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Phys. Rev. C **93**, 044327 — Published 22 April 2016

DOI: 10.1103/PhysRevC.93.044327

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Low-lying excited states of the neutron-rich calcium isotopes $^{48-52}$Ca have been studied via γ-ray spectroscopy following inverse-kinematics proton scattering on a liquid hydrogen target using the GRETINA γ-ray tracking array. The energies and strengths of the octupole states in these isotopes are remarkably constant, indicating that these states are dominated by proton excitations.

Insights about nuclear structure can often be found by examining the systematic behavior of a series of isotopes or isotones, and the advent of intense beams of exotic isotopes has opened new opportunities for such systematic studies. In the present work, we examine the systematic behavior of both octupole and quadrupole modes in the neutron-rich isotopes of calcium by means of inelastic scattering of protons in inverse kinematics. We report the results of inelastic proton scattering experiments on ^{49,51,52}Ca, and combine these results with previous results on ^{48,50}Ca [1] to examine quadrupole and octupole excitations in the A=48-52 Ca isotopes. While the energies of the 2_1^+ states in ^{48,50,52}Ca, which have large neutron excitation components, vary dramatically with neutron number, the energies of the 3_1 states in these isotopes are remarkably constant, demonstrating that these octupole states are dominated by proton excitations.

Furthermore, the inelastic proton scattering reaction on the odd-N isotopes ^{49,51}Ca allows us to identify members of multiplets that result from coupling of the odd neutron (in the case of ^{49}Ca) or neutron hole (in the case of ^{51}Ca) to the octupole phonons in ^{48,52}Ca. The deformation lengths for scattering to the multiplet members in ^{49,51}Ca can be explained in a simple weak-coupling picture, once again confirming the dominant proton character of the octupole phonons in the core nuclei.

The experiment was performed at the Coupled-Cyclotron Facility of the National Superconducting Cyclotron Laboratory at Michigan State University. A cocktail beam was produced by the fragmentation of a 130 MeV/u ^{76}Ge primary beam in a 376 mg/cm^2 ^{9}Be production target. The secondary products were separated by the A1900 fragment separator [2]. The momentum acceptance of the A1900 was 3%. A 45 mg/cm^2 aluminum achromatic wedge was used to enhance separation of the cocktail by Z.

Secondary beam particles were identified by energy loss in a silicon surface barrier detector and by their time of flight. The beam then traversed the Ursinus College Liquid Hydrogen Target, based on the design of Ryuto et al. [3]. The target was installed at the pivot point of the S800 magnetic spectrograph [4]. Projectile-like reaction products were identified by energy loss in the S800 ion chamber and time of flight. The secondary beam, composed of products spanning the range $14 \leq Z \leq 23$, included ^{49,51,52}Ca, the subjects of the present work. Total numbers of beam particles, average rates, and mid-target energies are given in Table I.

TABLE I. Beam yields, average rates, and mid-target kinetic energies

	Total Beam Particles	Rate [pps]	Mid-target KE [MeV/u]
^{49}Ca	3.7×10^7	90	94
^{51}Ca	5.1×10^6	12	86
^{52}Ca	3.3×10^5	0.81	84

The liquid hydrogen target consisted of a cylindrical aluminum target cell with 125 μm Kapton entrance and exit windows mounted on a cryocooler. The nominal target thickness was 30 mm. The target cell and cryocooler were surrounded by a 1 mm thick aluminum radiation shield with entrance and exit windows covered by 5 μm aluminized Mylar foil. A resistive heater mounted between the cryocooler and the target cell was used to maintain the temperature and pressure of the target cell at 16.00(25) K and 868(10) Torr throughout the experiment. The variation in the temperature and pressure of the target cell correspond to a 0.3 % uncertainty in target density.

