A. Navin, W. Mittig, L. Gaudefroy, M. Gelin, G. Mukherjee, F. Rejmund, P. Roussel-Chomaz, and Ch. Theisen, *Phys. Rev. C* **76**, 021304(R) (2007).
- [44] B. Fornal, R. V. F. Janssens, R. Broda, N. Marginean, S. Beghini, L. Corradi *et al.*, *Phys. Rev. C* **77**, 014304 (2008).
- [45] N. S. Chant and P. G. Roos, *Phys. Rev. C* **15**, 57 (1977).
- [46] T. Wakasa, K. Ogata, and T. Noro, *Prog. Part. Nucl. Phys.* **96**, 32 (2017).
- [47] G. Jacob and Th. A. J. Maris, *Rev. Mod. Phys.* **38**, 121 (1966).
- [48] G. Jacob and Th. A. J. Maris, *Rev. Mod. Phys.* **45**, 6 (1973).
- [49] P. Kitching, W. J. McDonald, Th. A. J. Maris, and C. A. Z. Vasconcellos, *Adv. Nucl. Phys.* **15**, 43 (1985).
- [50] M. Toyokawa, K. Minomo, and M. Yahiro, *Phys. Rev. C* **88**, 054602 (2013).
- [51] K. Amos, P. J. Dortmans, H. V. von Geramb, S. Karataglidis and J. Raynall, *Adv. Nucl. Phys.* **25**, 276 (2000).
- [52] A. Bohr and B. R. Mottelson, *Nuclear Structure: Single-Particle Motion and Nuclear Deformations* (World Scientific, Singapore, 1969), Vol. 1.
- [53] K. Yoshida, *Few-Body Syst.* **62**, 28 (2021).
- [54] F. G. Perey, *Direct Interactions and Nuclear Reaction Mechanism* (Gordon and Breach Science Publishers, New York, 1963), p. 125.
- [55] M. A. Franey and W. G. Love, *Phys. Rev. C* **31**, 488 (1985).
- [56] C. Möller, C. Barbieri, D. Bazin, C. A. Bertulani, A. Bonaccorso, W. H. Dickhoff *et al.*, *Kgl. Danske Videnskab. Selskab, Mat-fys. Medd.* **23**, 1 (1945).
- [57] T. Aumann *et al.*, *Prog. Part. Nucl. Phys.* **118**, 103847 (2021).
- [58] E. D. Cooper, S. Hama, B. C. Clark, and R. L. Mercer, *Phys. Rev. C* **47**, 297 (1993).
- [59] L. G. Arnold, B. C. Clark, R. L. Mercer, and P. Schwandt, *Phys. Rev. C* **23**, 1949 (1981).
- [60] K. Bennaceur and J. Dobaczewski, *Comput. Phys. Commun.* **168**, 96 (2005).
- [61] J. Bartel, P. Quentin, M. Brack, C. Guet, H.-B. Hakansson, *Nucl. Phys.* **A386**, 79 (1982).
- [62] F. Nowacki, A. Poves, E. Caurier, and B. Bounthong, *Phys. Rev. Lett.* **117**, 272501 (2016).
- [63] F. Browne, S. Chen, P. Doornenbal, A. Obertelli, K. Ogata, Y. Utsuno *et al.*, *Phys. Rev. Lett.* **126**, 252501 (2021).
- [64] M. Ahmad, J. W. Watson, D. W. Devins, B. S. Flanders, D. L. Friesel, N. S. Chant, P. O. Roos, and J. Wastell, *Nucl. Phys.* **A424**, 92 (1984).
- [65] V. Lapoux, V. Somà, C. Barbieri, H. Hergert, J. D. Holt, and S. R. Stroberg, *Phys. Rev. Lett.* **117**, 052501 (2016).
- [66] P. Egelhof, S. Bagchi, S. Bönig, M. Csatlós, I. Dillmann, C. Dimopoulou *et al.*, *J. Phys. Soc. Jpn. Conf. Proc.* **6**, 020049 (2015).
- [67] K. Tsukada, A. Enokizono, T. Ohnishi, K. Adachi, T. Fujita, M. Hara *et al.*, *Phys. Rev. Lett.* **118**, 262501 (2017).
- [68] T. Aumann, C. A. Bertulani, F. Schindler, and S. Typel, *Phys. Rev. Lett.* **119**, 262501 (2017).
- [69] T. Aumann, W. Bartmann, O. Boine-Frankenheim, A. Bouvard, A. Broche, F. Butin *et al.*, *Eur. Phys. J. A* **58**, 88 (2022).
- [70] M. H. Mahzoon, M. C. Atkinson, R. J. Charity, and W. H. Dickhoff, *Phys. Rev. Lett.* **119**, 222503 (2017).
- [71] D. Adhikari *et al.* (PREX collaboration), *Phys. Rev. Lett.* **126**, 172502 (2021).
- [72] B. T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz, *Phys. Rev. Lett.* **126**, 172503 (2021).
- [73] J. M. Lattimer, *Annu. Rev. Part. Nucl. Sci.* **71**, 433 (2021).