Study of Gamma Rays from the $Ca^{43}(p,p'\gamma)Ca^{43}$ Reaction and the Decay of K^{43} and Sc^{43}†

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A study has been made of the γ-ray spectra produced in the proton bombardment of Ca^{43} at proton energies of 2.550, 3.235, and 3.605 MeV. γ-ray branching ratios and excitation energies were determined for most states in Ca^{43} previously seen in decay-scheme and reaction studies up to an excitation energy of 2.25 MeV. An examination of the γ-ray spectrum following the radioactive decay of Sc^{43} shows that the logft value for a transition to a possible $\frac{9}{2}^-$ state below 1.5 MeV in Ca^{43} is greater than 5.7. Examination of the decay of K^{43} shows some discrepancies with previous work.

INTRODUCTION

THE low-lying energy levels of Ca^{43} have been the subject of extensive experimental[1] and theoretical[2–15] investigation for many years. Experimentally, the level energies are well known for excitation energies up to 4.5 MeV, but few spin and parity assignments have been made for levels above those which can be populated via β decay from K^{43}. γ-ray measurements have not been made at all to our knowledge for levels above 1.4 MeV. The theoretical predictions of the Ca^{43} level structure which have been made recently are summarized in Fig. 1. It can be seen that, while there is general agreement on the spins and parties of the first two exited states, there is considerable disagreement on the spin sequence for the higher states.

Since it is possible to predict not only the spins, but also the γ-transition strengths between the various shell-model states, measurement of γ-ray branching ratios is of interest. We have used the $Ca^{43}(p,p')Ca^{43*}$ reaction to populate excited states in Ca^{43} and have observed the γ rays from the de-excitation of these levels. Proton inelastic scattering is an attractive reaction for this purpose for a number of reasons. First, it produces relatively little background. Second, the reaction mechanism is not very selective of particular final states. Third, since the spin of the Ca^{43} target nucleus is $\frac{7}{2}$, it should be possible not only to excite the $J^\pi=\frac{9}{2}^-$ and $\frac{11}{2}^-$ states which are expected for levels of Ca^{43} with configurations arising from the coupling of $(f_{7/2})^3$ neutrons, but also the lower spin states with $J^\pi=\frac{3}{2}^-$ and $\frac{5}{2}^-$.

An investigation was also made of γ rays following the β decay of the $\frac{7}{2}^-$ ground state of Sc^{43}. This decay could populate a low-lying $\frac{9}{2}^-$ level in Ca^{43} and is thus a complementary approach to the search for such a level. γ rays following the β decay of K^{43} were investigated in order to resolve discrepancies between previously reported branching ratios and energies from these decays and those observed in the $(p,p'\gamma)$ reaction during the course of the present experiment.

EXPERIMENTAL PROCEDURE

γ rays produced by the proton bombardment of a thick enriched Ca^{43} target were observed with 8-, 20-, and 30-cc coaxial and 4-cc planar Ge(Li) γ-ray detectors placed about 4 cm from the target spot at 0° and 90° to the incident proton beam. The Ca^{43} was in the carbonate form and was cemented to a thick backing of graphite with a small amount of styrene cement. The abundances of the calcium isotopes present were: Ca^{40}, 12.78%; Ca^{42}, 0.65%; Ca^{43}, 81.12%; Ca^{44}, 5.4%; Ca^{46}, 0.05%; and Ca^{48}, 0.05%. The $Ca^{42,43,46}(p,\alpha)$ reactions are energetically allowed, but the cross sections were apparently small and only a few γ rays were observed that could possibly have been produced in this way. The other possible reactions are inelastic scattering in $Ca^{42,43,44}$ and the (p,n) reaction in $Ca^{43,48}$, as well as the capture reaction for all isotopes.