The GRETINA γ-ray tracking array [9] was installed in the configuration compatible with the liquid hydrogen target described in Ref. [1]. Projectile-frame γ-ray spectra of ^{49,51,52}Ca measured in coincidence with incoming and outgoing particle-identification gates corresponding to inverse-kinematics proton scattering are shown in

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TABLE II. Level energies, spins and parities, and γ-ray energies from Refs. [5–8], γ-ray energies, intensities relative to that of the $2_1^+ \to 0_{\mathrm{g.s.}}^+$ transitions, branching ratios (BR), and cross sections from the present work.

	E_{level} [keV]	J^π [$\hbar$]	E_γ [keV]	BR [%]	J^π [$\hbar$]	E_γ [keV]	I_γ [%]	BR [%]	σ [mb]
^{49}Ca		Refs. [5, 6]							
	2023.2(3)	$1/2^-$	2023.12(26)			2023	12(3)		0.6(1)
	3354.7(6)	$7/2^-$	3356.7(10)			3357	100(7)		1.6(3)
	3585.0(8)	$5/2^-$	3585.0(8)			3585	29(6)		1.4(3)
	3861(2)	$(1/2^-, 3/2^-)$	3859.7(9)			3861	34(6)		1.4(3)
	4013.6(6)	$9/2^+$	4017.5	9.2(8)		4018	29(14)		3.3(8)
			660.3	84(1)		660	67(6)		
			150.9	6.7(8)		—			
	4416(2)	$5/2^+$	4416			4416	30(3)		1.5(7)
	4757.0(10)	$(5/2^+)$	743.3		$(3/2^+)$	743	20(3)		1.0(1)
	4885(3)	$9/2^+$	1531	20(6)		—			0.2(1)
			875	80(23)		875	4(2)		
	5132.8(10)		1119			1119	9(2)		0.5(1)
^{51}Ca		Ref. [7]							
	2379	$(5/2^-)$	2379			2379	100(13)		< 0.9
	2937	$(3/2^-)$	2937			2937	< 22		< 0.8
	3462	$(7/2-)$	3462			3462	66(18)		< 1.0
	3845	$(7/2^+)$	1466		$(7/2^+)$	1466	93(18)		3.4(5)
	3941(10)				$(5/2^+)$	3941(13)	82(16)		2.9(4)
	4155	$(9/2^+)$	693		$(9/2^+)$	698(8)	52(11)		1.9(3)
^{52}Ca		Ref. [8]							
	2563.1(10)	2^+	2563.1(10)			2575(14)	100(23)		< 6
	3990	(3^-)	1427(1)		(3^-)	1421(9)	80(31)		9(3)
						330(3)	67(23)		

Fig. 1. Intensities of measured γ rays were extracted by fitting GEANT4 [10] simulations to the measured projectile-frame γ-ray spectra as described in Ref. [1]. The fits are the smooth curves in Fig. 1. Level energies, spins and parities, and γ-ray energies from Refs. [5–8], γ-ray energies and relative intensities, branching ratios (BR), and cross sections for ^{49,51,52}Ca from the present work are listed in Table II. The states of $^{48-52}$Ca populated in the present experiment are illustrated in Fig. 2. The γ-ray intensities, branching ratios, cross sections, and levels in ^{48,50}Ca observed in this reaction were reported previously [1].

Next, we examine the J^π assignments for the three radioactive nuclei for which (p,p') data are reported here for the first time — ^{49,51,52}Ca.

In ^{49}Ca, the ground state ($J^\pi = 3/2^-$) and the first excited state at 2023 keV ($J^\pi = 1/2^-$) have been established as the $p_{3/2}$ and $p_{1/2}$ single neutron states via the (d,p) reaction. The significant (p,p') cross sections seen here for the 3355 keV ($J^\pi = 7/2^-$) and 3585 keV ($J^\pi = 5/2^-$) states support a picture in which these states arise from the coupling of the $p_{3/2}$ neutron to the 2_1^+ state in the ^{48}Ca core nucleus. The $J^\pi = 7/2^-$ assignment for the 3355 keV state was made by Montanari et al. [11, 12] on the basis of γ-ray angular distribution and polarization measurements of the ground state transition with a heavy-ion transfer reaction. The 3585 keV state is populated weakly ($C^2S = 0.11$) in the (d,p) reaction [5], but the proton angular distribution in that reaction clearly indicates a $L = 3$ transfer. Therefore, the state's wavefunction includes a fragment of the $f_{5/2}$ single neutron state, and the state has $J^\pi = 5/2^-$.

