Coupled quadrupole-octupole excitations in ^{44}Ca and the decay of ^{44}K, ^{44}Sc^m, and ^{44}Sc^g †

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The decay of ^{44}K, ^{44}Sc^g, and ^{44}Sc^m to levels of ^{44}Ca have been studied. For decay of ^{44}K, approximately 125 γ rays have been observed using singles, Compton-suppression, and γ-γ-coincidence Ge(Li) spectroscopy. The decay data, used in conjunction with recent reaction spectroscopy data, have led to the identification of 35 levels in ^{44}Ca that are populated in β decay. The levels below 4500 keV are discussed within the framework of multiple vibrations. The levels at (J^π in parentheses) 3661.53 (1^-), 3676.07 (2^-), 3711.80 (4^-), 3913.8 (5^-), and 4358.42 keV (3^-) are suggested as the two phonon quadrupole-octupole pentad.

[RADIOACTIVITY ^{44}Ca, ^{44}K, ^{44}Sc^g, ^{44}Sc^m; measured E_γ, I_γ; decay, γ-γ coin: deduced levels, logft. Compton-suppression spectrometer.]

I. INTRODUCTION

The nucleus ^{44}Ca, with 24 neutrons, lies in the middle of the 20-to-28-neutron shell. As can be seen in Fig. 1, ^{44}Ca has the largest level density below 4 MeV of this series of calcium isotopes.[1] The major features of these can be accounted for by the coupling of the four $1f_{7/2}$ neutrons to a ^{40}Ca core[2] or more completely by including the $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$ shell model states.[3-6] Inclusion of particle-hole excitations were found necessary in order to explain the first excited 0^+ level and second excited 2^+ level in the ^{42}Ca to ^{46}Ca nuclei.[7-9] However, due to a lack of detailed data on the properties of the odd parity levels below 5 MeV no attempt has been made to account for these levels in relation to the known properties of the 3^- octupole excitations (see Fig. 1)[10] and its coupling to the quadrupole vibration.[11-15]

The levels of ^{44}Ca have been studied by a variety of techniques. A larger body of data has been obtained from charged-particle-reaction and Coulomb-excitation studies.[16-27] In addition, level properties have been studied by reaction spectroscopy such as $(p,p'\gamma)$[28-30] and Doppler-shift attenuation methods.[31] Recent neutron-capture γ-ray studies[32] have allowed the detailed study of level decay properties; however, these were limited to those levels that could be populated by the 3^- or 4^- capture state. Decay scheme studies[33-45] can provide detailed information on the properties of the lower spin levels of ^{44}Ca, since the decay parents ^{44}K and ^{44}Sc^g have J^π values of 2^- and 2^+, respectively. Thus, a combination of decay data and n-capture γ-ray data should provide a fairly complete set of data on the level decay properties of ^{44}Ca. However, past decay scheme studies of ^{44}K have been limited because of the low ^{44}Ca$(n,p)^{44}$K cross section and the low fluxes that are available for energetic neutrons. Here we have undertaken a detailed study using the (Lawrence Livermore Laboratory) LLL-ICT high flux 14-MeV neutron facility. In particular, we sought to identify levels in ^{44}Ca that could represent multiple vibration-coupled excitations[11,12,46,47] such as the 3^--octupole–2^+-quadrupole excitations that we have identified in heavier nuclei.[14,15]

II. EXPERIMENTAL PROCEDURE

A. ^{44}K decay

Sources of ^{44}K were prepared by irradiating calcium metal foils (> 99.999% pure) of natural isotopic abundance in the Livermore 14-MeV neutron generator at a flux of approximately 2×10^{12} neutrons/cm^2 s for 20-min periods. No chemical separation of the ^{44}K was made. However, only γ rays that decay with the proper half-life were considered for the decay scheme. Counting was delayed at least 10 min after completion of the irradiation to permit short-lived activities to decay. γ rays of ^{44}K were detected and identified by half-life on a variety of Ge(Li) systems available at LLL.

In the first set of experiments the energy region was set to 0–6 MeV. Sources were counted in sequence for periods of one half-life on each of four detectors: (1) 50 cm^3 with a 1.27-cm Pb-Cd absorber, (2) 50 cm^3 with no absorber, (3) 65 cm^3 with no absorber, and (4) 60 cm^3 with no absorber. This procedure was repeated until sufficient data were accumulated. Another set of experiments was done in the same way at 0–2 MeV using the following detectors: (1) the Livermore Compton suppression spectrometer (CSS) system,[48] (2) 50 cm^3, and (3) 60 cm^3, all without lead absorber. All spectrometer systems were routinely checked for efficiency and nonlinearity with standard sources. The spectra were analyzed by the computer code GAMANAL.[49,50] To obtain the most precise energy values, a series of experiments was done in which energy standards were matched in intensity with major photopeaks from the ^{44}K sources. The standards plus ^{44}K sources were counted simultaneously on the large detectors at 0–2 MeV with a 4096 channel analyzer and 0–5 MeV with an 8192 channel analyzer. The precision energy values of Tirsell and Multhauf[51] were used.

γ-γ coincidence events were detected using two 30-cm^3 true coaxial Ge(Li) detectors mounted at 180° with Pb antiscattering shields. The data were recorded with the LLL megachannel analyzer system[52,53] which uses a PDP-9 computer on line to sort and store the data on a magnetic disk. Energy slices using the major peaks as gates were then written on magnetic tape for analysis by GAMANAL.

B. ^{44}Sc^{m+g} decay

Sources of ^{44}Sc were prepared by the (γ, n) reactions on natural Sc at the Livermore linear accelerator or by the (α, dxn) reaction on natural Ca metal at the Berkeley 88-inch cyclotron. Scandium was chemically separated from the Ca targets before counting. The γ-ray singles spectra were observed and the decay of the individual γ rays was followed by the general techniques outlined above.

In addition, a ^{44}Ti source was prepared by the (α, xn) reaction on natural Ca at the 88-inch cyclotron.

