the $K=2$ band does not arise from a simple vibrational picture.

The Nilsson model, on the other hand, allows a more detailed comparison with the data since spectroscopic factors may be obtained from the wave functions of the intrinsic states, which are generally expressed as expansions of single-particle components. Figure 5 shows the Nilsson orbits computed for the mass region near $A=24$ by use of the parameters of Siemssen *et al.*[15] The Na^{23} ground state then arises from an odd proton in orbit No. 7 (prolate deformation is accepted for this region), and the $K=0^+$ band in Mg^{24} is produced by stripping a proton into that orbit. A $K=2^+$ band can be constructed by stripping a particle into the $K=\frac{1}{2}$ orbit No. 9. The 0^+ sixth excited state then may be pictured as two nucleons in orbit No. 5 or 9 and hence could not be strongly excited in the (He^3,d) reaction. (Such excitation would require a two-step process of promoting one particle in the target nucleus to orbit No. 5 or 9 before or after stripping into it.)

[15] R. H. Siemssen, L. L. Lee, Jr., and D. Cline, Phys. Rev. **140**, B1258 (1965).

With these assumptions, spectroscopic factors as a function of deformation have been determined by the methods of Siemssen *et al.* The results are shown in Fig. 6.

It can be seen that for $\eta \approx 3$ (the value taken by Robinson and Bent[7] as the best fit to the γ-decay data), all of the experimental spectroscopic factors are in reasonable agreement with the model. A better fit would be obtained if all of the measured spectroscopic factors were made smaller by about 10%.

It would be interesting to compare the asymmetric-rotor picture of, say, Bar-Touv and Kelson[16] with the present results, but unfortunately this is not now feasible.

ACKNOWLEDGMENTS

We would like to thank Dr. Dieter Kurath and Dr. John Erskine for many invaluable discussions. The technical assistance of J. Bicek and of the cyclotron group is gratefully acknowledged.

[16] J. Bar-Touv and I. Kelson, Phys. Rev. **138**, B1035 (1965).

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Lifetime Measurements from the $K^{39}(p,\gamma)Ca^{40}$ Reaction

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Lifetime measurements with a Ge(Li) detector have been made for several excited states of Ca^{40} by the Doppler-shift attenuation method utilizing the $K^{39}(p,\gamma)Ca^{40}$ reaction. Agreement with results of $(p,p'\gamma)$ lifetime measurements is found for the levels at 3.904, 5.280, and 6.285 MeV. New lifetime results are reported for levels at 5.615 MeV (>0.8 psec), 7.465 MeV ($0.010_{-0.006}^{+0.005}$ psec), and 7.562 MeV ($0.26_{-0.07}^{+0.14}$ psec. An upper limit of 1% is set for the branching of the 3.904-MeV (2^+) to the 3.354-MeV (0^+) levels. Comparison is made with Gerace and Green's predictions that the 5.280-, 3.904-, and 3.354-MeV levels form a rotational band. Calibration of the resonance spectrum with Co^{56} γ rays has resulted in precise establishment of level energies for Ca^{40}, a better Q value for the reaction of 8.3295 ± 0.0009 MeV, and the association of the lower member of the doublet near 5.615 MeV with the 4^- level in this region. New decay modes are established for the levels at 7.113, 7.562, and 7.811 MeV.

I. INTRODUCTION

A RECENT innovation in nuclear theory has been the prediction of coexistence of single-particle and collective modes of excitation in nuclei near closed shells.[1–5] Initial evidence for the existence of deformed states in addition to the usual spherical states in O^{18} and O^{16} was the observation of anamolously large $E2$ transition probabilities.[6] More conclusive evidence came from the observation that low-lying excited states in the oxygen nuclei could be fitted into rotational energy bands characteristic of deformed nuclei.[7] Since calculations based on this model have had significant success in explaining the experimental features of the oxygen isotopes which close the $1p$ shell,[1–4] it is essential to look at the calcium isotopes which close the $2s$-$1d$ shell and see if the same phenomenon repeats.

Ca^{40} does seem to exhibit nuclear excited states that can be fitted into even- or odd-parity rotational bands

* Work supported in part by the U. S. Atomic Energy Commission.
[1] G. E. Brown and A. M. Green, Phys. Letters **15**, 168 (1965).
[2] P. Federman and I. Talmi, Phys. Letters **15**, 165 (1965).
[3] W. H. Bassichis and G. Ripka, Phys. Letters **15**, 320 (1965).
[4] I. Kelson, Phys. Letters **16**, 143 (1965).
[5] P. Federman and I. Kelson, Phys. Rev. Letters **17**, 1055 (1966).

[6] J. D. Larson and R. H. Speak, Nucl. Phys. **56**, 497 (1964).
[7] E. B. Carter, G. E. Mitchell, and R. H. Davis, Phys. Rev. **133**, 1421B (1964).

with the characteristic $J(J+1)$ energy dependence. The initial suggestion for this was made on the basis of spin and parity assignments determined by inelastic α scattering experiments.[8] In the present work the collective nature of levels designated as members of rotation bands has been verified utilizing lifetime measurements by the Doppler-shift attenuation method (DSAM).[9] The $K^{39}(p,\gamma)Ca^{40}$ reaction was chosen for this study, in which γ-ray energy, intensity, and DSAM lifetime measurements were made at four resonances with a high-resolution Ge(Li) detector.