The 3861 keV state also has a significant (p,p') cross section, so it is likely to be a member of either the 2_1^+ core state multiplet or the multiplet arising from the coupling of the $p_{3/2}$ odd neutron to the core octupole vibration state. The data on this state available from (d,p) are ambiguous, and there is no information available on γ-decays from this state. However, Navon et al. [13] determined that the isobaric analog resonance in ^{49}Sc has $L = 1$, so that the wavefunction of this state must have an admixture of a $p_{3/2}$ or $p_{1/2}$ single neutron and the state has either $J^\pi = 3/2^-$ or $J^\pi = 1/2^-$.

The next state in ^{49}Ca seen in the present experiment is at 4014 keV and has the largest cross section in this isotope. This state was observed in (d,p) with $L = 4$, indicating that it has an admixture of the $g_{9/2}$ single neutron state and, therefore, $J^\pi = 9/2^+$. Montanari

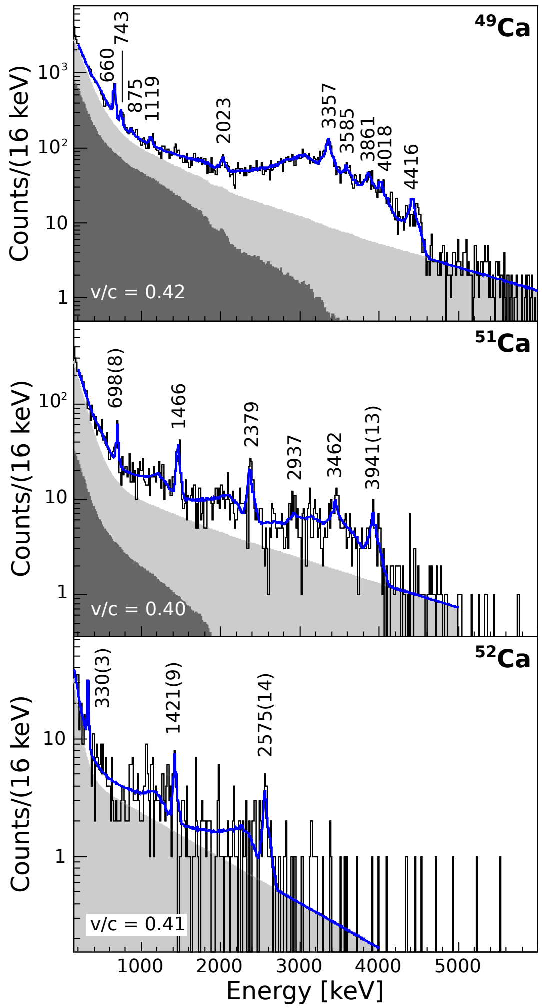

FIG. 1. Projectile-frame γ-ray spectra measured in coincidence with incoming and outgoing ^{49,51,52}Ca particle-identification gates. The solid curves are the GEANT4 fits. The shaded region is the background, consisting of nonprompt (dark gray) and prompt (light gray) components.

et al. [11, 12] confirmed this using angular distribution and polarization data for the 660 keV γ-ray. Therefore, we deduce that this state is the highest spin member of the multiplet resulting from the coupling of the $p_{3/2}$ odd neutron to the 3_1^- state in the ^{48}Ca core.