III. RESULTS

Figure 2 is the high energy portion of a typical spectrum taken on one of the large-volume detectors with Pb absorber. Table I lists the energies, relative intensities, and level assignments of the 128 γ rays identified in the decay of ^{44}K. The intensities are normalized to 1000 for the 1157-keV γ ray. Level assignments were made on the basis of coincidence data and energy sums as outlined below. Coincidence data for ^{44}K are shown by full circles in Figs. 3–7 and are given in Table II. Only γ rays positively identified as coincident

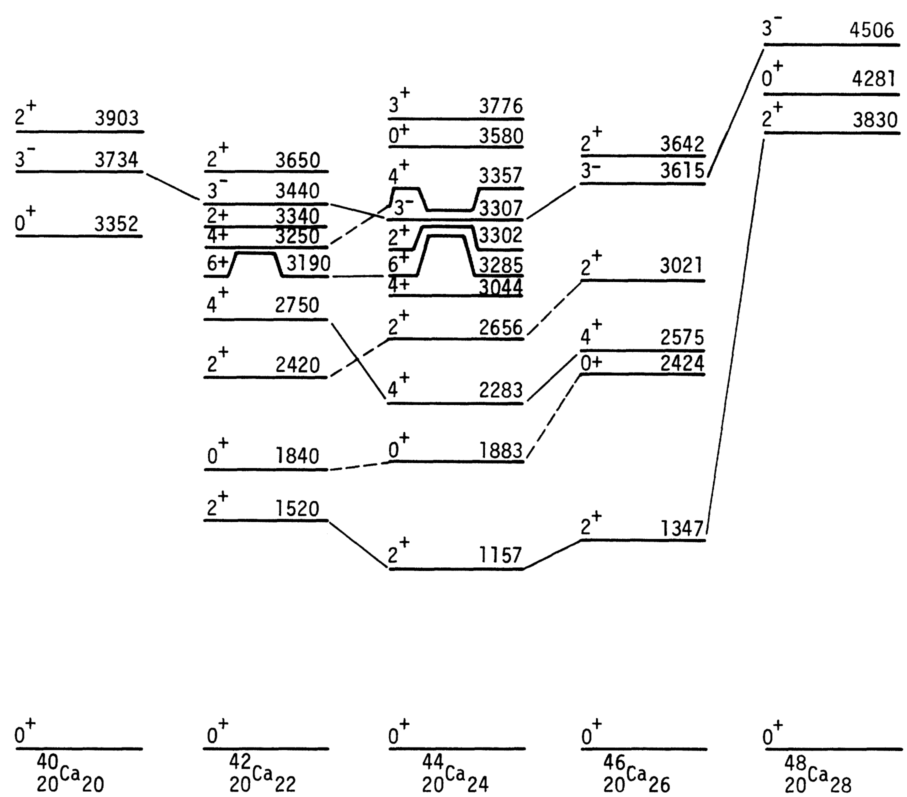

FIG. 1. Levels of even-even calcium isotopes from $N=20$ to $N=28$. Data taken from Ref. 1.

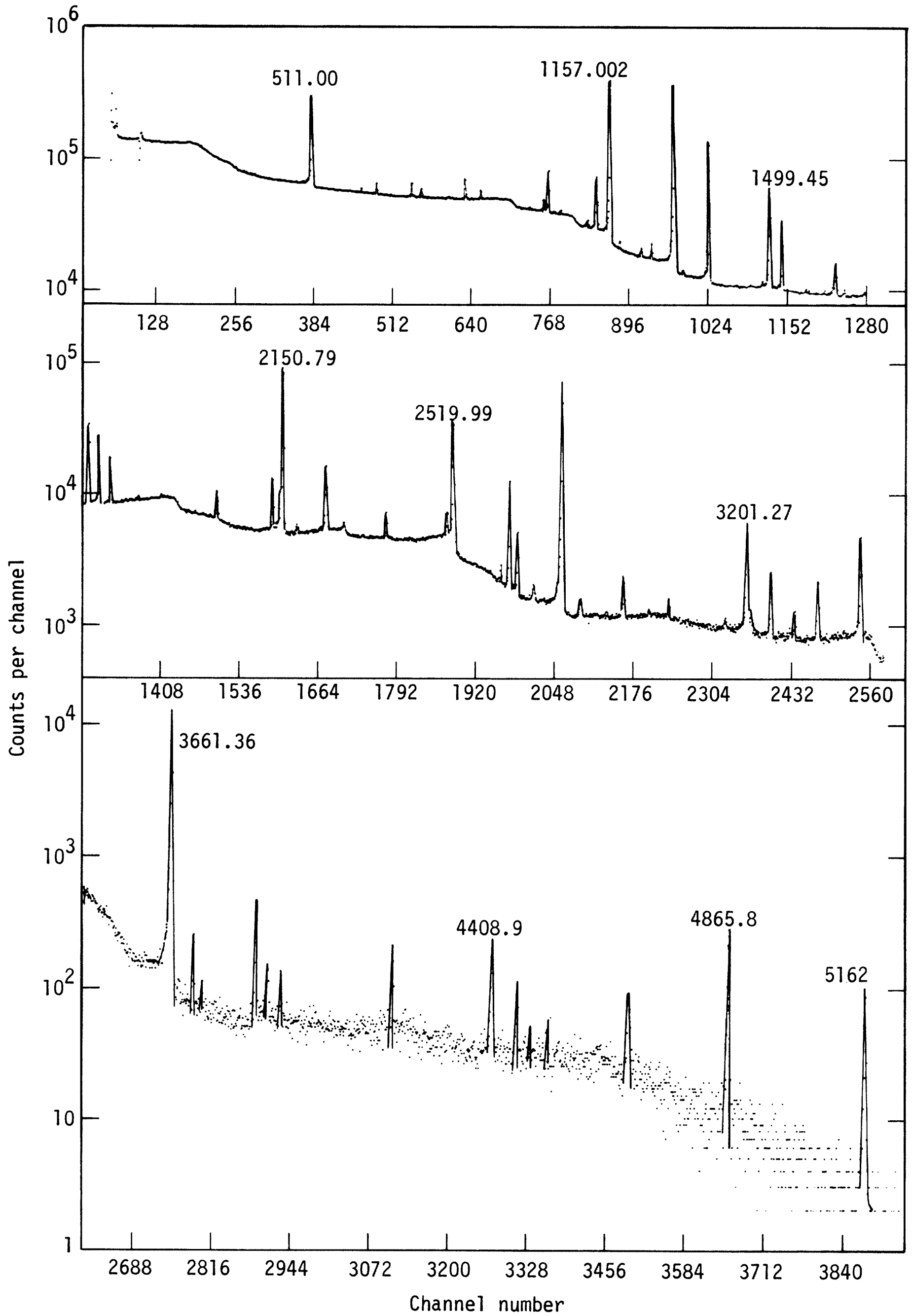

FIG. 2. Spectra of ^{44}K up to 5.2 MeV taken with 2.54 cm of Pb.

with the gate energy are listed. Table III lists energies and relative intensities for γ rays in the decay of $^{44}Sc^{m+g}$.

