Lifetimes of the $(f_{7/2})^3\ \frac{15}{2}^-$ states in ^{51}V and ^{43}Ca and $(f_{7/2})^2\ 4^+$ states in ^{50}Ti and ^{42}Ca via heavy-ion recoil-distance-method measurements*

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(Received 18 March 1974)

The recoil-distance method has been used in conjunction with heavy-ion reactions to measure the following mean lifetimes: $\tau=8.0\pm0.6$ and 34.1 ± 1.5 psec for the $(f_{7/2})^3\ (\frac{15}{2}^-)$ states at 2700 keV in ^{51}V and at 2754 keV in ^{43}Ca, and $\tau=7.7\pm1.5$ and 5.1 ± 0.4 psec for the $(f_{7/2})^2\ 4^+$ states at 2676 keV in ^{50}Ti and at 2752 keV in ^{42}Ca, respectively. The resulting $B(E2)$ strengths are interpreted in terms of effective charges for different model spaces.

[NUCLEAR REACTIONS ^{48}Ca(^{6}Li, $3n$) $E=26$ MeV, ^{48}Ca(^{6}Li, $p3n$) $E=26$ MeV, ^{48}Ca(^{7}Li, $4n$) $E=28$ MeV, ^{27}Al(^{18}O, pn) $E=30$, 35 MeV, ^{27}Al(^{18}O, $p2n$) $E=30$, 35 MeV, ^{27}Al(^{19}F, $2pn$) $E=36$ MeV; measured recoil distance. Deduced $T_{1/2}$, $B(E2)$, effective charges. Natural and enriched targets, Ge(Li) detector.]

The properties of $E2$ effective charges have been carefully investigated for nuclei around ^{208}Pb by Astner *et al.*[1] Their effective-charge results successfully account for core-polarization contributions to the $E2$ γ-ray transitions between the pure shell-model states in this region. A similar investigation[2] has recently been carried out in the region $40<A<56$ where the $1f_{7/2}$ shell is most important. For these nuclei, the influence of wave function admixtures in the effective-charge analysis is minimized by studying transitions between high spin states. Recent microscopic calculations by Kuo and Osnes,[3] of $E2$ effective charges near ^{40}Ca and the related isospin structure of the giant $E2$ resonances, give an added interest to these investigations. Two unmeasured $B(E2)$ strengths of considerable importance to this effective charge analysis involve the γ-ray decay of the states of maximum spin $(f_{7/2})^3\ \frac{15}{2}^-$ for three protons in ^{51}V and for three neutrons in ^{43}Ca. The purpose of the present paper is to report on recoil-distance method (RDM) lifetimes measurements, carried out with heavy-ion (HI) reactions, of the states strongly believed to be these $\frac{15}{2}^-$ states[4-6] in ^{51}V and ^{43}Ca. Lifetimes of the $(f_{7/2})^2\ 4^+$ states in ^{50}Ti and ^{42}Ca were also obtained as part of the present experiment. The $E2$ effective charges for these transitions are extracted from the resulting experimental $B(E2)$ strengths for $(f_{7/2})^n$ and $(fp)^n$ wave functions. These results allow a very complete interpretation of effective charge systematics for the $40<A<56$ region. An estimate of the core-polarization charge in ^{42}Ca has been made including $(fp)^4(sd)^{-2}$ configurations.

Rigorous spin-parity assignments have not been made for the $(f_{7/2})^3\ (\frac{15}{2}^-)$ states at 2700 keV in ^{51}V and at 2754 keV in ^{43}Ca,[5-7] because for high-spin states, γ-ray spatial correlations are the only rigorous experiments available and unfortunately for

$$J_i \xrightarrow{L} J_f$$

transitions with low L and high J_i, J_f, they are not uniquely sensitive to J_i and J_f. However, the circumstantial evidence for these assignments is quite strong. γ-ray studies following α-induced reactions leading to ^{51}V [5] and ^{43}Ca [6] strongly favor $J^\pi=\frac{15}{2}^-$ for these states. In the present HI-reaction experiment, the γ-ray angular distributions are in agreement with $\frac{15}{2}^-(E2)\frac{11}{2}^-(E2)\frac{7}{2}^-$ cascades, the HI excitation measurements when compared with local systematics and reaction-mechanism predictions favor the $\frac{15}{2}^-$ assignments, and the present lifetime results along with the lack of ground-state transitions also favor $\frac{15}{2}^-$ assignments. In addition, the energies of these states are consistent with the energy systematics of other $(f_{7/2})^{\pm3}$ states and theoretical expectations.[2]