The 4416 keV state, which also has a significant cross section in the present (p,p') experiment, was observed strongly enough in (d,p) to determine an $L=2$ transfer [5] and therefore $J^\pi = 3/2^+$ or $5/2^+$, and the analyzing power data from the same experiment give $J^\pi = 5/2^+$ definitively. Therefore, this state appears to be a member of the octupole multiplet. The 4757 keV state has a significant (p,p') cross section, but the (d,p) study was less conclusive regarding L transfer to this state, giving a tentative $L=2$ result. This state probably has positive parity and $J = 3/2$ or $5/2$. As in the case of the 4416 keV state, it is attractive to assign this state to the octupole multiplet because of its cross section and likely positive parity. If it is a member of this multiplet, then it has $J^\pi = 3/2^+$.

The 4885 keV state is weakly populated in (p,p'). While this state is also weakly populated in (d,p), there was enough information to determine $L=4$ and, therefore, a likely $J^\pi = 9/2^+$ assignment. Finally, the 5133 keV state was populated significantly here and has been seen in other reactions, but there is not sufficient information to make even a tentative J^π assignment.

It is likely (though not rigorously established) that the ground state of ^{51}Ca has $J^\pi = 3/2^-$ since $p_{3/2}$ is the lowest valence neutron orbit in ^{49}Ca and this orbit is likely filling in the $^{49-52}$Ca isotope chain. The present (p,p') measurement of ^{51}Ca identified three strong states at 3845, 3941 and 4155 keV. The strongest states observed in ^{48,49}Ca(p,p') are octupole vibration states, so it seems quite likely that the three strong states observed here in ^{51}Ca are associated with an octupole vibration as well — either the coupling of a $p_{3/2}$ neutron hole to the 3_1^- state in ^{52}Ca or a $p_{3/2}$ neutron to the corresponding state in ^{50}Ca. This multiplet should include states with $J^\pi = 3/2^+$, $5/2^+$, $7/2^+$ and $9/2^+$. Regardless of the specific spin assignments of these three strong states in ^{51}Ca, the energy centroid of these three state, 3.95(1) MeV, is approximately the same as the energies of the octupole states in ^{48,49}Ca.

In a simple weak-coupling model, the smallest cross section among these four states would be that for the smallest J, in this case the $3/2^+$ state. So we can tentatively conclude that the three states observed here are the $5/2^+$, $7/2^+$ and $9/2^+$ members of the multiplet. It is certainly possible that each of these multiplet members decays to the ground state via $E3$ transitions, as the $9/2^+$ octupole multiplet member in ^{49}Ca does. However, it is generally more likely that these states decay via $E1$, $M1$ or $E2$ transitions. Among the 3845, 3941 and 4155 keV states in ^{51}Ca, only the 3941 keV state decays directly to the ground state. Therefore, it is most likely that this state is the $5/2^+$ member of the octupole multiplet, decaying via an $E1$ transition.

The most likely J^π assignments for the 3845 and 4155 keV states depend on the assignments for the states to which they γ-decay at 2379 and 3462 keV. Both of these latter states are only weakly populated in the present (p,p') reaction, so it is unlikely that they are members of the octupole multiplet. Furthermore, coupling to the an octupole vibration is the lowest energy way to produce a positive parity state in ^{51}Ca, so the 2379 and 3462 keV states are likely to be of negative parity. Both of these states decay directly to the ground state, which we have tentatively assigned to be $J^\pi = 3/2^-$. So they may have $J^\pi = 1/2^-$, $3/2^-$, $5/2^-$, or $7/2^-$. The authors of a report on the β-decay of ^{51}K [14] argue for a $7/2^-$ assignment for the 3462 keV state on the basis of their results.