Decay schemes are shown in Figs. 3–7. Those for ^{44}K are broken into several regions. Figure 3 shows ^{44}K decay from all levels below 3308 keV, Figs. 4 and 5 show that from negative-parity levels above 3308 keV, while Figs. 6 and 7 show that from positive- or unknown-parity levels above 3308 keV. Figure 8 shows the decay scheme of $^{44}Sc^{m+g}$. Figures 3 and 8 are drawn to scale; in Figs. 4–7 the levels are shown equally spaced for clarity. The level energies shown include the recoil energy in every case. Table IV lists the log*ft*

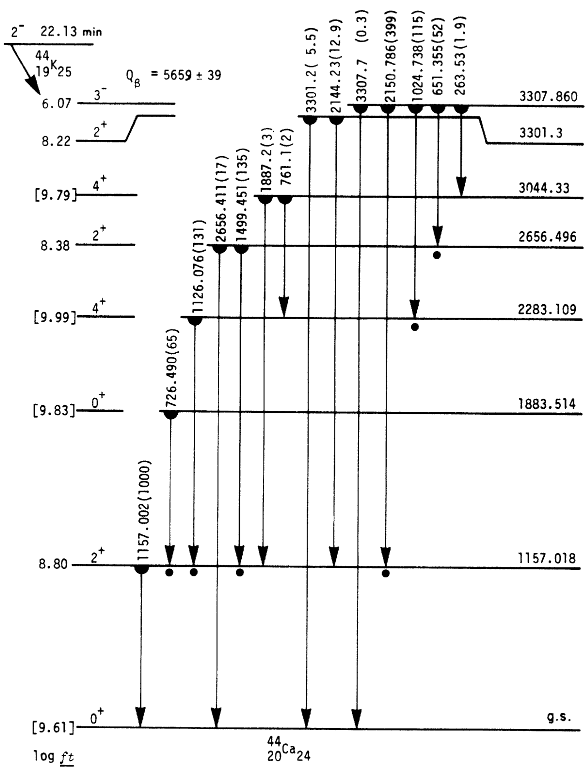

FIG. 3. ^{44}K decay to ^{44}Ca levels 3.3 MeV and less. (*Nota bene*: The *level* energy is the sum of the observed γ-ray energy plus *recoil* energy. For a 3000-keV γ ray in ^{44}Ca the latter represents 0.110 keV. The dots on the decay scheme represent confirmation of the placement of the γ ray by coincidence.)

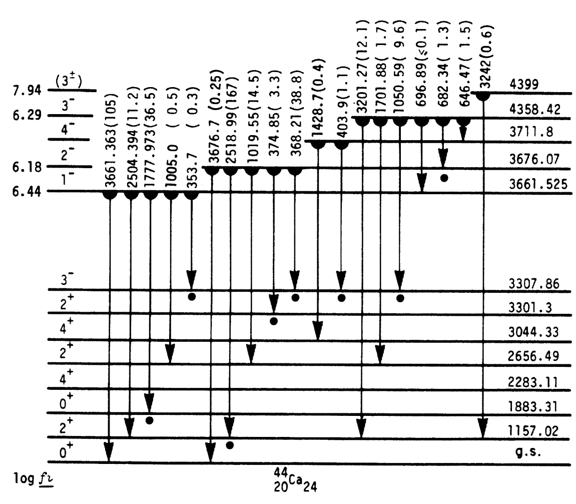

FIG. 4. ^{44}K decay to ^{44}Ca levels, negative-parity levels to 4.4 MeV.

TABLE I. The γ rays observed in the decay of 22.1-min ^{44}K to levels of ^{44}Ca.

E_γ	(ΔE_γ)	I_γ	(ΔI_γ)	Assignment From	To
174.350	(250)	1.0	(2)		
209.980	(250)	0.3	(2)		
263.532	(55)	1.9	(5)	3307	3044
353.665	(250)	0.3	(2)	3661	3307
368.207	(14)	38.8	(7)	3675	3307
374.845	(98)	3.3	(8)	3675	3301
403.862	(196)	1.1	(3)	3711	3307
463.300	(350)	0.3	(3)		
646.473	(315)	1.5	(5)	4358	3711
651.355	(9)	52	(2)	3307	2656
682.338	(29)	1.3	(7)	4315	3675
696.895	(-)	≤0.1		4358	3661
726.490	(16)	65	(2)	1883	1157
733.000	(400)	2.8	(1.2)	4409	3675
747.630	(28)	36	(2)	4409	3661
761.100	(300)	2	(1)	3044	2283
766.800	(500)	0.8	(7)		
772.975	(-)	≤0.1		2656	1883
876.530	(29)	29.8	(6)	4552	3675
891.095	(120)	1.6	(6)	4552	3661
983.577	(153)	3	(1)		
1005.000	(900)	0.5		3661	2656
1019.548	(68)	14.5	(6)	3675	2656
1024.738	(17)	115	(2)	3307	2283
1050.596	(95)	9.6	(1.4)	4358	3307
1074.137	(385)	1.5	(9)	3357	2283
1101.300	(450)	0.2	(2)	4409	3307
1106.260	(250)	1.7	(5)		
1107.978	(93) [a]	11.5	(8) [a]	4409 [a]	3301 [a]
1119.700	(350)	0.3	(2)	3776	2656
1126.076	(10)	131	(2)	2283	1157
1157.002	(3)	1000	(1)	1157	g.s.
1195.400	(-)	0.8	(7)	4552	3357
1222.500	(76)	8.3	(8)	4883	3661
1244.747	(53)	14.3	(5)	4552	3307
1272.760	(350)	1.4	(1.3)		
1285.000	(1000)	(≤0.3)		(4866	3580)
1363.700	(800)	0.2	(2)	5024	3661
1377.620	(450)	2	(1)		
1427.500	(400)	1.9	(9)		
1428.660	(400)	0.4	(2)	3711	2283
1499.451	(36)	135	(5)	2656	1157
1525.011	(-)	[c]		5201	3677
1575.864	(309)	3.0	(9)	4883	3307
(1582) [b]		≤0.1 [b]			
1625.049	(716)	0.6	(4)		
1634.520	(107)	4.0	(9)	5309	3675
1658.690	(181)	3.7	(9)	4315	2656
1701.879	(305)	1.7	(7)	4358	2656
1752.629	(10)	70	(1)	4409	2656
1777.973	(20)	36.5	(8)	3661	1883
1810.438	(682)	1.2	(8)	4409	2283
1884.542	(1000)	0.4	(3)	5561	3676
1887.205	(279)	2	(1)	3044	1157
1893.207	(438)	1.9	(9)	5201	3307
1896.000	(900)	1.9	(1.4)	4522	2656
1916.000	(800)	2.3	(1.2)	4572	2656
(1923)		≤0.9		5231	3308