γ-ray singles spectra were recorded at proton bombarding energies of 2.5, 3.2, and 3.6 MeV. Adequate counting rates were obtained with beam currents of 0.04 μA. The γ-ray energy scale was established relative to the radioactive sources: Co^{57}, Mn^{54}, Na^{22}, Bi^{207}, and ThC″. A spectrum obtained at 3.6 MeV is shown in Fig. 2. A coincidence run was also made with Ge(Li) and 3×3-in. NaI(Tl) γ-ray detectors at a proton energy of 3.3 MeV. Windows were placed on prominent lines

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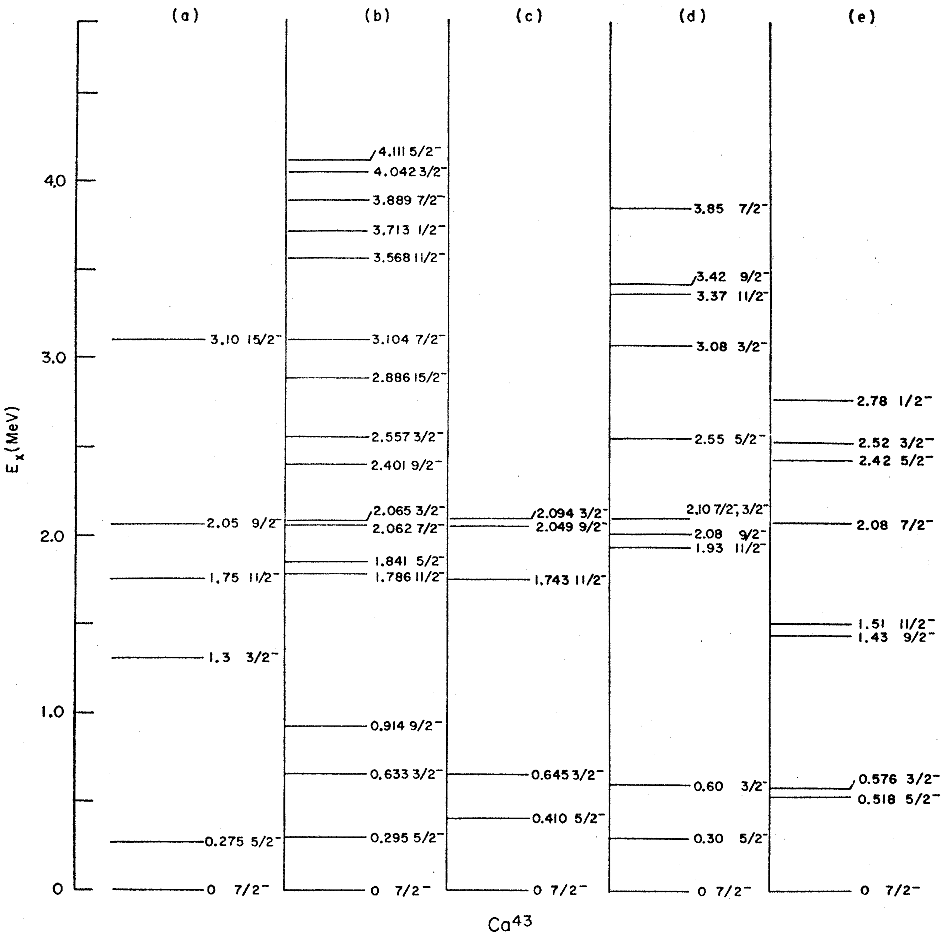

FIG. 1. Features of the Ca^{43} energy-level spectrum which have been predicted in recent theoretical calculations are shown here. The assumptions used in the various calculations differ widely. The spectrum in column (a) is that obtained for the coupling of $(f_{7/2})^3$ neutrons to an inert Ca^{40} core as given by McCullen *et al.* (Ref. 11). This approach successfully gives the spins of the first two excited states of Ca^{43}, and shows that there should be states of simple configuration with $J^\pi = \frac{9}{2}^-, \frac{11}{2}^-$, and $\frac{15}{2}^-$. The spectra shown in columns (b), (c), (d), and (e) are taken from Refs. 12, 13, 14, and 15, respectively.

seen in the NaI(Tl) spectrum and each coincident Ge(Li) spectrum was stored in a 1024-channel analyzer. Results from this run were used mainly to verify the assignment of lines seen in the singles spectra. Some of the γ rays observed in the singles spectra were assigned to levels in Sc^{43} formed in the $Ca^{43}(p,n\gamma)Sc^{43}$ reaction

TABLE I. Prominent lines observed in γ-ray spectra. The neutron-produced lines are from the detector and holder,[a] and the Na^{23} was a target contaminant. Many of the unassigned lines can be fitted into the level scheme of Sc^{44} which is produced in the $Ca^{43}(p,\gamma)Sc^{44}$ reaction.