II. EXPERIMENTAL PROCEDURE

The proton beam was produced by the University of Oregon 4-MeV Van de Graaff accelerator and bent through an angle of 45° by a homogeneous field analyzing magnet. After focusing by a quadrupole doublet the beam passes through a pair of water-cooled collimating apertures and then an in-line liquid-nitrogen cold trap located 10 in. in front of the target. Targets were made from natural K_2SO_4 and KI evaporated in vacuum on 0.010-in. gold backings. Direct water cooling of the targets permitted beam currents of 10 μA without appreciable target deterioration over periods of 24–48 h.

γ-ray spectra were obtained with a 20-cm^3 Ge(Li) detector biased at -2450 V. The low-noise electronics used and energy calibration procedures have been detailed elsewhere.[10] The relative photopeak efficiency was determined as a function of γ-ray energy from the measured photopeak areas and the known relative intensities of γ rays from a radioactive Co^{56} source. The ratio of counts in a double-escape peak and corresponding full-energy peak for Co^{56} γ rays gives directly the double-escape efficiency up to 3.5 MeV. High-energy points for determining a double-escape efficiency curve came from γ rays from the capture γ reactions $Al^{27}(p,\gamma)Si^{28}$ at $E_p=1.262$, 1.589, and 2.319 MeV and $K^{39}(p,\gamma)Ca^{40}$ at $E_p=1.486$ and 1.666 MeV. In each case a single high-energy γ ray populated a low-lying energy level. The over-all efficiency curve shown in Fig. 1 agrees well with recent Monte Carlo calculations.[11]

Lifetimes of nuclear levels populated in the decay of the resonance excited states at $E_p=1.344$, 1.374, and 1.486 MeV were measured by the DSAM. Doppler-shifted γ-ray spectra were measured at 0° and 90° at the $E_p=1.374$-MeV resonance, and at 0° and 120° at the $E_p=1.344$- and 1.486-MeV resonances. These spectra were obtained with 10-keV-thick targets over periods of 24 h at each angle with beam currents of 6–8 μA.

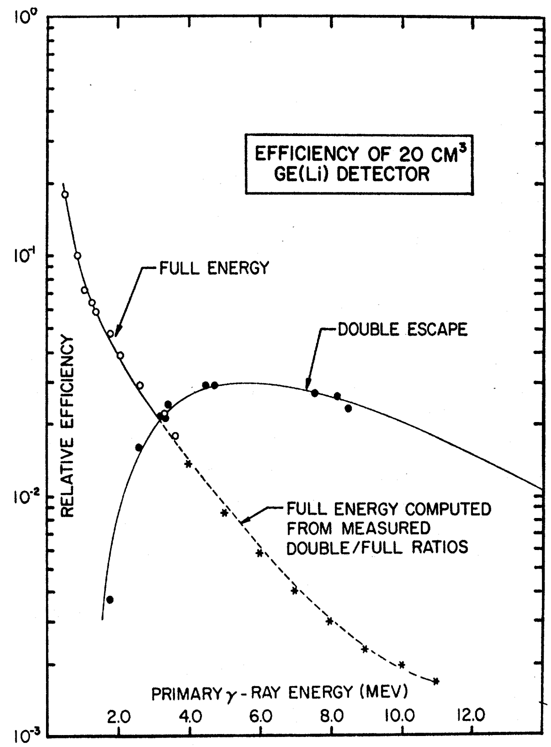

FIG. 1. The relative photopeak and double-escape-peak efficiency curves. The projected full-energy curve was obtained from the experimentally determined ratio of the photopeak intensity to double-escape-peak intensity. Points below 3.5 MeV were obtained with a Co^{56} source. Relative double-escape efficiency above this energy was obtained from $Al^{27}(p,\gamma)Si^{28}$ and $K^{39}(p,\gamma)Ca^{40}$ intensity measurements.

The attenuated Doppler shift was determined by measuring the difference in energy of a γ ray at the two angles noted above. From this measurement the quantity $F(\tau)$ can be obtained where $F(\tau)=\Delta\bar{E}_\gamma/\Delta E_{\gamma 0}$ is the ratio of the attenuated Doppler shift, $\Delta\bar{E}_\gamma=\bar{E}_\gamma-E_0$, to the maximum Doppler shift, $\Delta E_{\gamma 0}=E_0(v_0/c)\cos\alpha$. In these equations E_0 is the unshifted γ-ray energy, E_γ is the measured γ-ray energy corrected for recoil, v_0 is the initial velocity of the recoiling compound nucleus, and α is the angle between the incident proton direction and the γ-ray detector. To obtain the lifetime of an excited state the measured $F(\tau)$ is compared with the value deduced from the theory of ranges of heavy ions in a scattering medium,[12]

$$F(\tau)=\frac{1}{\tau}\int_0^\infty e^{-t/\tau}\left(\frac{v(t)}{v_0}\right)\langle\cos\phi\rangle dt\,, \tag{2.1}$$

where $\langle\cos\phi\rangle$ is the mean recoil scattering angle about the incident particle direction.[9] Both electronic and nuclear stopping are included in the theory as they are of the same order of magnitude. The nuclear specific energy loss curve was approximated by seven straight

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

[9] A. E. Blaugrund, Nucl. Phys. **88**, 501 (1966).