TABLE I (*Continued*)

E_γ	(ΔE_γ)	I_γ	(ΔI_γ)	Assignment From	To
1976.913	(691)	0.9	(7)	4160	2283
1992.421	(516)	1.2	(8)	4656	2656
2144.231	(76)	12.9	(8)	3301	1157
2150.786	(17)	391	(8)	3307	1157
2167.841	(580)	1.3	(7)	4824	2656
2200.300	(-)	0.2	(2)	3357	1157
2268.525	(953)	0.5	(4)	4552	2283
2280.800	(700)	≤0.5 [d]		5325	3044
2324.300		0.6	(4)	3580	1157
2338.287	(552)	0.7	(4)	4771	1883
2423.339	(587)	0.7	(4)	3580	1157
2497.291	(869)	0.6	(5)		
2504.394	(62)	11.2	(9)	3661	1157
2518.991	(18)	167	(3)	3675	1157
2598.355	(592)	0.7	(5)		
2619.164	(120)	3.6	(7)	3776	1156
2656.411	(30)	16.9	(8)	2656	g.s.
[2668	(-)]	(≤0.05)		(5325	2283)
2711		0.3	(3)	5367	2656
2740.400	(800)	0.11	(9)		
2745.000	(1000)	≤0.2			
2847.646	(693)	0.5	(3)	5130	2283
2937.800	(1000)	0.8	(3)	4094	1157
2973.000	(1000)	0.3	(2)		
2982.469	(149)	2.2	(3)	4866	1183
(3067.000	800)	(0.2	2)		
3103.175	(401)	1.1	(4)	4260	1157
3158.070	(201)	2.6	(4)	4315	1157
3201.274	(73)	12.1	(9)	4358	1157
3217.313	(546)	0.5	(3)	(4374	1157)?
3227.132	(763)	0.3	(2)	(4384	1157)?
3241.958	(485)	0.6	(3)	4399	1157
3252.072	(124)	2.7	(4)	4409	1157
3278.995	(650)	0.3	(2)	4437	1157
3301.210	(139)	5.5	(9)	3301	g.s.
3307.728	(450)	0.3	(1)	3307	g.s.
3395.508	(44)	28.7	(8)	4552	1157
3404.646	(551)	0.8	(4)	4561	1157
3415.538	(634)	1.0	(4)	4572	1157
3661.363	(11)	105	(2)	3661	g.s.
3676.732	(624)	0.25	(11)	3675	g.s.
3708.898	(124)	≤0.8		4866	1157
3726.634	(411)	0.5	(1)	4884	1157
3747.100	(-)	≤0.01		4904	1157
3755.173	(850)	0.14	(9)		
3868.555	(216)	1.1	(3)	5025	1157
3967.822		0.11	(9)		
4005		0.02	(2)	5161	1157
4044		≤0.05		5201	1157
4074.000	(1000)	0.08	(8)	5231	1157
(4162.545	765)	(0.09	8)		
4167.792	(543)	0.16	(8)	5325	1157
4210.100	(1000)	0.09	(8)	5367	1157
4355		≤0.05		5512	1157
(4337.935	747)	(0.09	9)		
4403.611	(625)	0.06	(4)	5560	1157
4408.911	(184)	0.92	(15)	4410	g.s.
4436.994	(647)	0.12	(8)	4437	g.s.
4471.537	(601)	0.11	(8)		

TABLE I (*Continued*)

E_γ	(ΔE_γ)	I_γ	(ΔI_γ)	Assignment From	To
4651		0.14	(8)	4651	g.s.
4865.812	(151)	2.8	(1)	4865	g.s.
4892.324	(782)	0.06	(5)	4892	g.s.
5025.400	(800)	0.03	(2)	5025	g.s.
5161.959	(101)	1.11	(7)	5162	g.s.
5231.000	(-)	≤0.01		5231	g.s.
(5561.300	1000)	(0.05	4)	5560	g.s.

[a] *Nota bene* 1107.8 is 4883 to 3580.
[b] See Ing *et al.* (Ref. 33).
[c] Obscured by contaminant.
[d] Possibly 18-min ^{88}Rb contaminant.

values calculated from the data for ^{44}K. The levels, spins, and parities are known or inferred from our data. The β-transition data was calculated from γ-ray relative intensities.

The properties of the levels below 3200 keV are well established by previous works. Above 3200 keV we will discuss the level sequence in terms of differences between our results and those of the previous workers. All levels below 6 MeV that have been experimentally observed are given in Table V. Below we discuss our new assignments and the significant differences with previous investigations.[33]

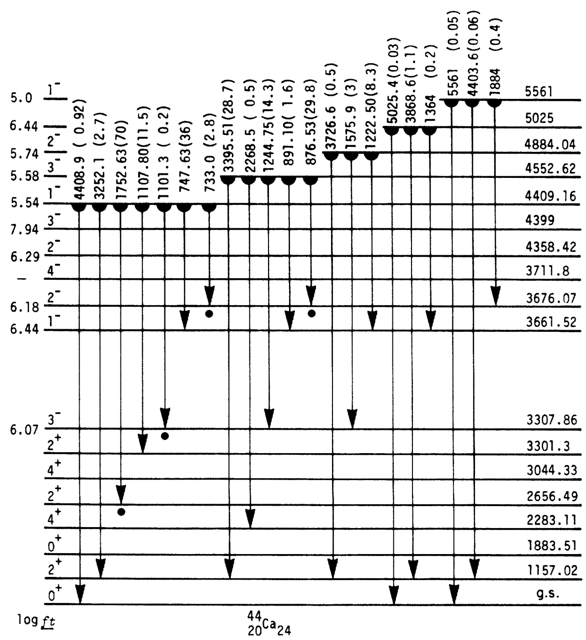

FIG. 5. ^{44}K decay to ^{44}Ca levels, negative-parity levels to 5.6 MeV.