Energy (keV)	Probable origin	Energy (keV)	Probable origin	Energy (keV)	Probable origin	Energy (keV)	Probable origin
62±2	Ta *K* x ray	372±2	$Ca^{43}(p,p'\gamma)Ca^{43}$	700±2		1274±2	$Na^{22} \xrightarrow{\beta^+} Ne^{22}$
68±2	$Ca^{43}(p,\gamma)Sc^{44}$	396±2	$Ca^{43}(p,p'\gamma)Ca^{43}$	762±2		1291±2	$Ca^{44}(p,\alpha\gamma)K^{41}$
78±2	$Ca^{43}(p,\gamma)Sc^{44}$	404±2	$Ca^{43}(p,p'\gamma)Ca^{43}$	770±2	$Ca^{43}(p,\alpha\gamma)K^{40}$	1393±2	$Ca^{43}(p,p'\gamma)Ca^{43}$ (sum peak)
110±2	$F^{19}(n,n'\gamma)F^{19}$	440±2	$Na^{23}(p,p'\gamma)Na^{23}$	800±2	$Ca^{43}(p,p'\gamma)Ca^{43}$	1460±2	
151±2	$Ca^{43}(p,n\gamma)Sc^{43}$	496±2		870±2		1482±2	
198±2	$F^{19}(n,n'\gamma)F^{19}$	511	Annihilation radiation	974±2	$Ca^{44}(p,\gamma)Sc^{45}$	1523±2	$Ca^{42}(p,p'\gamma)Ca^{42}$
222±2	$Ca^{43}(p,p'\gamma)Ca^{43}$	530±2	$Ca^{44}(p,\gamma)Sc^{45}$	985±2	$Ca^{44}(p,\alpha\gamma)K^{41}$	1676±2	$Ca^{43}(p,p'\gamma)Ca^{43}$
235±2		542±2	$Ca^{44}(p,\gamma)Sc^{45}$	1021±2	$Ca^{43}(p,p'\gamma)Ca^{43}$	1778±2	
282±2	$Ca^{43}(p,p'\gamma)Ca^{43}$	565±2	{$Ca^{43}(p,p'\gamma)Ca^{43}$; 1959 → 1395}	1156±2	{$Sc^{44} \xrightarrow{\beta^+} Ca^{44}$; $Ca^{44}(p,p'\gamma)Ca^{44}$}	1901±2	$Ca^{43}(p,p'\gamma)Ca^{43}$
297±2		593±2	$Ca^{43}(p,p'\gamma)Ca^{43}$			1931±2	$Ca^{43}(p,p'\gamma)Ca^{43}$
				1261±2	$Ca^{43}(p,p'\gamma)Ca^{43}$		
349±2		616±2	$Ca^{43}(p,p'\gamma)Ca^{43}$			1981±2	$Ca^{43}(p,p'\gamma)Ca^{43}$
356±2		654±2	$Ca^{43}(p,p'\gamma)Ca^{43}$ 1676–1022			2067±2	$Ca^{43}(p,p'\gamma)Ca^{43}$
						2090±2	$Ca^{43}(p,p'\gamma)Ca^{43}$
						2250±2	$Ca^{43}(p,p'\gamma)Ca^{43}$

[a] C. Chasman, K. W. Jones, and R. A. Ristinen, Nucl. Instr. Methods **37**, 1 (1965).

