SYSTEMATICS OF 3^- AND 5^- STATES IN $Ca^{40,42,44,48}$ AND Ti^{50} FROM INELASTIC ALPHA SCATTERING*

A. M. Bernstein and E. P. Lippincott
Physics Department and Laboratory for Nuclear Science,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 6 July 1966)

From the scattering of 31-MeV alpha particles the existence of three 3^- states in $Ca^{40,48}$, six 3^- states in $Ca^{42,44}$, and a 5^- state in $Ca^{40,42,48}$ (two in Ca^{44}) have been found. The fractionation of the 3^- strength and the rapid and similar drop of 3^- and 5^- strength in going from $A=40$ to $A=50$ appear to be in disagreement with current ideas about the nature of these states.

An important advance in theoretical nuclear spectroscopy in the past few years has been a microscopic description of negative-parity collective states by the particle-hole model.[1] In particular, the 3^- and 5^- states of Ca^{40} have been calculated.[2] The result, which is characteristic of this model, is that one 3^- state is moved downward in energy from its unperturbed position towards the ground state and takes up most of the octupole strength. In previous inelastic scattering experiments, performed both in this laboratory[3] and elsewhere,[4,5] three strong 3^- states were located in Ca^{40}. These results disagreed with the calculation in that the two higher energy 3^- states were found at a lower energy and with more relative strength than was predicted. In this Letter we present data which show that the 3^- strength is also strongly fractionated in $Ca^{42,44,48}$ and Ti^{50}. In addition, there is a surprisingly rapid drop in the total strength of the 3^- and 5^- states between $A = 40$ and $A = 50$.

A (31.0 ± 0.5)-MeV alpha-particle beam produced by the MIT cyclotron was scattered by approximately 1-mg/cm^2, enriched isotopic foils and detected by a solid-state detector. The beam intensity of $\approx 0.25\ \mu A$ and the resolution of 90 to 100 keV are a considerable improvement over the previous experiment.[3] Absolute differential cross-section measurements have been made to an accuracy of 10%. Within the experimental error, the elastic cross sections for the Ca isotopes are equal at corresponding maxima for angles less than 55°. Spin and parity assignments were made by comparing the differential cross sections with the distorted-wave Born-approximation (DWBA) theory.[6]

Figure 1(a) compares the DWBA curves with the data for the lowest 2^+, 3^-, and 5^- states in Ca^{40}, whose spins and parities have been previously determined.[7] The high quality of the fits (for angles smaller than 55°) and the differences between states of different spin, indicate how spin assignments are made. In general, the strongly excited states of a given spin and parity have cross sections which are remarkably similar in shape. This is illustrated in Fig. 1(b) for four 3^- states in Ca^{42}, and in Figs. 1(c) and 1(d) for the lowest 3^- and 5^- states in the Ca isotopes. Note the rapid decrease in magnitude in advancing through the shell.

Table I presents the excitation energies and relative strengths[8] for the 3^- and 5^- states found in this experiment. A striking feature of the results is the number of relatively strong 3^- states.[9] These data agree with the previous results for Ca^{40}.[3,4,5] A recent (α, α') experiment on $Ca^{42,44,48}$ at 42 MeV has also found several of the stronger 3^- and 5^- states seen in this experiment.[10] In addition, splitting of the 3^- strength has been observed in other nuclei. Two 3^- states have been identified in Fe^{54},[10] in Ti^{48},[11] and possibly in Ni and Zn isotopes.[12] Three or more 3^- states have been found in S^{32},[13] Cr^{52},[10,14] and Zr^{90}.[15] The fractionation of the 3^- strength appears to be quite general in medium-weight nuclei.