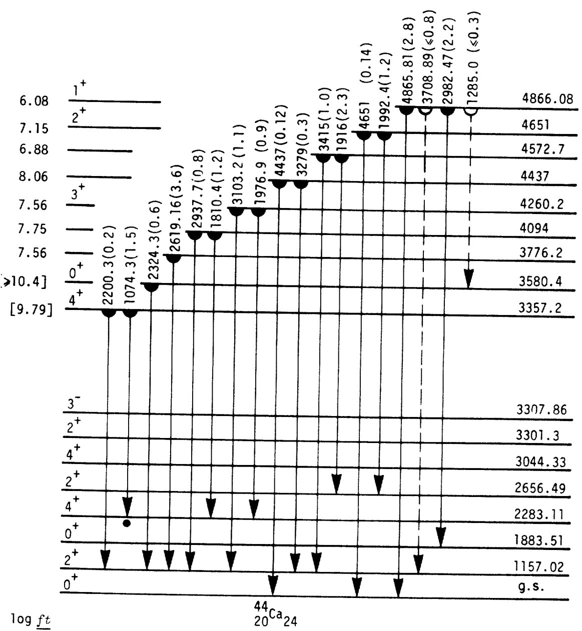

FIG. 6. ^{44}K decay to ^{44}Ca levels, positive-parity levels to 4.9 MeV.

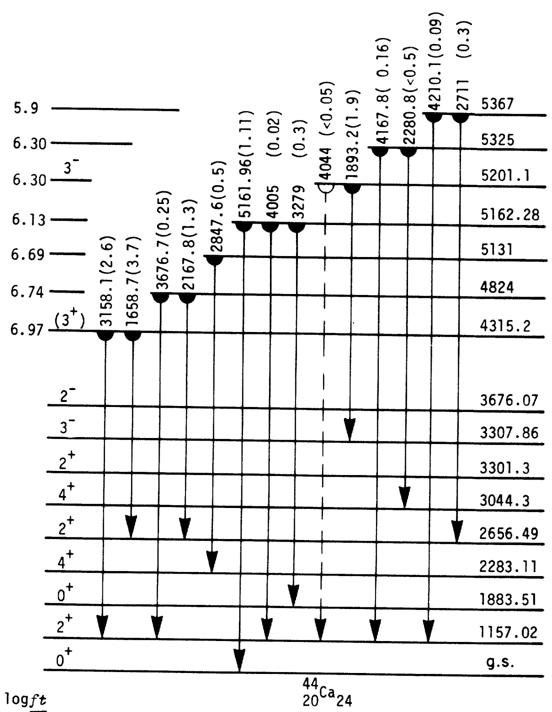

FIG. 7. ^{44}K decay to levels of ^{44}Ca.

The assignment of 1^- to the 3661-keV level is consistent with our log*ft* and branching ratios and also with the (p,p') data.[16] We favor $J^\pi = 2^-$ for the 3676-keV level based on the log*ft* value and the strength of the transition to the 3^- level at 3307 keV.

We were unable to measure the β branching to the 3711-keV level and hence favor a 4^- for the J^π assignment suggested by White and Birkett.[32] Our log*ft* value is consistent with either 2^+ or 3^+ for the 3776-keV level in accordance with reaction data.[30]

Ing *et al.*[33] reported an intensity for the 682-keV γ-ray transition from this level to the 3676-keV 2^- level approximately 9 times our value and did not place a 646-keV transition to the 3711-keV 4^- level. The assignment of 3^- to the 4358 keV is consistent with our log*ft* and branching ratios.

The assignment of 3^- to the level at 4552 keV is consistent with our log*ft* and branching ratio data. We see no transition to the 3044-keV 4^+ level by a 1509.5-keV γ ray as reported in Ing *et al.*[33] We did, however, see a weak 2268-keV transition to the 2283-keV 4^+ level.

We suggest either 1^+ or 1^- for the 4866-keV level. 1^+ is consistent with the fact that the level was not observed in either neutron-capture[32] or (p,p')[16] studies. However, the log*ft* indicates a 1^- assignment. We do not observe a 1190-keV γ ray as reported by Ing *et al.*[33] but do observe a 1285-keV γ ray which we place as a transition to the 3580-keV 0^+ level.

The 4884-keV level can be either 3^- or 2^- from the log*ft* and γ-ray branching; we prefer 2^- because the level is not observed in the (p,p') reaction studies.[16]

The 5025-keV level reported by Ing *et al.*[33] is further supported in this work by the observation of a 5025-keV transition to the ground state. The

TABLE II. γ rays observed in coincidence with various gate slices.

Gate [a]	γ rays in coincidence					
368	733	877	1025	1126	1157	
651	354	368	404	1101	1156	1499 2656
726	1157	1778				
877	368	651	375	1157	1499	2518
1025	1101	1126				
1126	1024	1072	1157			
1499	368	651	1157			
2151	368	1051	1101	1157		
2519	682	877	1157			

[a] The gates were approximately 2 to 3 keV wide centered on the γ-ray peak. See discussion in Mann, Walters, and Meyer (Ref. 53) for analysis techniques used.

TABLE III. The γ rays observed in the decay of $^{44}Sc^{m+g}$.

E_γ (ΔE_γ)	I_γ (ΔI_γ)	γ from decay of	Assignment	
271.241 (10)	778 (14)	*IT*	*IT*	
1001.825 (31)	12.3 (1)	*m*	3285	2283
1126.064 (40)	12.3 (1)	*m*	2283	1157
1157.002 (3)	1000	*g* and *m*	1157	g.s.
1499.451 (20)	9.01 (19)	*g*	2656	1157
2144.300 (100)	0.02 (2) [a]	*g*	3301	1157
2150.786 (–) [b]	0.011 (3)	*g*	3307	1157
2656.411 (30)	1.11 (4)	*g*	2656	g.s.
3301.200 (100)	0.0064 (8)	*g*	3301	g.s.
Limits				
729.49	≤0.014			
1887.2	<0.001		3044	1157

[a] This γ ray is masked by the more intense single escape peak of the 2656-keV photopeak. The γ-ray intensity was calculated from the known branching of the 3301-keV level in ^{44}K decay and is $I_{2144} = 0.015$.

[b] The γ-ray energy is taken from Table I.

summary of level energies in White and Birkett associates levels at 5031 keV observed in (p,p') reaction and at 5029 keV observed in (t,α) reactions to a 5005.7-keV level. It seems reasonable to associate these with the 5025-keV level. These arguments along with log*ft* and branching indicate an assignment of 2^- for this level.

We observe several levels previously seen in reaction studies[32] but not reported in β decay. We observe the 3301-keV 2^+ state reported in neutron capture[32] with approximately the same decay properties. We will return to discussion of this level later.

We observe the level at 3357 keV with decay properties in agreement with White and Birkett.[32] We prefer a spin assignment of 4^+ because of the large log*ft* value.

The 3580-keV level is observed in (p,p')[16] and (t,α) studies, but not in neutron capture. We observe a single weak transition to the 1157-keV 2^+ state and a large log*ft*. Therefore, we favor 0^+ for assignment.