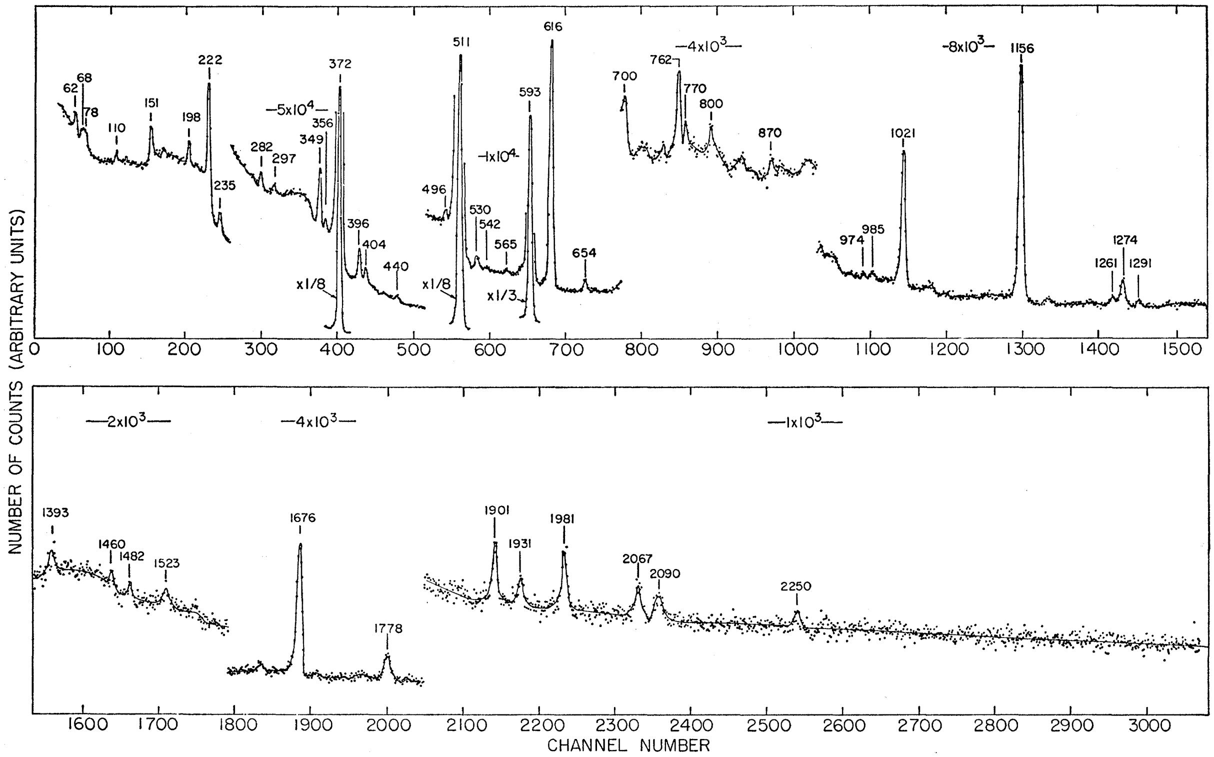

FIG. 2. Singles spectrum obtained for the γ rays produced by the proton bombardment of a thick Ca^{43} target at an energy of 3.6 MeV. In this particular run the γ rays were detected with a 30-cc coaxial Ge(Li) γ-ray detector at 0° to the incident beam at a distance of 4 cm from the target. Energies are given in keV. The ordinate is linear, going from zero to an appropriate maximum value which is shown over each section of the plot.

and to levels in Sc^{44} which were populated in the $Ca^{43}(p,\gamma)Sc^{44}$ reaction. A summary of the prominent lines and their sources, where known, is given in Table I. The decay scheme derived from these results, as well as the data from the decay of K^{43} and Sc^{43} described below, is shown in Fig. 3. The uncertainties in the quoted intensities are about $\pm 20\%$.

Since the decay of $Sc^{43}(\frac{7}{2}^-)$ could populate a $\frac{9}{2}^-$ state in Ca^{43} by allowed positron decay and K capture, a Sc^{43} source was prepared by means of the $Ca^{43}(p,n)Sc^{43}$ reaction. An 8-h bombardment with 3.6-MeV protons gave an adequate source strength for use with the Ge(Li) γ-ray detector. A typical spectrum is shown in Fig. 4. The 1156-keV line is from the decay of Sc^{44} formed in the $Ca^{43}(p,\gamma)Sc^{44}$ reaction. In the γ-ray spectrum for the Sc^{43} decay no lines other than the 372-keV γ ray were observed which could be ascribed to transitions to known levels in Ca^{43}. A limit on the intensity of any γ-ray transition with an energy greater than 511 keV was found to be 0.5% of the intensity of the 372-keV γ ray. This limit corresponds to $\log ft > 5.7$ for a transition to a $\frac{9}{2}^-$ state below 1.5-MeV excitation energy. This result is in diagreeement with a recent experiment of Baskova *et al.*,[16] who reported that a branch of 7% intensity with a $\log ft$ value of 4.8 went to the 594-keV state. A γ ray of 960-keV energy was also attributed[16] to population of the state at 990 keV in Ca^{43}.