To explore the most advantageous way to populate the high spin states of interest, γ-ray excitation studies of (HI; xp, yn) evaporation-type reactions[8] were made. Several were found to have large cross sections for exciting these states. In addition, the large recoil velocities of the residual nuclei that result from these HI-induced reactions have a considerable advantage for the RDM,[9] which is the technique required for the range of lifetimes of the present experiment. On the basis of a previous experimental survey[10] of Li-induced reactions and a systematic study[11] of the bombardment of (sd)-shell nuclei with O and F beams, the RDM lifetime measurements of the $(f_{7/2})^3(\frac{15}{2}^-)$ states in ^{51}V and ^{43}Ca and the $(f_{7/2})^2$ 4^+ states in ^{50}Ti and ^{42}Ca were carried out with the following HI reactions and beam energies: ^{48}Ca(^{6}Li, $3n$)^{51}V and ^{48}Ca-(^{6}Li,$p3n$)^{50}Ti at 26 MeV; ^{48}Ca(^{7}Li, $4n$)^{51}V at 28 MeV; ^{27}Al(^{18}O,pn)^{43}Ca and ^{27}Al(^{18}O,$p2n$)^{42}Ca at 30 and 35 MeV and ^{27}Al(^{19}F, $2pn$)^{43}Ca at 36 MeV. The level schemes and the transitions of interest for the four nuclei are shown in Figs. 1–3.

The RDM (plunger) apparatus used for the present measurements has been described previously in detail.[12] Targets for these measurements were of metallic ^{48}Ca ~ 150 μg/cm^2 thick evaporated onto a stretched 5 mg/cm^2 Au foil and of metallic Al ~ 250 μg/cm^2 thick either as a stretched foil or as an evaporated film on a stretched 1.1 mg/cm^2 Ni foil. The γ-ray spectra were measured with a Ge(Li) detector at 0° with respect to the beam. For each of the cases of interest, the stopped peak (I_0) was clearly resolved from the shifted peak (I_s). Typical γ-ray spectra taken for certain target-to-plunger separation distances D are shown in Figs. 1–3. The recoil velocities were extracted from the γ-ray spectra; average values for the Li induced reactions were ~0.9%c and those for the heavier ion reactions ~2.1%c. The ratios $R = I_0/(I_0 + I_s)$ as a function of D were evaluated from the peak areas I_0 and I_s following subtraction of a fitted background. One set of $R(D)$ data out of several of each

