Lifetimes of the First and the Third Excited States of Ca^{41}†

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The lifetimes of the $\frac{3}{2}^-$ first excited state of Ca^{41} at $E_x = 1.95$ MeV and the $\frac{3}{2}^-$ third excited state at $E_x = 2.47$ MeV have been measured by the attenuated-Doppler-shift method. The two states were populated through the $K^{41}(p,n)Ca^{41}$ reaction at bombarding energies only a little above threshold. The γ rays were detected with a lithium-drifted germanium detector. Measurements were made at 0° and 90° to the beam and with Ca^{41} ions recoiling into vacuum, carbon, KCl, and gold. Some attenuation of the Doppler shift results from the recoiling ion changing its direction on collision with a nucleus. At the low recoil velocities encountered, this effect is comparable with the attenuation due to the energy loss in electronic collisions and it was explicitly taken into account. The lifetime of the first excited state was found to be $(4.7_{-1.0}^{+2.5})\times10^{-13}$ sec; that of the third excited state is $\geqslant 7\times10^{-13}$ sec. The speed of the $E2$ transition to ground from the first excited state is thus about three times the Moszkowski single-particle estimate. In contrast, the speed of the $E2$ ground-state transition from the third excited state (which decays mainly to the first excited state) is less than 6×10^{-3} of the single-particle estimate. These results are compared with theoretical predictions.

I. INTRODUCTION

In the framework of the single-particle shell model, Ca^{41} consists of a single neutron in the $1f_{7/2}$ orbital outside the doubly magic core Ca^{40}. Low-lying excited states of Ca^{41} are then formed by placing the neutron sequentially into the $(2p_{3/2})$, $(2p_{1/2})$, and $(1f_{5/2})$ orbitals. If Ca^{40} is a good closed-shell nucleus, these states should be singlets and each should contain the orbital's entire single-particle strength. In contrast to this expectation, Ca^{41} is found to have two low-lying $\frac{3}{2}^-$ states (Fig. 1) between which the $p_{3/2}$ single-particle strength is roughly equally shared.[1] Several theoretical descriptions have now been put forward[2–4] to explain the level structure of Ca^{41}—in particular the presence of the two $\frac{3}{2}^-$ states. Since a critical test of these models is to compare their predicted γ-ray transition probabilities with the corresponding experimental values, it was decided to determine the lifetimes of the 1.95- and 2.47-MeV states in Ca^{41}.

Between the two $\frac{3}{2}^-$ states is the $\frac{3}{2}^+$ second excited state[5] at 2.01 MeV which, in a simple picture, can be taken to be a single-hole state of configuration $(d_{3/2})^{-1}\times(f_{7/2})^2$. The low cross section for the (d,p) reaction,[5] the $Ca^{42}(p,d)$ data,[6] and the speed of the $M2$ transition to the ground state[7] (which shows the typical retardation for a hole state[8]) all support this description.

The attenuated-Doppler-shift method was used to measure the lifetimes of the two $\frac{3}{2}^-$ states. In the present experiment, the initial velocity and direction of the recoiling Ca^{41*} nuclei are fixed by the kinematics of the reaction. These recoils then slow down in a medium and the (average) velocity at the time the γ ray is emitted is determined by measuring the Doppler-shifted energy

$$E_\gamma = E_{\gamma 0}[1+(v/c)\cos\theta],$$

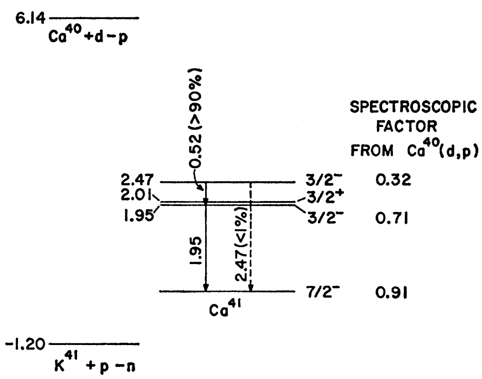

FIG. 1. Energy-level diagram showing the low-lying levels (MeV) of Ca^{41} of interest in the present work. The spectroscopic factors are from Ref. 20.