In our $(p,p'\gamma)$ work we find from the observed γ-ray energies that there is a level at 1393 ± 2 keV in agreement with the reaction data. The branching ratios for the γ decay of this level, however, are very different from those observed by Benczer-Koller, Schwarzschild, and Wu[17] for a level populated in the decay of K^{43} at an energy of 1373 keV. Thus there may be two levels with a separation of about 20 keV.

This possibility was investigated by preparing a K^{43} source by means of the $Ca^{43}(n,p)K^{43}$ reaction at a neutron energy of 15.2 MeV. γ-ray singles and coincidence spectra were then obtained. The portions of interest are shown in Figs. 5 and 6. Figure 5(a) shows the singles spectrum. The arrows indicate the positions of the 388- and 404-keV lines which would arise from the transitions $1373\rightarrow 989$ and $1393\rightarrow 989$. The intensities of the two lines are less than 4% of the 396-keV transition. This result is in disagreement with the result of Benczer-Koller *et al.*, who found the intensity of the 388-keV γ ray to be about 50% that of the 396-keV γ ray. Figures 5(b) and 5(c) show some of

[16] K. A. Baskova, S. S. Vasilev, M. A. Khamo-Leilia, and L. Y. Shavtvalov, Zh. Eksperim. i Teor. Fiz. 47, 1162 (1964) [English transl.: Soviet Phys.—JETP 20, 781 (1965)].

[17] N. Benczer-Koller, A. Schwarzschild, and C. S. Wu, Phys. Rev. **115**, 108 (1959).

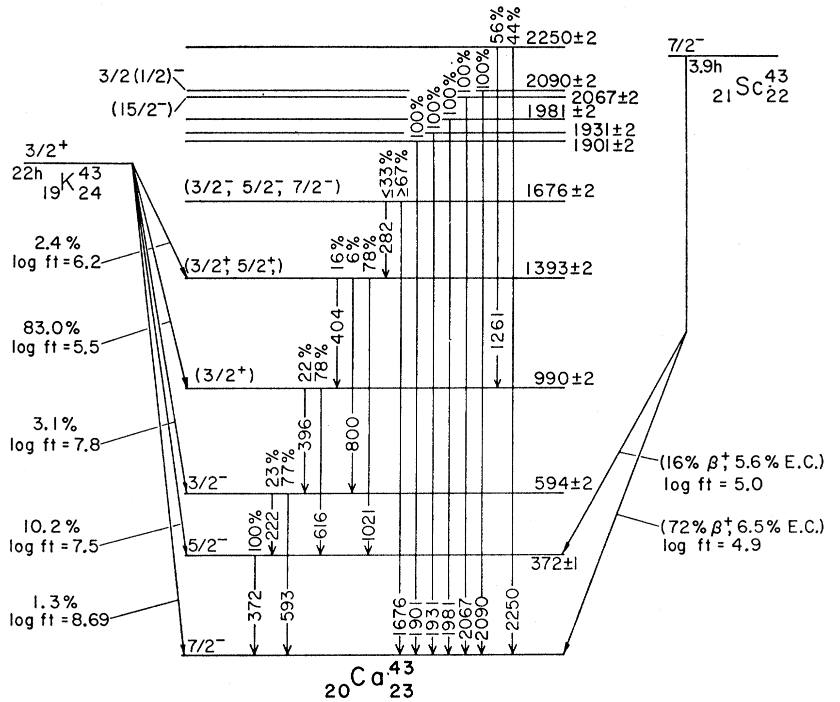

FIG. 3. Energy-level diagram for Ca^{43} showing a compilation of results from our experiment with other work. The level energies and γ-ray information is from the present work. Levels given in Table VI of Ref. 17 at 1959, 2050, (2109), and 2227 keV were not observed in the present experiment. The spin-parity assignments are from Refs. 1 and 17 except for the tentative assignment for the 1676-keV state which is based on arguments given here. The Sc^{43} positron-decay data is taken from Ref. 1. The K^{43} decay data is from the present work with the exception of the intensity and logft value for the ground-state decay which is taken from Ref. 17. The uncertainties in the intensities are about ±20%.