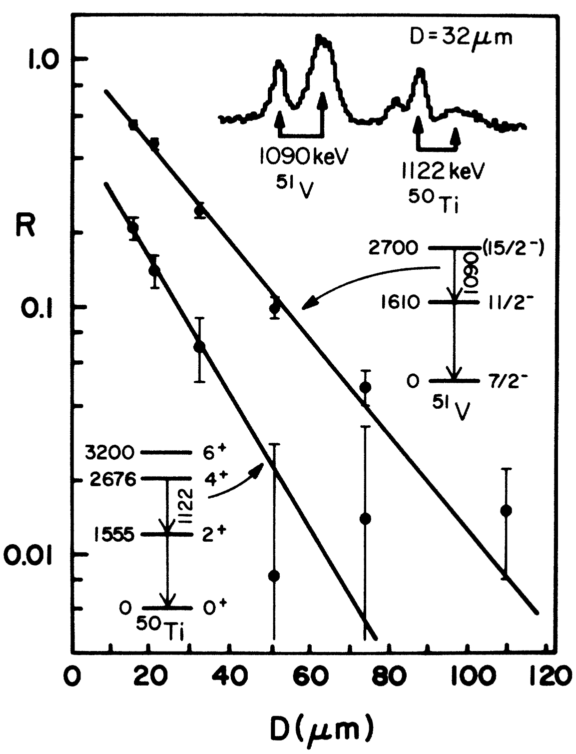

FIG. 1. Recoil-distance γ-ray spectrum and lifetime decay curves for the indicated ^{51}V$(\frac{15}{2}^-)\rightarrow\frac{11}{2}^-$ and the ^{50}Ti $4^+\rightarrow 2^+$ transitions. A portion of the γ-ray spectrum is inserted for a stopper distance $D = 32$ μm to show for a typical data point the stopped and shifted peaks I_0 and I_s. The decay curve data $R = I_0/(I_0+I_s)$ are plotted against the stopper distance D. Background ratios observed at large distance have been subtracted. The background ratios for ^{50}Ti are significant because of cascade feeding from the long-lived 6^+ state. The curve though the data points represents a least squares fit to theory.

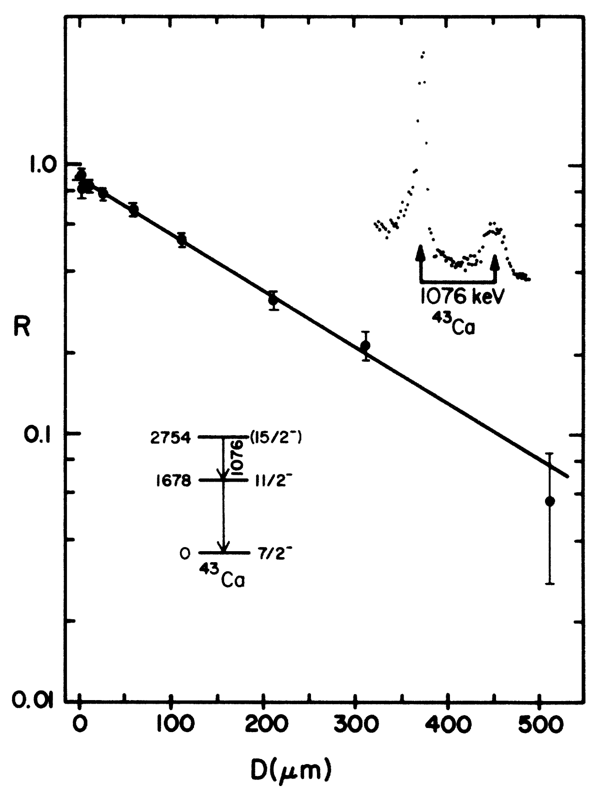

FIG. 2. Recoil-distance γ-ray spectrum and lifetime decay curve for the ^{43}Ca$(\frac{15}{2}^-)\rightarrow\frac{11}{2}^-$ transition. A portion of the γ-ray spectrum for stopper distance $D = 60$ μm is inserted to show the separation of the stopped and shifted peaks I_0 and I_s. The decay curve data $R = I_0/(I_0+I_s)$ are plotted against the stopper distance D. Background ratios observed at large distance have been subtracted. The curve through the data points represents a least squares fit to theory.

TABLE I. Mean lifetimes and experimental $B(E2)$ values from the present experiment.

Nucleus	Transition	τ (psec)	$B(E2)$ (e^2 fm^4)
^{51}V	$(\frac{15}{2}^-)\to\frac{11}{2}^-$	8.0 ± 0.6	66 ± 5
^{50}Ti	$4^+\to2^+$	7.7 ± 1.5	60 ± 12
^{43}Ca	$(\frac{15}{2}^-)\to\frac{11}{2}^-$	34.1 ± 1.5	16.6 ± 0.7
^{42}Ca	$4^+\to2^+$	5.1 ± 0.4	58 ± 5

case is shown in Figs. 1–3. Contributions to the ratios R for cascade feeding via the long lived 6^+ states for ^{50}Ti and ^{42}Ca have been subtracted as well as the small distance-independent background ratios observed at large D. Uncertainties of ±1.2 μm have been assigned to the relative distances D. The ratios $R(D)$ were fitted with a theoretical expression[9] that includes the observed spread in recoil velocities. These fits which yield the lifetimes are shown in Figs. 1–3 as solid lines. The mean lifetime results are collected in Table I. Corrections[9] for the detector solid angle and efficiency have been made.