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[1] L. L. Lee, Jr., J. P. Schiffer, and D. S. Gemmell, Phys. Rev. Letters **10**, 496 (1963).
[2] R. Bock, H. H. Duhm, and R. Stock, Phys. Letters **18**, 61 (1955).
[3] B. J. Raz, in Proceedings of the Symposium on the Structure of Low-Medium Mass Nuclei, Dayton, Ohio, 1964, Aerospace Research Laboratories Report No. 65–63, p. 13 (unpublished).
[4] W. A. Gerace and A. M. Green, in Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee, 1966, paper 8.10 (unpublished).
[5] T. A. Belote, A. Sperduto, and W. W. Buechner, Phys. Rev. **139**, B80 (1965).
[6] J. L. Yntema (private communication).
[7] R. E. Holland and F. J. Lynch, Bull. Am. Phys. Soc. **10**, 1116 (1965).
[8] R. D. Lawson and M. H. Macfarlane, Phys. Rev. Letters **14**, 127 (1965).

or the shift

$$\bar{E}_\gamma - E_{\gamma_0} = (E_{\gamma_0}/c)\langle v\cos\theta\rangle_{\text{av}}. \tag{1}$$

Since the rate of slowing down can be computed (as discussed further below), the average velocity at the time of emission is an unambiguous measure of the lifetime of the emitting states.

The lifetime of the 1.95-MeV level has previously been measured via the attenuated-Doppler-shift method.[9] In that measurement, however, a NaI(Tl) crystal was used instead of the Ge(Li) detector employed in the present investigation. Because of the poor resolution of the NaI(Tl) crystal (a linewidth of 120 keV for 2-MeV γ rays), the small ($\sim$1 keV) Doppler shift was only marginally observable in the earlier work and this difficulty is reflected in the large errors in this previous result. Furthermore, the earlier work took no account of the direction changes that took place as the recoiling nuclei collided with atomic nuclei. The present study therefore represents a considerable refinement.

II. THE EXPERIMENTAL METHOD

Figure 1 shows the low-lying levels of Ca^{41} with their main γ decay branches. The states were populated by the $K^{41}(p,n)Ca^{41}$ reaction which is endoergic ($Q_0 = -1.20$ MeV). At bombarding energies close to threshold, the neutron carries off little momentum and therefore conservation of momentum confines the recoils to a narrow cone about the beam axis. The 1.95-MeV state was populated through a resonance 25 keV above threshold[9]; a resonance for production of the 2.47-MeV state was found about 55 keV above the threshold. At the bombarding energies used, the half-angle of the cone of recoiling nuclei is only about 1.5° and 3°, respectively, for these two states. The target material was KCl in which the potassium was enriched to about 99% K^{41}.

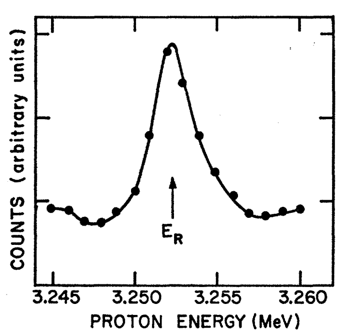

FIG. 2. Yield curve for the 1.95-MeV γ ray. The resonance at which the measurements on the first excited state were made is about 25 keV above threshold. This yield curve was taken with a 15 $\mu g/cm^2$ target, and the γ rays were detected with a NaI(Tl) crystal. The 1.95-MeV line was not completely resolved and much of the off-resonance yield was due to background. When targets as thick as about 50 $\mu g/cm^2$ were used, the resonance broadened and acquired a somewhat flat top. The uncertainty in the energy is $\pm$10 keV.

[9] C. M. Class, P. P. Singh, and S. S. Hanna, Bull. Am. Phys. Soc. 8, 358 (1963) and private communication.