Since calculations of the 3^- state for the nuclei studied in this experiment have been carried out only for Ca^{40}, a detailed comparison with theory cannot be made, but the present experimental results appear to be in qualitative disagreement with the present form of the particle-hole model. First, as is discussed in detail in Ref. 3, the large relative strengths of the upper two 3^- states in Ca^{40} are not predicted by the existing calculations. Second, we consider the effects of adding "valence" nucleons quite surprising. There is the 50% decrease in strength of the lowest 3^- state in going from Ca^{40} to Ca^{42}, and the 35% relative decrease in going from Ca^{48} to Ti^{50}. The sums

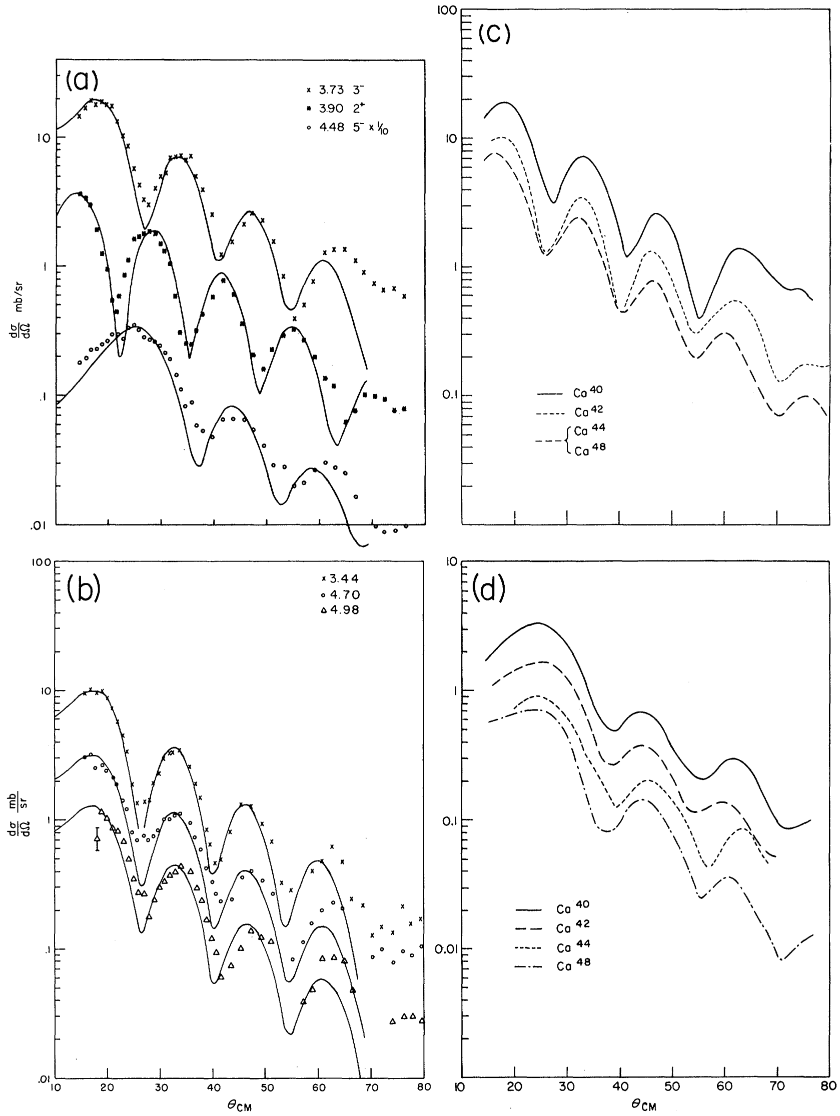

FIG. 1. Differential cross sections for the (α, α') reactions near 31 MeV. All cross sections are absolute with an error of 10% in each point. Figure 1(a) shows the cross section to the known 3^-, 2^+, and 5^- states in Ca^{40}. The solid lines are DWBA fits. Figure 1(b) shows the cross sections of three 3^- states in Ca^{42}. The solid lines are DWBA fits. Figures 1(c) and 1(d) show cross sections of the lowest 3^- and 5^- states, respectively, in the Ca isotopes studied. In this case, only lines drawn through the data are shown for clarity.