Of the four lifetime results summarized in Table I, there is previous lifetime information available only on the ^{42}Ca 4^+ state. Recent Doppler shift attenuation method (DSAM) results for this state are $\tau=1.8^{+2.0}_{-1.0}$, $2.9^{+2.0}_{-1.0}$, and 2.3 ± 1.0 psec.[4,13] A previous RDM result of $\tau=11.5\pm2.5$ psec obtained with the (α,p) reaction contained an unexpectedly large systematic error because of difficulties in subtracting the 6^+ state feeding when I_0 and I_s were not completely resolved.[14] A reanalysis of this data, in terms of a lower limit which is not very sensitive to this subtraction, gives a value $\tau>4$ psec. The present RDM result for the ^{42}Ca 4^+ state is $\tau=5.1\pm0.4$ psec which does not agree within the quoted uncertainties with the weighted average of the DSAM results.

The $E2$ effective charges for these transitions are obtained from a comparison of the experimental $B(E2)$ values with the corresponding theoretical values calculated for a given wave function truncation. The experimental $B(E2)$ values deduced from the present lifetime results are listed in Table I. Theoretical $B(E2)$ values for $(f_{7/2})^n$ wave functions are calculated in a straightforward manner, and the resulting effective charges are listed in Table II. The effective proton charges extracted from the $(\frac{15}{2}^-)\to\frac{11}{2}^-$ ^{51}V and the $4^+\to2^+$ ^{50}Ti transitions are consistent with the range $e_p=1.7$–2.0 obtained[2] for all $E2$ transitions in other 28-neutron isotones. The neutron effective charge extracted with these wave functions for the $(\frac{15}{2}^-)\to\frac{11}{2}^-$ ^{43}Ca transition agrees with e_n for other transitions between high

TABLE II. $E2$ effective charges from a comparison of experimental and calculated $B(E2)$ values for different wave functions. (The $(fp)^n$ wave functions are from Ref. 15).

Nucleus	Transition	Effective charge (e) $(f_{7/2})^n$	$(fp)^n$
^{51}V	$(\frac{15}{2}^-)\to\frac{11}{2}^-$	1.94 ± 0.07	
	$\frac{11}{2}^-\to\frac{7}{2}^-$	1.90 ± 0.16[a]	
^{50}Ti	$6^+\to4^+$	1.88 ± 0.03[a]	
	$4^+\to2^+$	1.69 ± 0.16	
	$2^+\to0^+$	1.76 ± 0.11[a]	
^{43}Ca	$(\frac{15}{2}^-)\to\frac{11}{2}^-$	1.03 ± 0.02	0.81 ± 0.02
	$\frac{11}{2}^-\to\frac{7}{2}^-$	1.60 ± 0.26[a]	1.33 ± 0.22[a]
^{42}Ca	$6^+\to4^+$	0.87 ± 0.01[a]	0.67 ± 0.01[a]
	$4^+\to2^+$	1.75 ± 0.07	1.44 ± 0.06
	$2^+\to0^+$	2.08 ± 0.04[a]	1.73 ± 0.03[a]

[a] Experimental data from Ref. 2.