Lifetimes were determined by measuring the attenuated Doppler shift in thick KCl targets. Data were taken at 0° and at 90°. In addition, for the 1.95-MeV level a series of measurements with recoils into vacuum, carbon, and gold with targets of varying thicknesses were performed in order to test the method. The targets were obtained by evaporating the KCl onto carbon foils and onto gold. Targets ranging in thickness from 2 to 60 $\mu g/cm^2$ were used. For recoil into vacuum, thin $K^{41}Cl$ targets (5 $\mu g/cm^2$) on carbon foils 10 $\mu g/cm^2$ thick were bombarded with the beam traversing the carbon before hitting the $K^{41}Cl$ target material. A thick gold beam stopper was placed $\sim$1 mm from the target. For the 90° (zero Doppler shift) measurements and for the recoil into gold, $K^{41}Cl$ layers of various thicknesses were evaporated onto the beam stopper. With adequate cooling these targets could withstand currents up to 2 μA.

Lithium-drifted germanium crystals detected the γ rays. During the course of the experiment several different detectors were used, ranging in size from 2.5 to 9 cm^3. Signals from the detectors were fed directly into a low-noise preamplifier, followed by the low-noise main amplifier and window amplifier. Output pulses from the window amplifier were then sorted and stored in a 1024-channel pulse-height analyzer. A half-width of 6 keV was typical for the 1.95-MeV line. Reference lines that bracketed the line being measured were recorded simultaneously. Energies were then determined relative to the reference lines. This was done with the aid of computer programs that decomposed each region of interest in each spectrum into a peak and a background. The data analysis characterized the position of each peak by its centroid, its median, and the center of the Gaussian that best fitted the peak. No significant difference was found in the Doppler shifts as determined by the various methods. In all of the analyses, it was demonstrated that the results were invariant under any reasonable assumptions as to the backgrounds under any of the peaks.

Figure 2 shows the yield curve of the 1.95-MeV γ ray in the region just above the threshold for formation of the 1.95-MeV state. All the measurements were made at the peak of the 3.25-MeV resonance, the width of which was found to be no greater than 2 keV. The spectra from two successive measurements, one at 0° and the other at 90°, are shown for comparison in Fig. 3, in which the 1.95-MeV line of Ca^{41} is bracketed by the 1.81- and 2.12-MeV reference γ lines from the Mn^{56} source. The energy of the 1.95-MeV γ line is clearly higher for the 0° measurement.

Before determining the position of the 1.95-MeV line, the small contribution from the single-escape peak from the 2.95-MeV transition from the Mn^{56} decay[10] had to be subtracted. Since the intensity of this Mn^{56} peak was never more than 10% of that of the 1.95-MeV line,

[10] P. Kienle and R. E. Segel, Phys. Rev. 114, 1554 (1959).

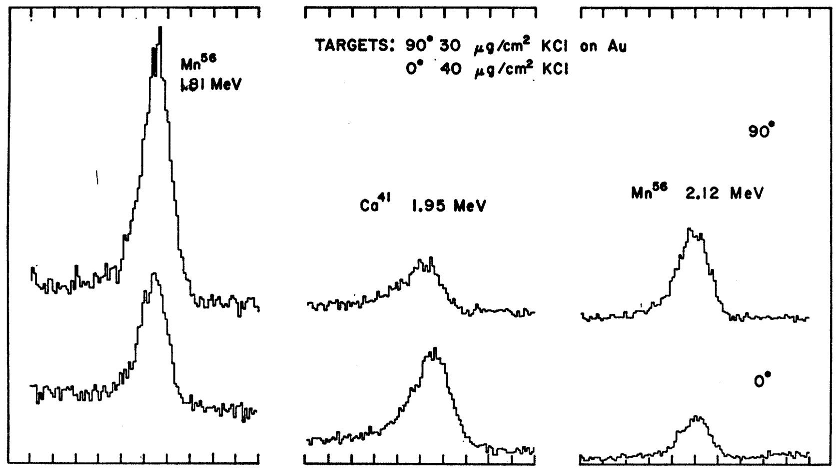

FIG. 3. Spectra showing the Doppler shift of the γ ray from the first excited state when the recoils are stopped in KCl. Small drifts between the two runs were compensated for by shifting the entire spectrum so that the reference lines show no shift. In the analyses, the position of the 1.95-MeV peak was always determined relative to the position of the reference lines.

any reasonable error in making this correction would produce only a negligible error in the shift of the 1.95-MeV line.