of the strengths of the 3^- states which are presented in Table II drop monotonically from $A = 40$ to $A = 50$. Another large effect of the "valence" nucleons is the presence of six 3^- states in Ca^{42} and Ca^{44} while there are three 3^- states in the closed-shell nuclei Ca^{40} and Ca^{48}. Another aspect of this can be seen by reference to Table II. The sum of the strengths of the higher excited 3^- states, relative to the lowest 3^- state in each nucleus, reaches a maximum in Ca^{44} which indicates the role of the "valence" neutrons in redistributing the octupole strength. The last column of Table II gives the relative strength of the 5^- states. In Ca^{44} we have used the sum of the strengths of the two states that were found. It is interesting that the 5^- strength drops in going from Ca^{40} to Ca^{44} only somewhat more rapidly than the 3^- strength. This similarity is quite unexpected on the basis of the particle-hole model because, in Ca^{40}, excitation of a particle into the $f_{7/2}$ shell is much more important for the 5^-

Table I. Strength of 3^- and 5^- states.

Nucleus	Excitation energy (MeV)	Relative 3^- strength: Normalized to lowest 3^- state in each nucleus (%)	Relative 3^- strength: Normalized to lowest 3^- state in Ca^{40} (%)
		3^- states	
Ca^{40}	3.73	100	100
	6.29	28	28
	6.58	16	16
Ca^{42}	3.44	100	51
	4.70	36	17
	4.98	14	7.1
	5.52	8	4.0
	5.68	11	5.6
	6.17	17	8.7
Ca^{44}	3.30	100	34
	4.38	42	14
	4.90	20	6.9
	5.22	16	5.6
	5.65	22	7.6
	7.02	16	5.4
Ca^{48}	4.50	100	34
	5.37	18	6.3
	7.68	51	18
Ti^{50}	4.42	100	22
	7.10	57	13
		5^- states	
		Relative 5^- strength normalized to 5^- state in Ca^{40} (%)	
Ca^{40}	4.48	100	
Ca^{42}	4.10	51	
Ca^{44}	3.91	25	
	4.55	12	
Ca^{48}	5.73	22	

Table II. Sums of strengths of 3^- and 5^- states.[a]

Nucleus	Number of 3^- states	Sum of strengths of higher excited 3^- states relative to the lowest 3^- state (%)	Sum of total 3^- strength in each nucleus relative to the total 3^- strength in Ca^{40} (%)	Total 5^- strength in each nucleus relative to the Ca^{40} 5^- state (%)
Ca^{40}	3	44	100	100
Ca^{42}	6	86	65	51
Ca^{44}	6	116	51	37
Ca^{48}	3	69	40	22
Ti^{50}	2	57	24	...

[a]See Ref. 8.

state than it is for the 3^- state.[3] Therefore, as $f_{7/2}$ neutrons are added, one would expect a much larger effect on the 5^- state.

A general feature of collective models that seems to be qualitatively violated by these experimental results is that the strengths do not increase when the states move nearer to the ground state, and in fact decrease in going from Ca^{40} to Ca^{44}. A possible explanation is that there is a large decrease in the ground-state correlations in going from Ca^{40} to Ca^{44}. This could decrease the transition rates to the 3^- and 5^- states in Ca^{42} and Ca^{44} relative to Ca^{40} in approximately the same way. At the present time there is evidence for an effect of this type from stripping reactions.[16] This implies that more complicated particle-hole configurations will have to be taken into account in future calculations.

We would like to thank the cyclotron staff for their help with the experiment, and several of our colleagues for their careful reading of this manuscript. We wish to thank the authors of the several unpublished papers for sending us their results before publication.

---

*This work is supported in part through funds provided by the Atomic Energy Commission under Contract No. AT(30-1)-2098.

[1]G. E. Brown, Unified Theory of Nuclear Models (North-Holland Publishing Company, Amsterdam, 1965). This book contains a description of the particle-hole model and references to the original literature.