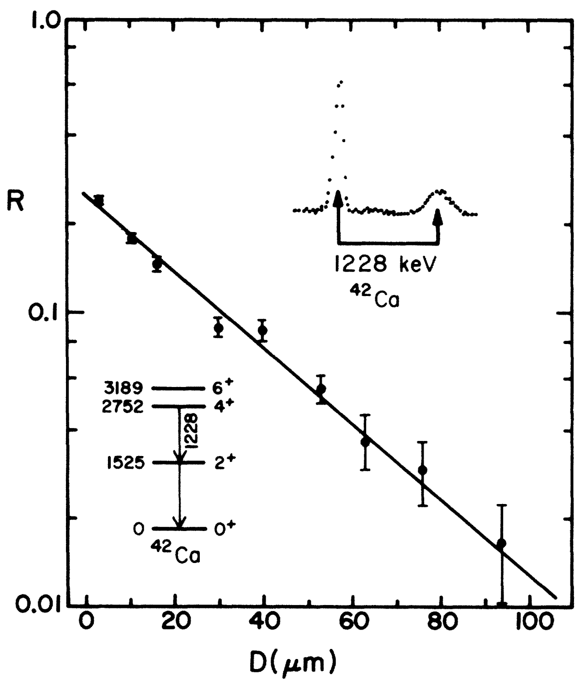

FIG. 3. Recoil-distance γ-ray spectrum and lifetime decay curve for the ^{42}Ca $4^+\to2^+$ transition. A portion of γ-ray spectrum for a stopper distance $D=92$ μm is inserted to show the separation of the stopped and shifted peaks I_0 and I_s. The decay curve data $R=I_0/(I_0+I_s)$ are plotted against the stopped distance D. Background ratios observed at large distance, which result mainly from cascade feeding from the long-lived 6^+ state, have been subtracted. The curve through the data points represents a least squares fit to theory.

spin states in the low mass Ca isotopes, although transitions between lower spin states including the $4^+ \to 2^+$ ^{42}Ca transition show enhanced e_n values which presumably result from deformed core contributions.[2] The effective charges for the $\frac{11}{2}^- \to \frac{7}{2}^-$ transitions in ^{51}V and ^{43}Ca and the $6^+ \to 4^+$ and $2^+ \to 0^+$ transitions in ^{50}Ti and ^{42}Ca are also given in Table II for comparison purposes.

The neutron effective charges have also been extracted for the expanded $(fp)^n$ wave functions of McGrory[15]; they are listed in Table II. The e_n for the $E2$ transitions in ^{43}Ca and ^{42}Ca are reduced by ~20% in comparison with those from the $(f_{7/2})^n$ wave functions. The influence of the $p_{3/2}$ orbital is observed considerably more strongly in the effective-charge comparisons for the Sc isotopes.[2] The extraction of effective charges with $(fp)^n$ wave functions for the 28-neutron nuclei is complicated by the neutron core excitations which are required to achieve wave functions of good isospin[16]; recent calculations show the effective charges for these nuclei to be comparable to those for the high spin transitions in nuclei near ^{40}Ca.[17]

Effective charge calculations[2] for $(fp)^{n+m}(sd)^{-m}$ wave functions that are more directly related to core-polarization contributions yield a further reduction, for example, $\delta e = 0.49 \pm 0.3$ for the $4^+ \to 2^+$ transition in ^{42}Ca, assuming $e_n = \delta e$ and $e_p = 1 + \delta e$. These calculations give essentially the same value for the ^{42}Ca $6^+ \to 4^+$ transition but leave the δe for the $2^+ \to 0^+$ transition still slightly enhanced. This larger model space has also been used for the nuclei near ^{40}Ca to explore the isospin properties of the core-polarization effective charges.[2]

Note added in proof: K. P. Lieb and M. Uhrmacher [Z. Phys. 267, 399 (1974)] have used ^{28}Si + ^{16}O and the RDM to measure mean lifetimes of 39 ± 5 and 3.8 ± 0.4 psec for the 2754-keV level of ^{43}Ca and the 2752-keV level of ^{42}Ca, respectively. The ^{43}Ca result is in agreement with our value of 34.1 ± 1.5 psec, the ^{42}Ca result disagrees somewhat with our result of 5.1 ± 0.4 psec.

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*Work supported in part by the National Science Foundation, the U.S. Atomic Energy Commission, and the New Zealand University Research Grants Committee.

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