Table I summarizes the shifts obtained with various targets. At energies for which the target thickness was sufficient to give a flat top to the resonance, the beam energy was adjusted such that the resonance reaction took place near the front surface of the target. The range of the (80 keV) Ca^{41} recoils was only about 16 $\mu g/cm^2$; therefore, when the thicker KCl targets were used, virtually all of the Ca^{41} recoils would come to rest in the target. From the 0° data we find the shift for recoils stopping in KCl to be (0.90±0.15) keV. This is (23±4)% of the full shift, which is taken to be 3.88 keV as calculated from the kinematics. The present shifts are in good agreement with, but considerably more accurate than, the shifts that were measured by Class, Singh, and Hanna.[9]

A number of checks were made in order to test the validity of the measurements and ensure that consistent results were being obtained. One such check was to observe the increase in γ-ray energy as the thickness of the unbacked KCl targets was decreased—i.e., to measure E_γ for Ca^{41} recoiling into the vacuum after being only partially slowed down in the target. As expected, a larger percentage of the full shift was observed when unbacked targets of thickness less than the range of the recoils were used. In fact, the expected shift as a function of target thickness was calculated by use of the thick-target shift given above, and the experimental points were found to agree (to within experimental error) with the calculated values. Another check was to have the recoils from thin KCl targets stop in a material denser than KCl. In this case they slow down more rapidly and a smaller shift should be obtained. Indeed, only about 13% of the full shift was found when thin KCl targets backed by gold were used. Finally, since carbon has about the same effective slowing down time as KCl, about the same shift should be obtained with thin KCl on carbon as with thick KCl. When the recoils were stopped in carbon, a shift of (0.90±0.20) keV was found, in good agreement with the results from thick KCl targets. Thus, all of the checks confirmed the validity of the data. The extraction of a lifetime from the shift data is discussed below after the measurements on the 2.47-MeV state are presented.

Since the 2.47-MeV state decays predominantly[1] to the 1.95-MeV state, its lifetime was determined by Doppler-shift measurements on the 0.52-MeV connecting γ ray. In these measurements, the 2.47-MeV state was populated through the resonance observed at E_p =3.815 MeV (55 keV above threshold) in the yield curve for this γ ray. Although no coincidence requirements were needed for the measurements on the 1.95-MeV state, coincidences between the 0.52- and the 1.95-MeV transitions had to be recorded for the lifetime measurement of the 2.47-MeV state in order to isolate the 0.52-MeV line from annihilation radiation. The 0.52-MeV γ line was detected with the Ge(Li) detector and a NaI(Tl) crystal 25 cm in diameter by 20 cm thick was used to detect the 1.95-MeV γ ray. The NaI crystal was positioned at 90° to the incident beam and was close to the target so as to subtend as large a solid angle as possible. An additional coincidence circuit between the Ge(Li) and a second scintillation detector gated the reference lines. The second scintillation counter, a thin plastic, detected β rays from radioactive

TABLE I. Doppler shifts of the 1.95-MeV γ ray from the first excited state of Ca^{41}, as observed with different combinations of target thickness and backing. Each entry is the (weighted) average of more than one run.

Average target thickness (KCl) ($\mu g/cm^2$)	Backing	ΔE (keV)	$\Delta E/\Delta E_{full}$
50	vacuum	0.9±0.2	0.23±0.04
5	vacuum	2.3±0.3	0.60±0.06
13	gold	0.5±0.2	0.13±0.04
8	carbon	0.9±0.2	0.23±0.04

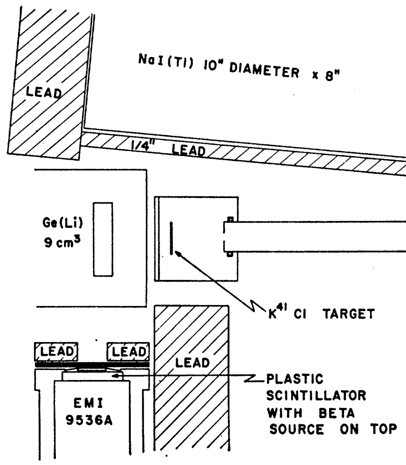

FIG. 4. Experimental arrangement for the Doppler-shift measurements on the third excited state. The NaI(Tl) crystal detected the 1.95-MeV γ ray and a coincidence with the Ge(Li) detector isolated the 0.52–1.95-MeV cascade. The plastic scintillator detected electrons so as to provide reference lines in the coincidence spectrum. The Ge(Li) detector was moved to 90° for the measurement of the unshifted line. For the measurements on the first excited state, only the Ge(Li) detector was used; it was simply moved from 0° to 90°.

sources that were mounted on the phosphor. Figure 4 shows the experimental arrangement that was used in the measurements on the upper $\frac{3}{2}^-$ state.