The 4155 keV state decays exclusively to the 3462 keV state. If the 3462 keV state is $J^\pi = 7/2^-$, then the 4155 keV state is likely $J^\pi = 5/2^+$, $7/2^+$ or $9/2^+$ because $E1$ is the most likely parity-changing transition. But if

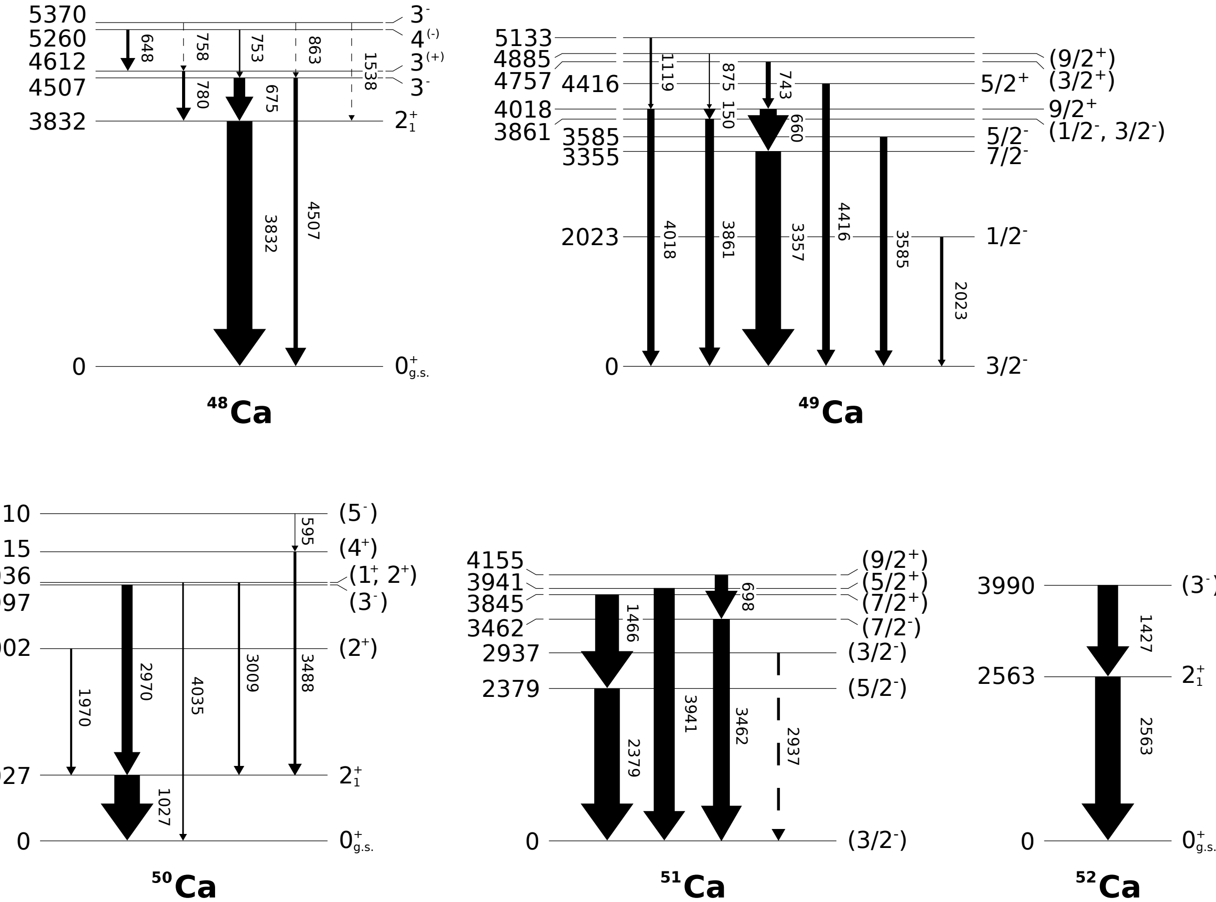

FIG. 2. Partial level schemes of $^{48-52}$Ca showing levels populated in the present work. Arrow widths are proportional to the measured γ-ray intensities.

the 4155 keV had $J < 9/2$, it would likely decay to one of the lower-energy states, which are probably lower-spin positive-parity states, because of the E_γ^3 dependence of the $E1$ transition probability. So we tentatively assign the 4155 keV state to be $J^\pi = 9/2^+$. The 3845 keV member of the octupole multiplet decays to the 2379 keV state, so we tentatively assign $J^\pi = 7/2^+$ for that state.