the results of the coincidence runs. Windows were set on the composite 372–396- and 590–620-keV peaks observed with a 3×3-in. NaI(Tl) scintillator. Coincident γ rays were detected with an 8-cc coaxial Ge(Li) γ-ray detector. The results obtained are similar to those from the singles run. The intensity of a 388-keV peak is less than 2% of the 396-keV γ intensity, but a small peak at 404 keV is seen which is assigned to a transition between the state at 1393 keV and the 990-keV state. In addition, in Fig. 6 a higher-energy γ ray with an energy of 1020 keV is observed in coincidence with the 372–396-keV γ rays. This corresponds to the transition from the 1393-keV level to the 372-keV level and is consistent

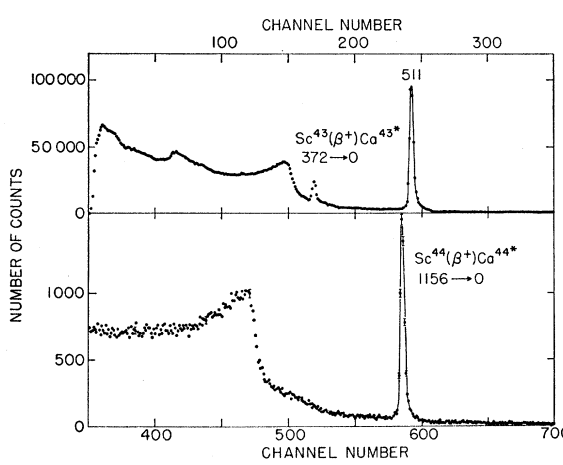

FIG. 4. γ-ray spectrum from the decay of a Sc^{43} source. No γ rays were observed which could be attributed to the population of states in Ca^{43} lying above the first level at 372 keV.

with the 404-keV γ ray also observed. The intensity of the 800-keV transition from the 1393-keV state was too small to permit it to be observed. Our results from both the K^{43} decay and $(p,p'\gamma)$ work are in internal agreement, but do not agree with the results of Benczer-Koller *et al.* A comparison of the logft values obtained in the present experiment with those obtained by Benczer-Koller *et al.* are given in Table II.

RESULTS AND DISCUSSION

The γ rays observed in the singles spectrum (Fig. 2) and listed in Table I have been incorporated into the level scheme shown in Fig. 3. Most of the γ rays have been assigned to this level scheme on the basis of energy agreement between summed cascade transitions and cross over transitions and between measured γ-ray energies and the excitation energies determined from reaction studies.[1] In many cases, these assignments have been corroborated by the previously mentioned coincidence measurements. The level energies found in this experiment are in agreement with the summary of Ca^{43} level energies tabulated by Dorenbusch *et al.*[18] The intensities shown are those measured at 0°; no corrections have been made for any differences in the angular distributions of the γ rays.

Our results for the position of the levels at about 372, 594, and 990 keV are in accord with past work for the most part. The major discrepancies are for the energies of the (372±1.0)- and (989.5±1.5)-keV states

[18] W. E. Dorenbusch, T. A. Belote, and O. Hansen, Phys. Rev. 146, 734 (1966).