Figure 5 shows the coincident γ-ray spectra for (a) a 90° run with gold backing, (b) a 0° run with a thick (60 μg/cm^2) KCl target on a carbon backing, and (c) a 0° run with a thin (5 μg/cm^2) unbacked KCl target. These spectra were recorded with a dispersion of about 0.25 keV per channel. Calibrating peaks due to 0.56-, 0.50-, and 0.47-MeV γ rays are also shown. The lines through the peaks are the Gaussians fitted by use of the error-matrix minimization code.[11] When the recoils were allowed to emerge into vacuum, a Doppler shift of about 0.93 keV was observed. After correcting for the slowing down in the KCl, this value is in satisfactory agreement with the calculated full shift of 1.1 keV. On the other hand, no statistically significant Doppler shift was observed when the recoils were stopped in KCl. After combining the data from several pairs of measurements at 0° and at 90°, an upper limit of 220 eV (i.e., 20% of the full shift) was placed on the shift when the recoils are stopped in KCl. Limited counting statistics and the smallness of the full shift combined to limit the accuracy of this measurement.

III. DETERMINATION OF LIFETIMES

The mean energy of the γ rays at an angle θ to the initial recoil direction can be written

$$\bar{E}_\gamma = E_{\gamma_0}(1+F\cos\theta), \qquad (2)$$

where F multiplied by c is the average projection of the recoil velocity along the initial recoil direction. The experimental value of F can be obtained from the difference $\Delta\bar{E}_\gamma$ between mean γ-ray energies observed at two angles θ_1 and θ_2 through the relation

$$FE_{\gamma_0} = \Delta\bar{E}_\gamma / (\cos\theta_1 - \cos\theta_2). \qquad (3)$$

For any given lifetime, the value of F can be calculated if the slowing-down properties of the ion are known. In fact, we can write

$$F = \frac{1}{c}\left[\int_0^\infty e^{-t/\tau}\langle v(t)\cos\phi(t)\rangle_{\rm av}dt \bigg/ \int_0^\infty e^{-t/\tau}dt\right], \qquad (4)$$

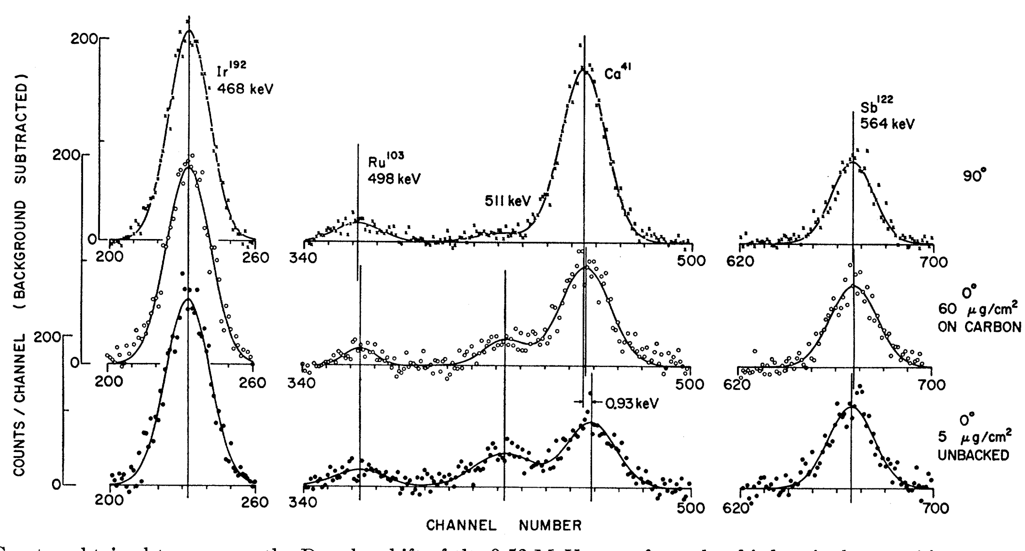

FIG. 5. Spectra obtained to measure the Doppler shift of the 0.52-MeV γ ray from the third excited state. After correcting for the slowing down in the target, the full shift was observed when the recoils were allowed to emerge into vacuum. The small shift observed when the recoils were stopped in KCl and carbon was not reproducible; only an upper limit could be placed on the shift.