[10] E. F. Gibson, K. Battleson, and D. K. McDaniels, Phys. Rev. **172**, 1004 (1968).

[11] W. J. Snow, Argonne National Laboratory Report No. ANL-7314, 1967 (unpublished).

[12] J. Lindhard, M. Scharff and H. E. Schiott, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **33**, 1 (1963).

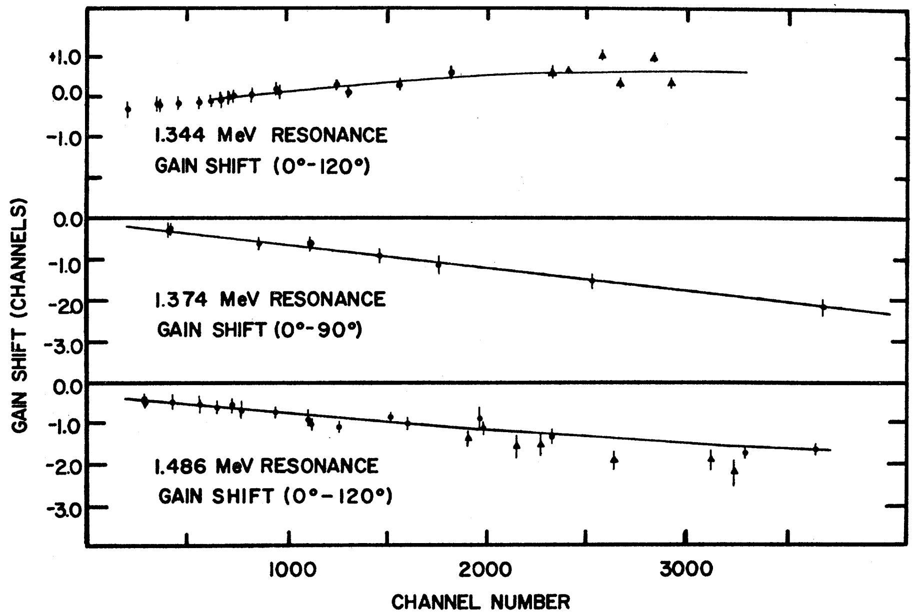

FIG. 2. Plots of the discrete gain changes which occurred in moving the detector from one angle to the next in the Doppler-shift measurements at the E_p = 1.344-, 1.374-, and 1.486-MeV resonances. Solid circles represent data obtained from Co^{56} lines; triangles are points obtained from γ rays which decayed from the resonance state, corrected for full Doppler shift.

lines. The details of this calculation of $F(\tau)$ for a slowing-down medium containing a mixture of elements are then similar to the calculations of Blaugrund.[9]

Errors are introduced in the Doppler-shift analysis from the uncertainty in γ-ray peak centroids and from the uncertainty in the correction for the small gain and