In ^{52}Ca, the cross section for populating the 3990 keV state — which was observed by Gade et al. [8] via the two-proton knockout reaction from ^{54}Ti and tentatively assigned $J^\pi = 3^-$ — is strong, as is the case for the 3^- states in ^{48,50}Ca. Thus, the present (p,p') result provides additional support for the tentative 3^- assignment for the 3990 keV state in ^{52}Ca by Gade et al.

It is worth noting that a strong 330 keV γ ray was observed in coincidence with ^{52}Ca residues in the present study. It has not been seen in other reactions, and we are unable to place it in the level scheme. We can rule out the possibility that this γ ray feeds the 2_1^+ state directly, because the intensity of the 2563 keV $2_1^+ \to 0_{g.s}^+$ transition is significantly below the combined intensities of the 330 keV and 1427 keV γ rays. While we cannot rule out the possibility that the 330 keV γ ray feeds the state at 3990 keV, we consider it to be unlikely. The intensity of this γ ray indicates that the state it de-excites is highly collective. Proton-scattering cross sections measured in nearby neutron-rich calcium isotopes [1, 15] suggest that such a state would have $J^\pi = 3^-$ or 2^+. However, in either of these cases, we would expect there to be a strong γ-ray branch to the 2_1^+ state, which we do not observe. It is possible that this 330 keV γ-ray may feed an isomer in ^{52}Ca so that we would be unable to connect it to either of the other states in that nucleus observed here. Such a scenario has been observed in ^{48}Ca, in which a collective 5_1^- state populated in proton scattering de-excites via a strong $E1$ transition to the long-lived 4_1^+ state. [1]

With the present results on ^{49,51,52}Ca and the previous results on ^{48,50}Ca, we can examine the systematic behavior of quadrupole and octupole states in these isotopes. It is remarkable how quickly the 2_1^+ state drops from a high energy characteristic of a doubly-magic nucleus in ^{48}Ca (3832 keV) down to 1027 keV in ^{50}Ca, and then back up to 2563 keV in ^{52}Ca. This behavior reflects the isolation of the $p_{3/2}$ neutron orbit between the $N = 28$ major shell closure and the strong $N = 32$ subshell closure, and the dominance of neutron components in the 2_1^+ states of these nuclei.

In contrast, the 3_1^- states in ^{48,50,52}Ca are close in energy (4507, 3997, and 4318 keV, respectively). Montanari et al. [11, 12] argued on the basis of an RPA calculation of the 3_1^- state in ^{48}Ca that one proton-one hole excitations dominate the wavefunction of this state. This would imply that adding neutrons to ^{48}Ca would have little impact on the energy of the octupole state and would explain why the 3_1^- states in ^{48,50,52}Ca are at similar energies.

Furthermore, the proton dominance of the octupole states in ^{48,50,52}Ca would imply that the odd neutron in ^{49}Ca or ^{51}Ca would be a spectator to the octupole excitation of the core, which is the definition of weak coupling. The octupole energies shown in Figure 3a for the odd-A isotopes ^{49,51}Ca are the centroids of the octupole states reported here for these nuclei. These centroids fit well into the systematic behavior of the 3_1^- states in the even-A isotopes, as they should in a weak-coupling picture.

Of course, proton dominance of the octupole excitations in the even-A isotopes and weak coupling in the odd-A isotopes should also be evident in the (p, p') excitation strengths. Fig. 3b shows that the (p, p') cross sections to the 3_1^- states in ^{48,50,52}Ca are identical, to within experimental uncertainties. The cross sections to the octupole multiplet members in ^{49,51}Ca have much smaller cross sections, but that is to be expected, because in the weak-coupling model the strength of the octupole vibration of the core nucleus is distributed among the multiplet members in the odd-A nucleus. However, the sum of the cross sections of the individual octupole states in ^{49}Ca, 5.8(11) mb, is equal to that of the 3_1^- state in its weak-coupling core nucleus, ^{48}Ca. The same is true in ^{51}Ca: The sum of the octupole state cross sections, 8.2(7) mb, is equal to the 3_1^- state cross section in its weak-coupling core nucleus, ^{52}Ca.