A level near 4094 is seen in all reaction studies. We suggest that the level at 4092 keV reported by White and Birkett[32] may be different than the 4094-keV level that we observe. This is based on the following arguments: (1) The 1808.92-keV transition to the 2283-keV 4^+ level is significantly different in energy than the 1810.44-keV transition we observe; (2) we observe no 806.9-keV transition to the 3285-keV 6^+ level; and (3) the 2937.7-keV transition to the 1157-keV 2^+ level is not observed in the neutron capture work. We suggest a low spin positive-parity assignment, possible 2^+ for the level at 4094.

The level at 4399 keV is seen in all reaction studies. We suggest either 3^+ or 3^- based on the log*ft* and decay.

The level at 4409 keV is seen in (p,p') reaction studies, but not in neutron capture. These facts along with the log*ft* and transition data indicate a 1^- assignment to this level.

The level at 4651 keV is seen in all the reaction studies. Our data are consistent with the 2^+ assignment.

The level at 5130 keV is seen in all the reaction data except (t,α). We place the level on the basis

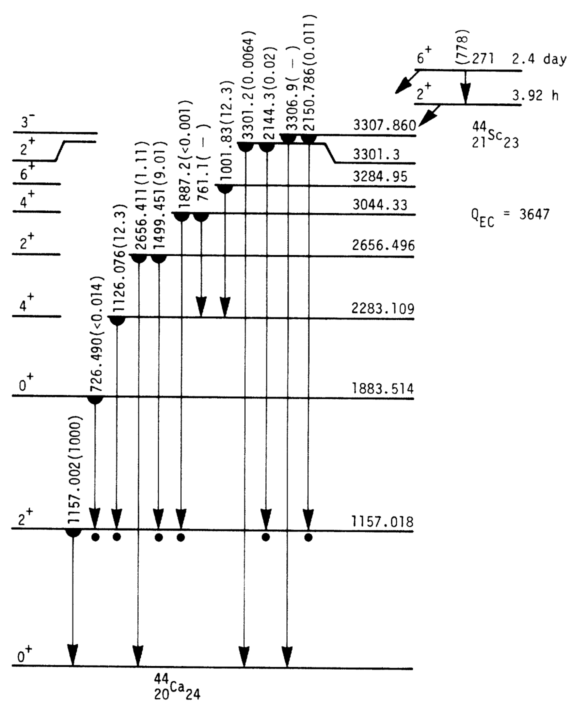

FIG. 8. Decay of $^{44}Sc^m$ and $^{44}Sc^g$.

of the 2847.6-keV transition, although we do not observe the 1773- and 3973-keV γ rays reported by White and Birkett.[32] Our logft value is consistent with either a 2^+ or 4^+ assignment.

We place a level at 5201.1 keV which corresponds to the group of levels at 5215 to 5225 keV observed in (p,p') and (t,p) studies. The logft and decay data are consistent with a 3^- assignment.

Finally, we postulate eight new levels at 4260, 4315, 4437, 4573, 4824, 5325, 5367, and 5561 keV. We suggest 3^+ as the most probable J^π value for the levels at 4260, 4315, 4573, and 4824 keV. No assignments can be made for the 4437-, 5325-, and 5367-keV levels. The 5561-keV level has a logft of 5.0 and a relatively strong transition to the ground state which makes 1^- the most probable spin and parity.

We do not observe levels at 5157, 5309, and 5556 keV reported by Ing *et al.*[33] and have assigned the γ rays to other transitions in most cases. We also find their 3303.8-keV level to be 3301.3 keV based on 3301.2 ± 0.1- and 2144.23 ± 0.08-keV transitions to lower states. We do not observe 3304.1- and 2146.5-keV γ rays. We assign the 646.5 ± 0.3-keV γ ray to decay of the 4358-keV level. Our assignment of the 2^+ level at 3301.3 ± 0.3 keV is in good agreement with the level observed in neutron-capture studies at 3301.4 ± 0.4 keV.

TABLE IV. Logft values for observed levels.

Level energy (keV)	J^π	% β to level [a]	Logf_0t [b]	Logf_1t [b,c]
g.s.	0^+	34 [d]		9.61
1157	2^+	0.96	8.80	
1183	0^+	1.54		9.83
2283	4^+	0.52		9.99
2656	2^+	0.41	8.38	
3044	4^+	0.17		9.79
3301	2^+	0.21	8.22	
3307	3^-	29.3	6.07	
3357	4^+	0.08		9.79
3580	0^+	>10.01		≥10.4
3661	1^-	6.33	6.44	
3676	2^-	10.93	6.18	
3711	4^-	···		
3776	3^+	0.35	7.56	
4094	(3^+)	0.11	7.75	
4260	3^+	0.11	7.56	
4315	(3^+)	0.36	6.97	
4358	3^-	1.52	6.29	
4399	3^+	0.03	7.94	
4409	1^-	7.21	5.54	
4437		0.02	8.06	
4552	3^-	4.29	5.58	
4572	(3^+)	0.19	6.88	
4651	2^+	0.08	7.15	
4824		0.09	6.74	
4866	$1^\pm$	0.36	6.08	
4884	$3^-,2^-$	0.71	5.74	
5025	(2^-)	0.07	6.44	
5131		0.02	6.69	
5162		0.06	6.13	
5201		0.12	6.30	
5231		≤0.02	6.36	
5325		0.01	6.30	
5367		≤0.02	≤5.79	
5561		0.04	4.95	

[a] Percent β transitions to each level were calculated from γ-ray relative intensities using 34% transition to the ground state (Ref. 36).

[b] We use 5659 ± 39 keV for the Q_β value and 22.13 ± 0.19 min for $T_{1/2}$ as given by Ref. 1, p. 532.

[c] Logf_1t values were calculated for levels of known spin and parity.

[d] We adopt the value of 34% for population of the ground state given by Levkovskii and Kazachevskii (Ref. 36).

IV. DISCUSSION

The levels of ^{44}Ca below 3400 keV, shown in the left side of Fig. 9, can be accounted for by assuming, for the description of the positive-parity levels, a soft core model or a linear combination of seniorities-2 and -4 states and deformed states. The negative-parity level at 3308 keV can be identified as the octupole excitation. However, no attempt has been made to describe the higher lying levels, in particular the negative-parity levels between 3600 and 5000 keV. Here we wish to discuss the latter in terms of two-phonon quadrupole-octupole vibrations (TPQOV) of the type that have been calculated for heavier nuclei by Lipas and co-workers.[11,12]

The positive parity levels of ^{44}Ca and their properties have been discussed most recently by McCullen and Donahue[31] who measured the lifetimes to the ^{44}Ca level up to 3300 keV. They used previously established models to describe these levels of ^{44}Ca and their properties. The calculations used a wave function that was a linear combination of $(1f_{7/2})^4{}_{\nu=0,2}$, $(1f_{7/2})^4{}_{\nu=4}$, and rotational basis state to force a fit to the experimental energies. The percent of each configuration in the levels below 3300 keV is given in the bottom right corner of Fig. 10 as the proportion: $(f_{7/2})^4{}_{\nu=0,2}/(f_{7/2})^4{}_{\nu=4}/$rotational. These wave functions were then used to calculate the (d,p) spectroscopic factors, lifetimes, and decay properties of the levels. In general they found good agreement with this $(f_{7/2})^4$ + rotational-band calculation. In more phenomenological terms the core can be considered as a soft vibrator.