[11] W. C. Davidon, Argonne National Laboratory Report No. ANL-5990, 1959 (unpublished); W. J. Snow, Argonne National Laboratory Report No. ANL-6904, 1964 (unpublished).

where v is the magnitude of the recoil velocity, ϕ is the angle between the recoil direction at time t and the initial recoil direction, and τ is the mean life of the state. The lifetime (i.e., mean life) is then extracted by determining over what range of lifetimes the calculated value of F agrees with the experimental value.

It is apparent that the essence of the extraction of the lifetime from the measured Doppler shifts consists in using the slowing-down properties of the recoil ion to establish a time scale for the γ decay. The ions lose energy both by interactions with the outer electrons and by nuclear collisions. For the higher recoil velocities, the interaction with the electrons predominates. These interactions produce little spread in angle. For velocities $v \lesssim (c/137)Z^{2/3}$, a condition which was well satisfied in the present case, the energy loss dE/dx due to electronic stopping is closely proportional to the ion velocity.[12] A simple expression for the specific energy loss in collisions with electrons has been given by Lindhard, Scharff, and Schiott,[12] although the experimental data[13] show a periodic Z dependence which does not appear in the theory. The present work made use of the theoretical values, which have been assumed to have a 20% uncertainty.

At ion velocities less than about 10^8 cm/sec, the energy loss due to nuclear collisions becomes significant[12]; and since the initial recoil velocities in the present experiment were about 10^8 cm/sec, these effects must be taken into account here. Nuclear collisions both slow down the recoils and scatter them in angle; these effects are discussed in some detail by Blaugrund.[14] The rate of energy loss can be approximated as varying inversely with the velocity,[15] and thus a simple expression for $v(t)$ can be obtained. Even more important than the energy loss in the nuclear collisions is the change in recoil direction (Fig. 6). Starting from the expression for a universal differential nuclear-scattering cross section given by Lindhard *et al.*,[12] Blaugrund[15] has developed an expression for $\langle\cos\phi(t)\rangle_{av}$. Expressions similar to those given by Blaugrund have been used in computing F by use of Eq. (4).

The accuracy to which F can be calculated obviously depends on the accuracy of the universal cross section of Lindhard *et al.*[12] Blaugrund, Youngblood, Morrison, and Segel[16] have summarized the experimental data and show that these allow a considerable uncertainty in the theoretical expression.

As mentioned above, the value of F for the 1.95-MeV

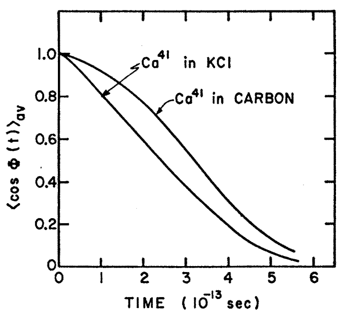

FIG. 6. Average cosine of the angle between the direction of the recoil at time t and the initial recoil direction for Ca^{41} ions of initial velocity 0.6×10^8 cm/sec.

state was measured for the recoils stopping in both carbon and KCl. The average change in direction was computed to be much larger when the recoils were stopped in KCl (Fig. 6). In Fig. 7 the calculated values of $F(\tau)$ for both stopping media are compared with the experimentally determined values. It can be seen that the two measurements lead to lifetimes that agree within the experimental errors. The different relative importances of the nuclear collisions in the two measurements render their agreement particularly significant. Further confirmation of the validity of the measurements is found in the fact, mentioned above, that the variation of the measured shifts with target thickness was in satisfactory agreement with the calculated curve. Combining the result obtained when the ions stopped in carbon $[\tau=(4.4_{-1}^{+3})\times10^{-13}$ sec, assumed density of the carbon foil backing $=1.6$ g/cm$^2]$ with those obtained when they stopped in KCl $[\tau=(5.0_{-1}^{+3})\times10^{-13}$ sec$]$, we find that the mean life of the 1.949-MeV state is