The deformation lengths extracted for the octupole states in $^{48-52}$Ca using the coupled-channels code ECIS95 [16] and the global optical potential of Ref. [17] are shown in Fig. 3c. ECIS does not allow for the input of non-integer spins, so to analyze the cross sections in the odd-A isotopes, the experimental cross sections were first multiplied by the factor $(2\lambda + 1)(2j + 1)/(2I + 1)$, which is taken from the weak coupling result in [18]. Here, λ is the angular momentum of the phonon (in this case 3), j is the angular momentum of the single nucleon being coupled to the phonon (here $j = 3/2$), and I is the angular momentum of the multiplet member in the odd-A nucleus. Then, ECIS is used to find the deformation length δ_3 that fits each multiplet member. The deformation length for each multiplet member is shown in Fig. 3c. Even the deformation lengths for the odd-A multiplet members are remarkably constant near 1 fm, validating the weak-coupling interpretation for these multiplets.

To conclude, the (p, p') reaction in inverse kinematics has been used to measure $^{48-52}$Ca. The energies and strengths of the octupole states in these isotopes are remarkably constant with changing neutron number, providing strong evidence that these octupole states are dominated by proton excitations. This is even true for the odd-neutron ^{49,51}Ca isotopes, in which the weak coupling of the odd neutron to the core even-even nuclei appears to describe the observed behavior well. This is in strong contrast with the 2_1^+ states, for which the energies vary strongly with neutron number. This behavior is consistent with the 2_1^+ states being dominated by neutron excitations.

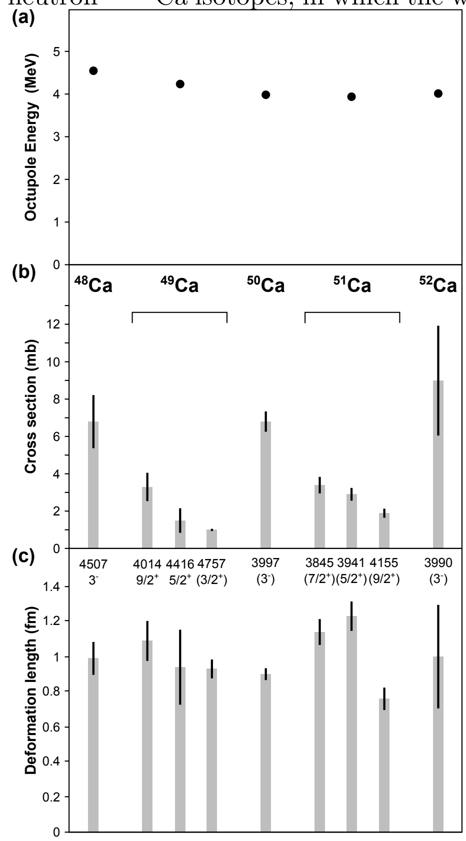

FIG. 3. (a) Energies (b) proton-scattering cross sections, and (c) proton-scattering deformation lengths of octupole excitations in $^{48-52}$Ca.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under Grant Nos. PHY-1303480, PHY-1064819, and PHY-1102511. GRETINA was funded by the US DOE - Office of Science. Operation of the array at NSCL is supported by NSF under Cooperative Agreement PHY-1102511(NSCL) and DOE under grant DE-AC02-05CH11231(LBNL). We also thank T.J. Carroll for the use of the Ursinus College Parallel Computing Cluster, which is supported by NSF grant no. PHY-1205895.

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