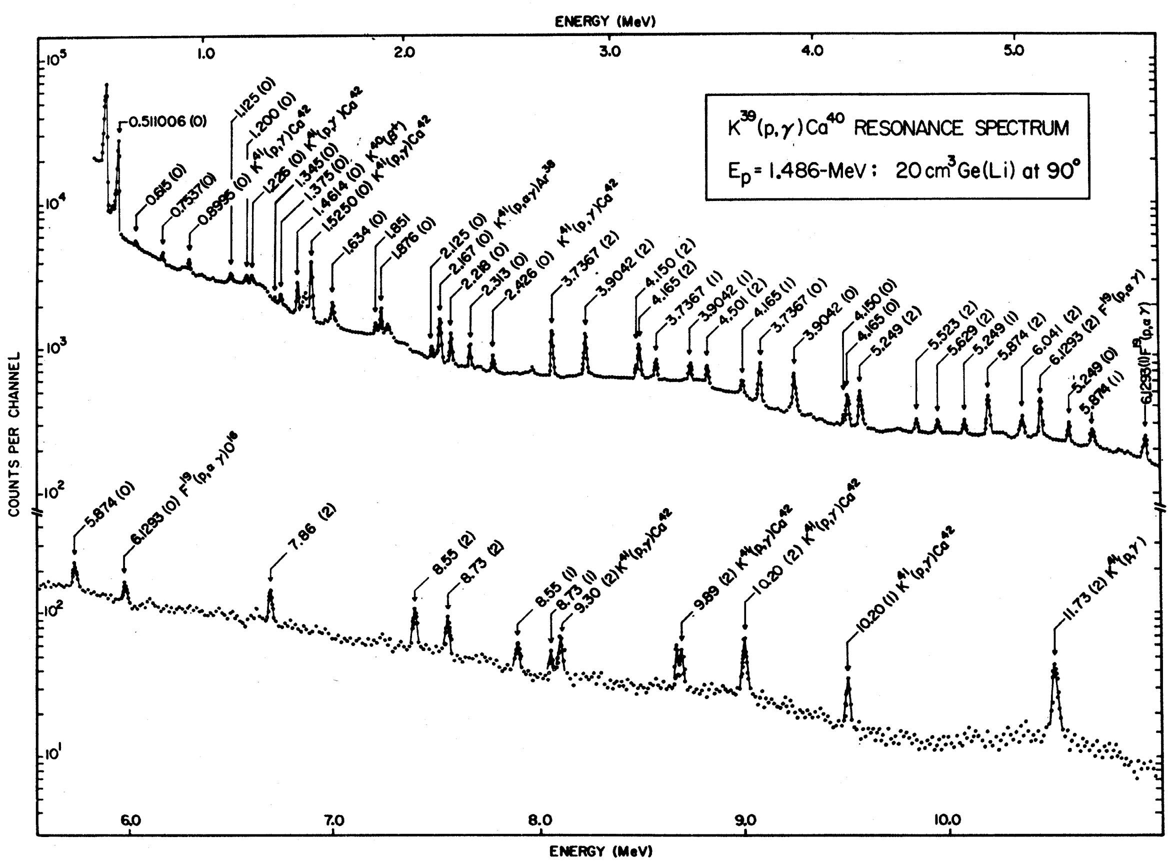

FIG. 3. The E_p = 1.486-MeV resonance spectrum recorded at 90° with a 20-cm³ Ge(Li) detector. The $K^{41}(p,\gamma)Ca^{42}$ peaks are due to the K^{41} present in the natural potassium-iodide target. Other contaminant lines are labeled on the figure.

zero shifts in the electronics that occur between angles. The centroid errors were identified with the standard deviation of the corresponding parameters in the least-squares peak fitting. The correction for zero and gain shifts for each resonance studied is shown in Fig. 2. The circular data points are the measured shifts of γ rays that are known to be unshifted in energy such as Co^{56} lines; triangles are the gain shifts of γ rays de-exciting the resonance state which are assumed to be fully shifted. A discussion of the error in $F(\tau)$ associated with the uncertainties in the nuclear and electronic specific energy loss curves is given in the Appendix.

III. RESULTS

A. Resonance Spectra

The γ-ray decay modes of Ca^{40} states below an excitation energy of 10.0 MeV were investigated by recording the resonance spectra of the $K^{39}(p,\gamma)Ca^{40}$ reaction at incident proton energies of 1.344, 1.374, 1.486, and 1.575 MeV. Relative intensities of the γ rays were obtained from data recorded with the Ge(Li) detector at 55° to the incident beam in the case of the 1.344- and 1.575-MeV resonances, from a suitable average of data recorded at 0° and 90° for the 1.374-MeV resonance. The germanium detector was located about 2 in. from the target and subtended a solid angle of about 4×10^{-2} sr. A typical resonance spectra obtained at $E_p=1.486$ MeV is shown in Fig. 3. This spectrum also contains some contaminant γ rays from a nearby $K^{41}(p,\gamma)Ca^{42}$ resonance as natural potassium contains 6.9% K^{41}. A distinguishing feature of this resonance is the strong de-excitation to the second and third excited

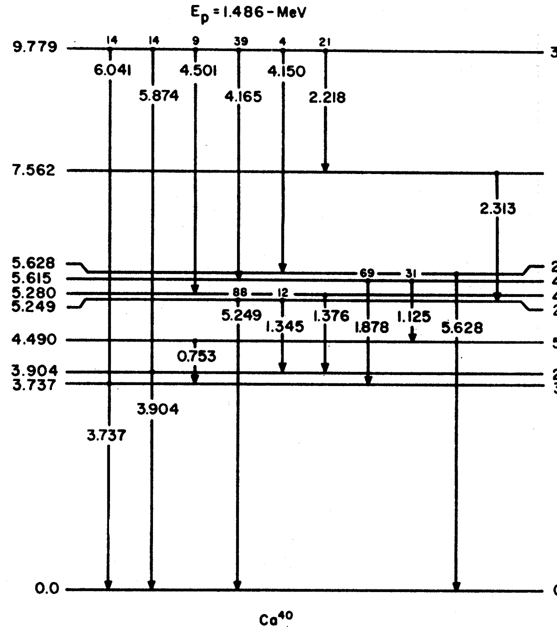

FIG. 4. Decay scheme for the $E_p=1.486$-MeV resonance excited state.

states at 3.737 and 3.904 MeV. The complete decay scheme for this resonance is summarized in Fig. 4.

Branching ratios determined for the four resonances excited in this work are presented in Table I and compared with the results of previous investigators.[13] The branching ratios for the decay of the $E_p=1.344$-MeV resonance level are seen to be in good agreement with previous measurements. The $E_p=1.374$-MeV resonance level is observed to decay to the 4.490-MeV level in addition to previously reported decay modes, but no transition is observed to the 7.69-MeV level. The $E_p=1.486$-MeV resonance level decays to the 7.562-MeV level rather than to the 7.46-MeV level as pre-

TABLE I. Branching ratio determinations for resonance levels of Ca^{40} populated in the $K^{39}(p,\gamma)Ca^{40}$ reaction.