$$\tau_{1.95}=(4.7_{-1.0}^{+2.5})\times10^{-13}\text{ sec},$$

where the error includes the uncertainty in the slowing-down properties as well as the uncertainties in the measured Doppler shifts. Expressing the speed in single-particle units, as estimated by Moszkowski,[17] we find that the value (including the statistical factor) is $|M|^2=2.9_{-2.0}^{+0.8}$. The present result agrees with that of Class *et al.*[9]

For the 2.47-MeV state, the upper limit on F obtained

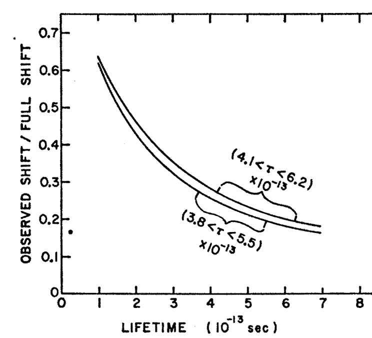

FIG. 7. Doppler shift as a function of lifetime when Ca^{41} recoils with an initial velocity of 0.6×10^8 cm/sec are stopped in KCl and C. The stated range of lifetimes allowed in each of the measurements includes no allowance for uncertainties in the slowing-down curves.

[12] J. Lindhard and M. Scharff, Phys. Rev. **124**, 128 (1961); J. Lindhard, M. Scharff, and H. E. Schiott, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. **33**, No. 14 (1963).

[13] L. C. Northcliff, Ann. Rev. Nucl. Sci. **13**, 67 (1963); J. H. Ormrod, J. R. MacDonald, and H. E. Duckworth, Can. J. Phys. **43**, 275 (1965); J. R. MacDonald, J. H. Ormrod, and H. E. Duckworth, Z. Naturforsch. **21a**, 130 (1966).

[14] A. E. Blaugrund, Nucl. Phys. (to be published).

[15] E. K. Warburton, D. E. Alburger, and D. H. Wilkinson, Phys. Rev. **147**, 2180 (1963).

[16] A. E. Blaugrund, D. H. Youngblood, G. C. Morrison, and R. E. Segel, this issue, Phys. Rev. **158**, 893 (1967).

[17] S. A. Moszkowski, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Vol. II, p. 865.

TABLE II. Partial lifetimes and strengths of the $E2$ transitions to the $\frac{7}{2}^-$ ground state from the two low-lying $\frac{3}{2}^-$ states in Ca^{41} and Sc^{41}.

Energy of state (MeV)	Partial lifetime (10^{-13} sec)	Strength (single-particle units) Moszkowski[a]	Woods-Saxon[b]	Reference
		Ca^{41}		
1.95	$4.5_{-1.0}^{+2.5}$	$2.9_{-1.0}^{+0.8}$	1.7 ± 0.6	c
2.47	>700	<0.006	···	c
		Sc^{41}		
1.71	5.2 ± 1.6	4.8 ± 1.5	2.2 ± 0.6	d
2.41	>210	<0.022	···	e

[a] Reference 17. [b] Reference 19. [c] Present work.
[d] D. H. Youngblood, J. P. Aldridge, and C. M. Class, Phys. Letters 18, 291 (1965).
[e] R. C. Bearse, R. E. Segel, and D. H. Youngblood (private communication).

when the recoils were stopped in KCl leads to a lower limit for the mean life of the state, namely,

$$\tau_{2.47} > 7\times10^{-13} \text{ sec.}$$

The state decays mainly to the first excited state, and for this $M1$ transition $|M|^2<0.35$. (Here the statistical factor cannot easily be estimated and we have set it equal to unity.) Segel, Kennedy, Lee, and Schiffer[18] have searched for the ground-state transition from the 2.47-MeV state and found it to be less than a 1% branch. This $E2$ transition thus has a partial lifetime greater than 7×10^{-11} sec, which corresponds to a strength $|M|^2<6\times10^{-3}$.