[2]Vincent Gillet and E. A. Sanderson, Nucl. Phys. 54, 472 (1964).

[3]R. W. Bauer, A. M. Bernstein, G. Heymann, E. P. Lippincott, and N. S. Wall, Phys. Letters 14, 129 (1965).

[4]J. Saudinos et al., Compt. Rend. 252, 260 (1961); W. S. Gray, J. J. Kraushaar, and R. A. Kenefick, Nucl. Phys. 67, 565 (1965).

[5]D. Blum, R. Barreau, and J. Bellicard, Phys. Letters 4, 109 (1963).

[6]R. H. Bassel, G. R. Satchler, R. M. Drisko, and E. Rost, Phys. Rev. 128, 2693 (1962).

[7]L. P. Leenhouts and P. M. Endt, Phys. Letters 5, 69 (1963); M. A. Grace and A. R. Poletti, Nucl. Phys. 78, 273 (1966).

[8]The DWBA analysis has been performed following Ref. 6 in which a collective model of the nuclear states has been assumed. The strength of a state is taken as β_l^2, where β_l is the fractional root-mean-square deformation of the ground state. The relative values of β_l^2 are approximately equal to the relative cross sections. The absolute value of β_3 for Ca^{40} (3.73 MeV) is 0.24, in good agreement with the value found in the Ca^{40} (e,e') experiment.[5]

[9]In Ti^{50} only two 3^- states and no 5^- states were found. This may not be significant, however, since the target used was only 70% isotopically pure, whereas the Ca targets used were ≥95% pure.

[10]R. J. Peterson, Phys. Rev. 140, B1479 (1965); thesis, University of Washington (1966) (unpublished). The Ca targets used in this experiment were thin (particularly Ca^{48}) and contained large C and O contaminations which precludes proper identification of weaker states.

[11]K. Matsuda, Nucl. Phys. 33, 536 (1962).

[12]H. W. Broek, Phys. Rev. 130, 1914 (1963).

[13]R. Lombard, P. Kossangi-Demag, and G. R. Bishop, Nucl. Phys. 59, 398 (1964).

[14]J. Bellicard, P. Barreau, and D. Blum, Nucl. Phys. 60, 319 (1964); J. R. Meriwether, I. Gabrielli, D. L. Hendrie, J. Mahoney, and B. G. Harvey, Phys. Rev. 146, 712 (1966).

[15]E. J. Martens and A. M. Bernstein, to be published.

[16]T. A. Belote, A. Sperduto, and W. W. Buechner, Phys. Rev. 139, B80 (1965); E. Kashy, A. Sperduto, H. A. Enge, and W. W. Buechner, Phys. Rev. 135, B865 (1964); W. E. Dorenbusch, T. A. Belote, and Ole Hanson, Phys. Rev. 146, 734 (1966); T. A. Belote, J. Rapaport, and W. E. Dorenbusch, to be published.

ANOMALOUS ISOTOPE SHIFT OF THE NUCLEAR CHARGE RADIUS*

F. G. Perey
Oak Ridge National Laboratory, Oak Ridge, Tennessee

and

J. P. Schiffer
Argonne National Laboratory, Argonne, Illinois
(Received 11 July 1966)

It is shown that the isospin dependence of the shell-model potential gives rise to the experimentally observed "anomalous" isotopic shift of nuclear charge radii. The charge radii calculated from a Woods-Saxon potential are in qualitative agreement with experimental determinations from electron scattering and from muonic x rays.

The purpose of the present note is to point out that the isospin-dependent term in the optical potential[1] naturally brings about anomalies in the isotopic shift of the nuclear charge distribution, of the type that have been observed in a series of recent experiments on muonic x rays[2,3] and electron scattering[4] as well as in earlier results on the optical isotope shift.[5] This anomaly consists in the experimental observation that within the isotopes of one element