E_p (MeV)	E_i (MeV)	E_f (MeV)	Branching ratio (%) Previous[a]	Present
1.344	9.640	7.562	10	7
		3.904	50	50
		3.737	40	43
1.374	9.668	7.693	5	...
		7.113	30	18
		6.285	40	37
		4.490	...	6
		3.904	5	12
		3.737	20	27
1.486	9.779	7.562	...	21
		7.46(7.57)	25	...
		5.628	...	4
		5.615	35	39
		5.280	...	9
		3.904	20	14
		3.737	20	14
1.575	9.864	7.811	...	5
		7.29	2	...
		6.94	2	...
		3.904	5	5
		3.353	12	16
		0.0	79	74

[a] From the summary of Ref. 13.

TABLE II. Energies of Ca^{40} excited states.

Grace and Poletti[b]	E_x(MeV)[a] Erskine[c]	Present
3.3510±100		3.3535±14
3.7310±100	3.7380±50	3.7367±3
3.9000±100		3.9042±3
4.4820±100	4.4900±50	4.4904±6
5.2000±100		
5.2440±100		5.2487±6
5.2740±100		5.2796±4
5.6060±100	5.6140±60	5.6150±4
5.6190±100		5.6282±12
5.9040±100	5.9020±60	
6.0280±100	6.0260±50	
6.2850±100	6.2860±50	6.2847±6
7.1140±100	7.1160±60	7.1133±4
7.4550±100		7.4648±18
7.5580±100		7.5615±7

[a] Errors quoted are the uncertainties in the final digits.
[b] Reference 15.
[c] Reference 14.

[13] P. M. Endt and C. Van der Leun, Nucl. Phys. **A105**, 1 (1967).

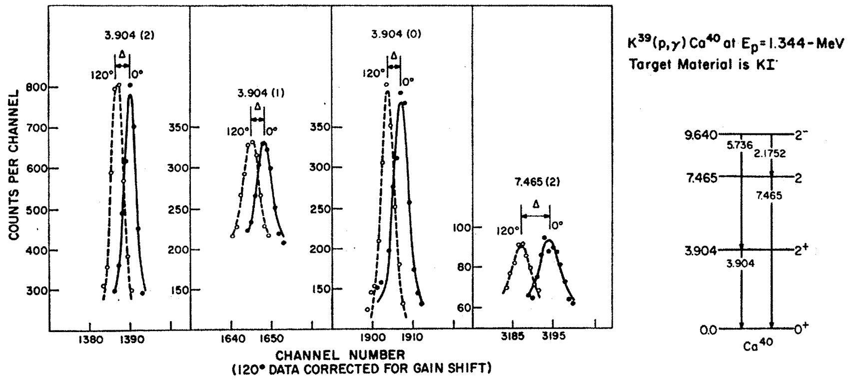

FIG. 5. Experimental results of the Doppler-shift measurements at the $E_p = 1.344$-MeV resonance using a Kl target. The lifetimes of the 7.465- and 3.904-MeV levels populated in the decay of the resonance excited state are inferred from the attenuated Doppler shifts measured at 120° and 0°.

viously conjectured, to both members of the doublet at 5.62 MeV rather than to just one member, and to the 5.280-MeV level in addition to previously reported decay modes. The $E_p = 1.575$-MeV resonance level is proposed to decay by a 2.053-MeV transition to the 7.811-MeV level, but no transitions are observed to the 7.29- or 6.94-MeV levels.

Level energies determined in this work are presented in Table II and compared with the most precise previously reported results of Erskine[14] from a study of the $K^{39}(He^3,d)Ca^{40}$ reaction and of Grace and Poletti[15] from a study of the $Ca^{40}(p,p')Ca^{40}$ reaction. The only level energy that gives an ambiguous comparison with previous measurements is that for the 7.465-MeV level Grace and Poletti[15] report levels at 7.455 ± 0.010 and 7.473 ± 0.010 MeV. Either of these levels could be identified with the present measurement.

Grace and Poletti also reported levels at $5.606(4^-)$ and $5.619(J=2)$ MeV. Erskine found a level with $J^\pi = 4^-$ at 5.619 MeV. The values found for the energies of this doublet in the present study are 5.615 and 5.628 MeV. The fact that almost all of the energies of the Ca^{40} levels found by Grace and Poletti are about 4–8 keV lower than the results of the present investigation suggests that the lower member of the doublet is the 4^- level.

Branching ratios for the lower-lying levels of Ca^{40} are summarized in Table III. Decay of the levels at 7.811 and 7.562 MeV has not previously been observed. Two new decay modes are proposed for the level at 7.113 MeV; 17% to the 5.615-MeV 4^+ level and 23% to the 4.490-MeV 5^- level in addition to the known branch to the 3.737-MeV 3^- level.

The speculated in-band transition[16] $2^+(3.904\text{ MeV}) \rightarrow 0^+(3.354\text{ MeV})$, $E_\gamma = 0.550$ MeV, has not been observed. A determination of the relative intensity of this transition is of importance in determining the amount of deformation of the ground-state wave function. Previous observations of the 0.550-MeV γ ray was not pos-

TABLE III. Branching ratio determinations for lower excited levels of Ca^{40}.