IV. DISCUSSION

The fact that the transition from the first excited state does appear to show some enhancement may be taken as evidence for some collective motion in the state. However, Schiffer[19] has pointed out that if the diffuseness of the nuclear well is taken into account, the estimate for the speed of the single-particle $E2$ transition is increased several fold. It thus appears that in view of the combined theoretical and experimental uncertainties, the measured lifetime of the first excited state is not in itself decisive in determining the nature of the state.

The most striking result from the present work is the strong inhibition of the $E2$ decay to the ground state from the third excited state. In fact, this is certainly one of the weakest $E2$ transitions that is known. The (d,p) data[20] assure that the state contains a significant single-particle component, and this alone should contribute an $E2$ speed that is more than an order of magnitude greater than the upper limit that is observed for the state as a whole. (Strictly speaking, a single neutron will contribute a negligibly small $E2$ strength. However, a wealth of evidence requires that a neutron in a single-neutron state be endowed with an effective charge.) Thus, another contributor to the $E2$ amplitude must be almost exactly canceling the single-particle contribution.

We note that the upper limits on the dipole decays of the 2.47-MeV state are not unreasonable. The upper limit $|M|^2<0.35$ for the $M1$ decay to the 1.95-MeV state still permits the transition to be an allowed $M1$, although a lifetime much longer than the present upper limit would be surprising. The strong inhibition ($|M|^2 \lesssim 10^{-3}$) of the $E1$ transition to the 2.01-MeV, $\frac{3}{2}^+$ second excited state follows naturally from the two-particle–one-hole nature of this state.

Table II lists the lifetimes for the $E2$ transitions to ground from the first and third excited states in Ca^{41} and in Sc^{41}. The similarity between the two nuclei is very striking. In both cases the transition from the first excited state is somewhat faster than single-particle speed, while in neither case has a sensitive search unearthed the ground-state transition from the upper $\frac{3}{2}^-$ state.

It is appealing to ascribe the two anomalous features of the low-lying states of Ca^{41} [the two closely spaced $\frac{3}{2}^-$ states that share the $p_{3/2}$ strength in the $Ca^{40}(d,p)Ca^{41}$ reaction and the strongly inhibited $E2$ branch from the upper $\frac{3}{2}^-$ state] to the same cause, namely, a superposition of collective core excitation on an intrinsic single-particle ($p_{3/2}$) state. This core excitation, or deformation, would not only split the single-particle state but would also provide the $E2$ amplitude necessary to cancel the single-particle $E2$ amplitude from the upper state. Any enhancement needed for the lower state could also be provided. Such a picture in which the core excitations known from Ca^{40} as well as the experimental situation in Ca^{41} and Sc^{41} are considered has, indeed, been developed.[3,4] The model predicts about the right strengths for the $E2$ transitions from the first excited states in Ca^{41} and Sc^{41}; and for each of these nuclei it indicates that the ground-state transition from the third excited state will be severely inhibited. Although the experimentally established upper limit on the strengths of the cross-over transitions from the upper $\frac{3}{2}^-$ states is considerably smaller than the predicted strengths (the γ ray in Ca^{41} is at least an order of magnitude slower than predicted), the model correctly predicts the main features of the decay of the two low-lying $\frac{3}{2}^-$ states in each of these two nuclei. On this basis, therefore, the model must be adjudged a success.

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[18] R. E. Segel, E. F. Kennedy, L. L. Lee, Jr., and J. P. Schiffer (private communication).

[19] The transition probability was calculated by using Woods-Saxon wave functions in the usual radial integrals. The well depth was adjusted to fit the observed binding energies, and the radial parameters were $r_0=1.25$ F and $a=0.65$ F. The lifetimes of the single-particle $2p_{3/2}\rightarrow 1f_{7/2}$ transition from the first excited state to the ground state were calculated to be 7.95×10^{-13} sec for Ca^{41} and 11.5×10^{-13} sec for Sc^{41}, on the assumption of unit effective charges. [J. P. Schiffer (private communication).]

[20] L. L. Lee, Jr., J. P. Schiffer, B. Zeidman, G. R. Satchler, R. M. Drisko, and R. K. Bassel, Phys. Rev. 136, B971 (1964).