The 3^- octupole core vibration[54] is observed at

TABLE V. Experimentally observed levels of ^{44}Ca below 6 MeV.

Decay data (This study) [a]	(n,γ) data White [b]	(p,p')	(d,p)	(t,α)	(t,p)	J^π	Mean life (ps)
g.s.	0	0	0	0	0	0^+	···
1157.018 (11)	1156.94 (14)	1158	1162	1158	1157	2^+	5.1
1883.514 (15)	1883.44 (33)	1883	1886	1887	1903	0^+	20
2283.109 (20)	2283.13 (17)	2282	2289	2288	2285	4^+	2.8
2656.496 (25)	2256.33 (20)	2655	2668	2659	2655	2^+	< 0.03
3044.33 (7)	3044.37 (23)	3045	3052	3052	3044	4^+	6.7
3284.95 (7)	3285.02 (25)	3285	3296			6^+	17
3301.30 (20)	3301.39 (36)	3300	3302		3298	2^+	50
3307.860 (35)	3307.71 (25)	3307		3307		3^-	
3357.20 (20)	3357.25 (26)	3357	3367	3360		4^+	< 0.04
3580.40 (20)		3586			3592	0^+	
3661.525 (30)		3663		3670		1^-	
3676.07 (4)	3676.43 (32)	3678	3682		3671	2^-	
3711.80 (4)	3711.99 (27)	3713	3729	3716		4^-	
3776.20 (4)	3776.39 (43)	3777	3792	(3770)		3^+	< 1.0
	3913.75 (28)	3914	3880	3915		5^-	
	3922.62 (28)	3924	3934			(5^+)	< 0.8
	4011.44 (46)	4012	4026	4022			
4094 (1)	4092.0 (3)	4107	4104	4099		(4^+)	
	4195.8 (4)	4197	4207	(4310)		> 3	< 1.0
4260.2 (4)						3^+	
4315.2 (3)						$(2^-, 3^+)$	
4358.42 (5)	4358.32 (34)	4361		4363	4357	3^-	
4399 (1)	4400.00 (15)	4401	4410	(4400)	(4396)	$3^\pm$	
4409.16 (5)		4412				1^-	
4437 (1)							
	4479.8 (6)	4482	4491	4488	4479	(2^+)	
4552.62 (5)		4555				3^-	
	4564.9 (4)	4568	4569	4565	4562	5^-	
4572.7						(3^+)	
	4584.0 (3)	4588	4598			(4^+)	< 5
			4616				
4651 (1)	4651.0 (4)	4655	4662	4660	4646	2^+	
	4690.0 (6)		4696				
	4803.6 (5)	4807	4826				
4824							
4866.08 (5)						$1^\pm$	
4884.04 (5)		4889				2^-	
	4904.5 (4)		4914	4912	4898		
			4992	4991	4991		
	5005.7 (4)		5016		5015	$(4^-, 5^-)$	
5025.6 (1)		5031		5029		(2^-)	
	5096.8 (5)	5097		5103		$(4^-, 5^-)$	
5130.7 (4)	5130.0 (4)	5133	5143	(5120)			
5162.28 (5)						1,2	
5201.1 (1)		5215	(5172)	5222 ± 20		3^-	
	5230.5 (4)	5235	5243	5235	5245		< 6
	5289.3 (4)	5290	5296				
	5300.4 (4)	5303		5306			
5325 (1)							
	5342.2 (6)		5351	5344	5333		
5367 (1)							
	5375.0 (6)		5385		5361		
			5405	5404			
	5458.9 (5)		5468	5518			
	5548.4 (4)		5558	5579			
5560.6 (3)						1^-	
			5666	5660	5646	3^-	
	5733.4 (4)		5743	5741	5729		< 5

TABLE V *(Continued)*

Decay data (This study) [a]	(n,γ) data White [b]	(p,p')	(d,p)	(t,α)	(t,p)	J^{π}	Mean life (ps)
	5775.8 (4)		5776	5810			
			5832				
	5866.7 (5)		5873	5891	5864		

[a] Energy level value is given in keV and the error in last significant figure is given in parentheses; thus 1157.018 (11) represents 1157.018 ± 0.011 keV.
[b] D. H. White and R. Birkett (Ref. 32).

approximately 3500 keV in all the even-even calcium nuclei as shown in Fig. 1. Roehmer[10] has studied the properties of the octupole state in a wide range of nuclei. For example, he finds the 3^- octupole state in $^{38}_{18}Ar$ to have a lifetime of 110 fs, and that the level decays to ground state with an $E3$ speed of 5 single particle units (s.p.u.),[55-57] while the $E1$ to the first 2^+ level is hindered by approximately 1000 over the single particle estimate. The speed of the $E3$ from the octupole state to ground state is found to be approximately constant in a given mass region.[10] The lifetime of the 3^- octupole vibration in ^{44}Ca which occurs at 3308 keV has not been measured. However, the lifetime of the level can be estimated by using our branching ratios and the $E3$ speed of 5 s.p.u. measured for ^{38}Ar. This gives a lifetime of 190 fs and $E1$ hindrances of 6900, 2600, 1450, and 2500 to the 1157- (2^+), 2283- (4^+), 2656- (2^+), and 3044-keV (4^+) level, respectively. These are consistent with the $E1$ decay properties of octupole states in both light and heavier nuclei.[10, 13-15]