E_i (MeV)	E_f (MeV)	E_γ (MeV)	$J_i \rightarrow J_f$	Branching ratio (%) previous[a]	present
7.811	5.201	2.610	$(?) \rightarrow 0(1)$	···	100
7.562	5.249	2.313	$(?) \rightarrow 2$	···	100
7.465	0.0	7.465	$(?) \rightarrow 0^+$	100	100
7.113	5.615	1.498	$(?)^- \rightarrow 4^-$	···	17
	4.490	2.623	$(?)^- \rightarrow 5^-$	···	23
	3.737	3.376	$(?)^- \rightarrow 3^-$	100	60
6.285	4.490	1.795	$3^- \rightarrow 5^-$	75	69
	3.904	2.381	$3^- \rightarrow 2^+$	25	31
5.628	0.0	5.628	$2 \rightarrow 0^+$	100	100
5.615	4.490	1.125	$4^- \rightarrow 5^-$	35	31
	3.737	1.878	$4^- \rightarrow 3^-$	65	69
5.280	4.490	0.790	$4^+ \rightarrow 5^-$	5	9
	3.904	1.376	$4^+ \rightarrow 2^+$	95	91
5.249	3.904	1.345	$2 \rightarrow 3^-$	20	12
	0.0	5.249	$2 \rightarrow 0^+$	80	88
5.201	3.904	1.296	$0(1) \rightarrow 2^+$	100	>90
	0.0	5.201	$0(1) \rightarrow 0^+$	···	<10
4.490	3.737	0.753	$5^- \rightarrow 3^-$	100	100
3.904	3.354	0.550	$2^+ \rightarrow 0^+$	···	<1
	0.0	3.904	$2^+ \rightarrow 0^+$	100	100
3.737	0.0	3.737	$3^- \rightarrow 0^+$	100	100

[a] From the summary of Ref. 13.

TABLE IV. Lifetimes of Ca^{40} levels excited in the $K^{39}(p,\gamma)Ca^{40}$ reaction.

Level	J^π	$F(\tau)$[a]	Lifetimes (psec) present[b]	other[c]
3.904	2^+	0.83 ± 0.05	0.019 ± 0.006	0.064 ± 0.019
5.280	4^+	0.21 ± 0.10	$0.23_{-0.06}^{+0.19}$	$0.26\ \pm0.08$
5.615	4^-	-0.05 ± 0.07	>0.8	
6.285	3^-	0.14 ± 0.04	$0.37_{-0.09}^{+0.16}$	$0.41\ \pm0.12$
7.465	2	0.91 ± 0.05	$0.010_{-0.006}^{+0.005}$	
7.562	?	0.19 ± 0.06	$0.26_{-0.07}^{+0.14}$	

[a] Errors associated with $F(\tau)$ measurements are due to uncertainties in centroid determinations and the correction for gain and zero shifts.
[b] Errors associated with the lifetime results are based on an assumed 15% uncertainty in the nuclear specific energy loss curve as well as the uncertainty in $F(\tau)$.
[c] From the results of Ref. 17.

[14] J. R. Erskine, Phys. Rev. **149**, 854 (1966).
[15] M. A. Grace and A. R. Poletti, Nucl. Phys. **78**, 273 (1966).
[16] W. J. Gerace and A. M. Green, Nucl. Phys. **A93**, 110 (1967).

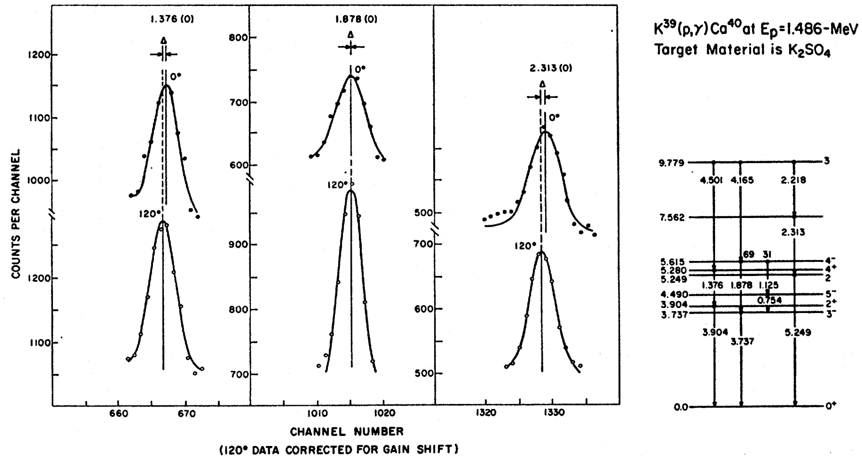

FIG. 6. Experimental results of the Doppler-shift measurements at the E_p=1.486-MeV resonance using a K_2SO_4 target. The lifetimes of the 5.280-, 5.615-, and 7.562-MeV levels are inferred from the attenuated Doppler shifts measured at 120° and 0°.

sible with low-resolution NaI(Tl) detectors because of the strong 0.511006-MeV annihilation line which was always present. A careful search was made here for the 0.550-MeV γ ray at the E_p=1.344-MeV resonance which decays 50% of the time to the 3.904-MeV state with a negative result. An upper limit of 1% can be set on the intensity of this γ ray relative to that of the ground-state transition.

The resonances at E_p=1.374 and 1.486 MeV decay to the ground state not only via high-energy transitions to low-lying excited states, but also through cascades involving only γ rays of an energy less than 3.5 MeV. As their energies can be determined very precisely with respect to the Co^{56} lines, this offers a way to accurately measure the reaction Q value. A resulting mean value of 8.3295±0.0009 MeV was obtained with the largest contributing error in this value coming from the uncertainty of the resonant proton energy. The present value for Q is 0.0038 MeV less than but within 1 standard deviation of the Q value from the 1964 atomic mass tables of (8.3333±0.0041) MeV.

B. Ca^{40} Lifetimes

The results for a typical DSAM measurement at the E_p=1.344-MeV resonance are shown in Fig. 5. An attenuated Doppler shift was observed for both the 3.904- and 7.465-MeV ground-state transitions. The measured shifts of the 3.904-MeV photopeak, single-, and double-escape peaks all agree within error. Data from a similar measurement at the E_p=1.486-MeV resonance is shown in Fig. 6. Levels at 7.562, 5.628, 5.615, and 5.280 MeV are populated at this resonance; DSAM measurements were made for all but the weakly populated 5.628-MeV level. The resulting mean lifetime of $0.23_{-0.09}^{+0.19}$ psec for the 5.280-MeV level is in good agreement with the value of 0.26±0.08 psec obtained from the higher momentum transfer $Ca^{40}(p,p'\gamma)Ca^{40}$ reaction at E_p=13 MeV.[17]

[17] J. R. MacDonald, D. F. H. Start, R. Anderson, A. G. Robertson, and M. A. Grace, Nucl. Phys. **A108**, 6 (1968).

The nuclear lifetimes measured in the present work are summarized in Table IV and compared with previous measurements. Where a comparison can be made with the lifetime measurements from the $(p,p'\gamma)$ work the agreement is good except for the 3.904-MeV level. The agreement between these results for low momentum transfers to the recoiling nucleus and the measurements made in the much higher momentum transfer $(p,p'\gamma)$ reaction at proton energies of 13 MeV [17] further justifies the usage of the theoretical results for dE/dx of heavy ions in a scattering medium.[12]

IV. DISCUSSION

Since no previous information exists for the 7.562-MeV level, the measured lifetime of $0.26_{-0.07}^{+0.14}$ psec can be used to restrict slightly the possible spin-parity possibilities. The $E3$ and $M3$ transition strengths are much too large to be admissable, so that the spin of the 7.562-MeV level must be less than 5. The large $M2$ strength of greater than 190 Weisskopf units further restricts the parity of the spin 0 and 4 possibilities to positive parity.

Erskine[14] has suggested that the 3.351-MeV 0^+, 3.904-MeV 2^+, 5.206-MeV $0^\pm$, 5.250-MeV 2^+, and 5.280-MeV 4^+ states might be collective in nature since

TABLE V. Reduced transition probabilities for in-band transitions in Ca^{40}.[a]

Transition	Gerace and Green[b]	Present experiment	MacDonald *et al.*[c]	Blum *et al.*[d]
$2_1^+(3.904) \to 0_1^+(0)$	7.8	48±15	14.2±3.5	29±9
$2_1^+(3.904) \to 0_2^+(3.354)$	203	<8560	<3400	
$4_1^+(5.280) \to 2_1^+(3.904)$	300	719_{-594}^{+187}	620_{-170}^{+250}	

[a] All reduced transition probabilities are in units of e^2-fm^4.
[b] Reference 16.
[c] Reduced transition probabilities are computed from lifetimes measured by the Doppler-shift attenuation method from the $Ca^{40}(p,p'\gamma)Ca^{40}$ reaction, Ref. 17.
[d] Reduced transition probabilities are computed from form factors determined by inelastic electron scattering from the $Ca^{40}(e,e')Ca^{40}$ reaction; P. D. Blum, P. Barreau, and J. Bellicard, Phys. Letters 4, 109 (1963).

they are not observed in the $K^{39}(He^3,d)Ca^{40}$ reaction which strongly excites the single-particle states of Ca^{40}. As noted in Sec. I, Gerace and Green[16] suggest that the 0^+, 2^+, and 4^+ members of the first rotation band in Ca^{40} are at 3.354, 3.904, and 5.280 MeV, respectively. This rotational ($K=0$) band was based on a prolate deformation ($\beta>0$) and corresponded to two-particle–two-hole and four-particle–four-hole excitations. Combining the present life-time measurements of the 3.904- and the 5.280-MeV levels with the measured branching ratios, the reduced transition probabilities can be calculated and compared with the theoretical predictions of Gerace and Green[16] for the in-band transitions. This camparison is summarized in Table V. The present results are in agreement with the suggestion of possible collective modes of excitation in the spherical nucleus Ca^{40}. Further evidence for enhanced $E2$ transitions in this closed-shell nucleus is given by the lifetime measurements of MacDonald *et al.*,[17] of the levels at 5.21 and 5.25 MeV.