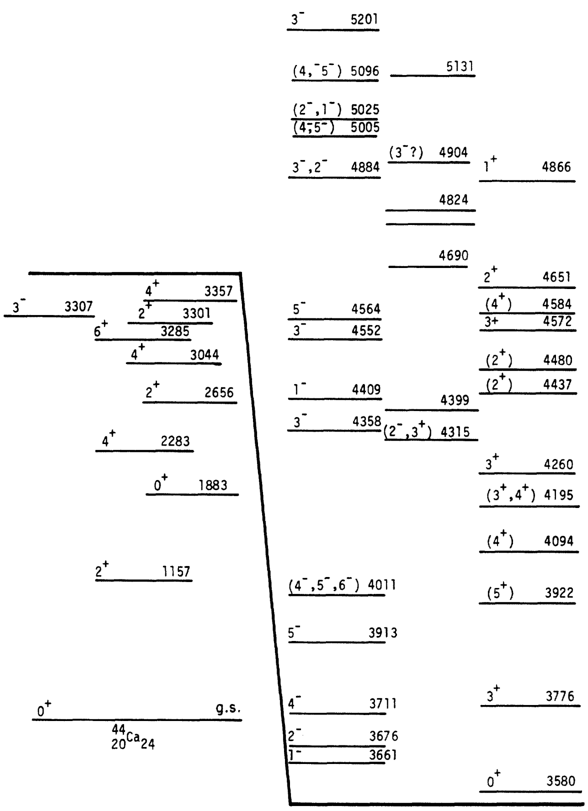

FIG. 9. Levels of ^{44}Ca. In the right-hand part of this figure the left-hand set of levels are those that can be assigned negative parity, on the right side are those assigned positive parity. No parity assignment can be made with the existing data for those in the middle.

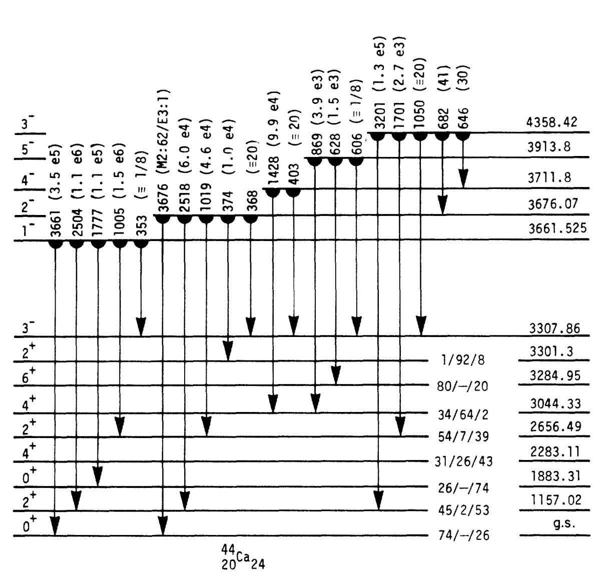

FIG. 10. Decay properties of the proposed TPQOV pentad. Transition energies are given to 1 keV only. The number in parentheses is the hindrance factor for the transition relative to a fiducial (see text). The abbreviation 4.0e5 is used to represent $4.0\times10^{+5}$. [*Nota bene*: The decay of the 3914-keV level is taken from the data of White and Birkett (Ref. 32); see text for origin of 606.0-keV γ ray.] Values in the lower right-hand corner of the figure next to the level energy are the % contribution to the wave functions calculated by McCullen and Donahue (Ref. 3), given as: $(f_{7/2})^4{}_{v=0,2}/(f_{7/2})^4{}_{v=4}$/rotational.

The properties of TPQOV were calculated first on a phenomenological basis by Lipas[58] and later on a semimicroscopic basis by Raduta, Sandulescu, and Lipas.[12] The later calculations showed that the ordering of the expected pentad of levels with J^π of 1^-, 2^-, 3^-, 4^-, and 5^- depended upon the available microscopic states. However, their general results show the 1^-, 2^-, and 4^- to be low lying; the 3^- to be highest lying and the 5^- to be in the middle of the pentad of levels. In cases where the core quadrupole vibration is relatively low lying, the lowest member of the TPQOV can be observed at an energy which is only 70% of the sum of the energies of the 3^- octupole and 2^+ quadrupole vibration. The decay of the TPQOV levels would be expected to proceed via an enhanced $E2$ transition to the octupole state and by highly hindered $E1$ transitions to the quadrupole vibration. Such is the case in nuclei such as ^{114}Cd and ^{124}Te, where members of the TPQOV have been identified.[12,15]

For ^{44}Ca, a pentad of levels arising from a TPQOV might be expected to occur at approximately 4.4 MeV or lower in view of the "softness" of the quadrupole vibration. The levels at 3662 (1^-), 3676 (2^-), 3712 (4^-), 3914 (5^-), and 4358 (3^-) keV, shown in Fig. 10, could be considered as members of this pentad. These levels and their decay properties are taken from this work and the neutron-capture γ-ray data of White and Birkett (*Nota bene*: We have taken the 606.0-keV γ ray observed but unassigned by White and Birkett and assigned it as representing the decay of the 3913.8-keV level to the 3307.8-keV level.)

Since no lifetimes are available for these levels, we have assumed a speed of 8 s.p.u. for the transitions that require $E2$ character and an arbitrary value of 20 for the transitions that are at least $M1$ character since this is a typical value for hindrance in known cases. For the levels where we assume a $M1$ multipolarity for the fiducial transition, the $E1$ hindrances must be considered as lower limits only. The hindrance for the $E1$ transitions were calculated using the experimental branching ratios and are given in parentheses after the transition energy in Fig. 10. As expected, the $E1$ transitions are found to have a hindrance of 10^3 to 10^7. It should be noted that the 5^- level would be expected to be mixed with the seniority-4 state $[d_{3/2}^{-1}(f_{7/2})^3{}_{7/2}]5^-$ identified in the calcium nuclei. We note that the observed 3676-keV level to ground state transition may proceed via an $E3$ rather than a highly hindered $M2$.

Although of speculative nature, it is tempting to consider some of the higher-lying negative-parity levels as arising from the coupling of the 3^- octupole vibration with the higher positive-parity vibrational states. The characteristic of this type of excitation would be expected to be preferred decay to the TPQOV pentad and hindered decay to the levels below 3400 keV. Such are the characteristics of the 4409- (1^-), 4552- (3^-), and 4884-keV (2^-) levels. However, other configurations could account for their decay characteristics.

V. SUMMARY

We have investigated the levels of ^{44}Ca that are populated in the decay of ^{44}K and ^{44}Sc^{m+g}. These data with the neutron capture γ-ray data of White and Birkett[32] have led to the suggestion that the negative-parity levels of ^{44}Ca between 3600 and 4400 keV may be accounted for by considering two-phonon quadrupole-octupole vibrations of the type calculated by Lipas and co-workers[11,12,58] for heavier nuclei. More positive identification must await the measurement of the lifetimes of the levels that form the TPQOV pentad and the availability of the semimicroscopic calculations for the calcium nuclei. Identification of similar excitations in other even-even calcium and light nuclei would be of interest.

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