A different way of understanding the strong branching of the 3.904-MeV 2^+ level to the ground state has been put forth recently by Goldhammer and Prosser[18] and Lowe, Poletti, and Wilkinson[19] to explain the similar phenomena in O^{16}. They interpret the ground-state and first-excited-state wave functions as admixtures of a primitive ideally spherical state ϕ_0 and a pure rotational state ϕ_r. If we follow the notation of Goldhammer and Prosser we find that the mixing ratio for these two states for Ca^{40} is given as

$$\left(\frac{\beta}{\alpha}\right)^2 = \frac{\epsilon_0}{\epsilon_r} = \frac{0.040}{3.314} = 1.21\times10^{-2}, \tag{4.1}$$

where ϵ_r is determined by the condition that $(5.280-\epsilon_r)/(3.904-\epsilon_r)=10/3$. With this value of $(\beta/\alpha)^2$ we can then compute

$$R_{\mathrm{th}} = \frac{\text{Rate }(3.904\rightarrow 3.354)}{\text{Rate }(3.904\rightarrow 0)} = \left(\frac{\alpha}{\beta}\right)^2\left(\frac{0.550}{3.904}\right)^5 = 4.6\times10^{-3}. \tag{4.2}$$

This is certainly less than our upper limit of 10^{-2}, but is higher than the ratio predicted by Gerace and Green which is seen from Table V to be about 1.1×10^{-3}. [*Note added in manuscript:* After the work reported in this paper was concluded, MacDonald, Wilkinson, and Alburger[20] reported an upper limit of 3×10^{-4} for this branching ratio.

[18] P. Goldhammer and F. W. Prosser, Jr., Phys. Rev. **163**, 950 (1967).
[19] J. Lowe, A. R. Poletti, and D. H. Wilkinson, Phys. Rev. **148**, 1045 (1966).
[20] J. R. MacDonald, D. H. Wilkinson, and D. E. Alburger, Bull. Am. Phys. Soc. **13**, 695 (1968).

APPENDIX: ESTIMATE OF ERROR DUE TO UNCERTAINTY IN SLOWING-DOWN THEORY

The accuracy of the Doppler-shift attenuation method for measuring nuclear lifetimes depends both on the precision with which the γ-ray energy shifts can be measured and on the accuracy of the theories describing energy loss and scattering of a heavy ion of low velocity in a general medium. The analysis of the experimental errors was outlined in Sec. II. An estimate of the error in $F(\tau)$ due to uncertainty in the slowing-down theory follows. We assume that the theoretical nuclear stopping power $(dE/d\rho)_n$ is in error by approximately 15%.[21] This estimate results in a maximum error in $F(\tau)$ of about 8% as shown in Fig. 7. An uncertainty in the electronic stopping power also contributes to the uncertainty in the theoretical $F(\tau)$; however, since the magnitude of $(dE/d\rho)_e$ is considerably smaller than $(dE/d\rho)_n$ for the recoil velocities in the present work, the error introduced in $F(\tau)$ is correspondingly smaller. An error of 20%[22] in the theoretical electronic stopping power produces a maximum error of about 2% in the theoretical value of $F(\tau)$, as is also shown in Fig. 7. A reasonable estimate, then, of the uncertainty in the theoretical $F(\tau)$ is approximately 10% for lifetimes longer than 10^{-13} sec as indicated by Fig. 7, while for shorter lifetimes the uncertainty in $F(\tau)$ is somewhat less than 10%.

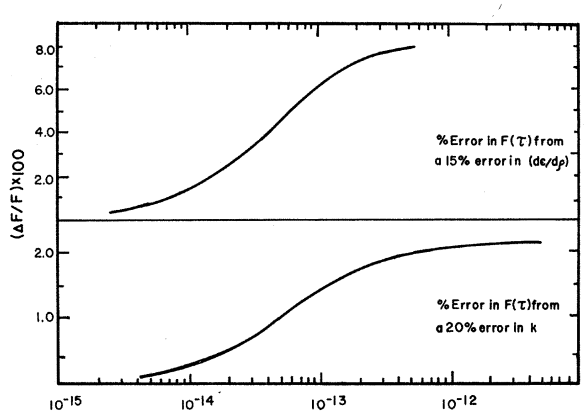

FIG. 7. An estimate of the percent error in the theoretical $F(\tau)$ produced by an error of 15% in $(dE/d\rho)_n$ is shown in the upper portion of the figure while the percent error produced in $F(\tau)$ by a 20% error in $(dE/d\rho)_e$ is shown in the lower portion of the figure.

[21] E. K. Warburton, J. W. Olness, and A. R. Poletti, Phys. Rev. **160**, 938 (1967).
[22] A. Van Wijngaarden and H. E. Duckworth, Can. J. Phys. **40**, 1749 (1962); J. H. Ormrod and H. E. Duckworth, *ibid.* **41**, 142 (1963); J. H. Ormrod, J. R. MacDonald, and H. E. Duckworth, *ibid.* **43**, 225 (1964); J. R. MacDonald, J. H. Ormrod, and H. E. Duckworth, Z. Naturforsch **21**, 130 (1966).