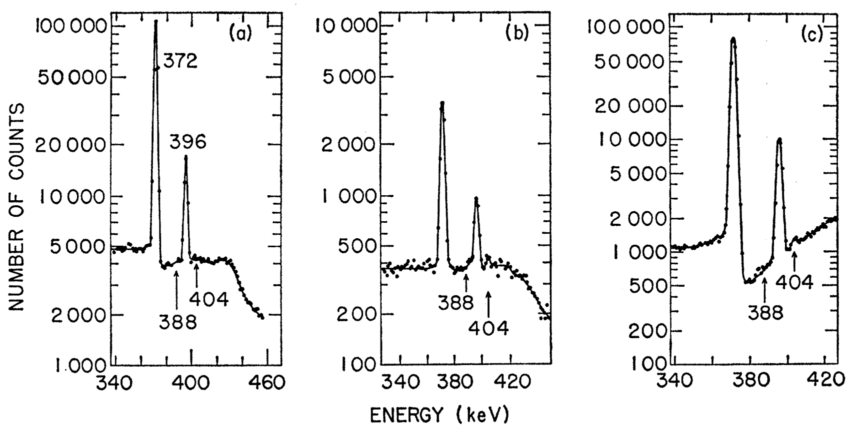

FIG. 5. Portions of the γ-ray singles and coincidence spectra from the decay of K^{43} are shown. The singles spectrum is shown in (a). Coincidence spectra are shown in (b) and (c). In (b) the lines are in coincidence with the composite peak in NaI from the 372–396-keV γ rays as well as with Compton events from the 593- and 616-keV γ rays. In (c) the coincidence channel was placed on the composite peak from the 593–616-keV γ rays. No evidence is seen for the 388-keV γ ray which was observed by Benczer-Koller *et al.* (Ref. 17), but a weak 404-keV transition is seen, which is consistent with our inelastic scattering results.

where our values are to be compared with the values of 373.7±0.4 and 992±0.7 keV obtained by Backstrom and Lindqvist.[19] The branching ratios are in reasonable agreement with those of Benczer-Koller, Schwarzschild, and Wu.[17]

The spin and parity assignments for the states below the 1393-keV state are quite unambiguous. The assignment to be made for the 1393-keV state is not so clear. The K^{43} β decay to this state has $\log ft = 6.2$, which is consistent with an allowed transition and spin and parity assignments of $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$. Dorenbusch *et al.*[18] consider the $\frac{1}{2}^+$ possibility unlikely because of the small angle behavior of the $Ca^{42}(d,p)Ca^{43}$ stripping cross section. They also find that neither $l_n = 2$ or 3 transitions give a good fit to the data, although $l_n = 2$ seems to fit the forward peak best. The measured γ-ray branching ratios are in reasonable agreement with the single-particle transition strengths for a $\frac{3}{2}^+$ level. However, the $\frac{5}{2}^+$ assignment cannot be ruled out on this evidence because of the possibility of large retardations in the $E1$ transitions to the ground and first two excited states.

The 1676-keV level has been observed in a number of different particle reactions.[1] The angular distribution[18] for the $Ca^{42}(d,p)Ca^{43}$ reaction does not show a well-defined stripping pattern so that no information can be obtained on the spin and parity assignment. Belote *et al.*[20] studied the angular distribution of inelastically scattered deuterons and concluded that the level was excited by an $L = 2$ transition. This indicates that the level has negative parity and possible spin values of $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, $\frac{9}{2}$, and $\frac{11}{2}$. By analogy with the level structure of the similar nucleus V^{51} it was then argued that a possible assignment is $\frac{11}{2}^-$. Such a choice does not seem consistent with the γ-ray data discussed below.

We have observed a 282-keV γ ray in singles and in coincidence runs which indicates that the 1676-keV level decays to the 1393-keV level as well as to the ground state. The singles spectrum alone does not establish that the 1393-keV state is fed by the decay of the 1676-keV state. It is possible that decays from the (1957±4)-keV state to the 1676-keV state which would have an energy of 279±6 keV are responsible for the observed line at 282 keV. The coincidence run showed, however, that at least part of the intensity of the 282-keV transition is in coincidence with γ rays from lower states and hence that the 1676-keV state feeds the 1393-keV state. The values given for the relative intensities of the 282- and 1676-keV lines in Fig. 3 must then be regarded as an upper limit for the intensity of the 282-keV line and a lower limit on the intensity of the 1676-keV line. The existence of the transition to the 1393-keV state ($J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$) makes the previous suggestion of $\frac{11}{2}^-$ unlikely. Possible spin and parity assignments based on the observed γ-ray decay of the 1676-keV state depend on the assignment made for the 1393-keV state. If the 1393-keV state has $J^\pi = \frac{3}{2}^+$, then, based on relative single-particle transition strengths, and including reasonable estimates of retardations and enhancements, only assignments of $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{5}{2}^+$ seem reasonable. If the 1393-keV state has $J^\pi = \frac{5}{2}^+$ then the possibilities are $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$. The $\frac{5}{2}^+$ assignment can be ruled out on the basis of the $L = 2$ assignment for the inelastically scattered deuterons made by Belote *et al.*[20] The lack of transitions from the 1676-keV level to the other low-lying states with spins of $\frac{3}{2}$ and $\frac{5}{2}$ is disturbing, but it is, of course, possible that the intensities were

TABLE II. Intensities and $\log ft$ values for K^{43} β decay.

Excitation energy of final state in Ca^{43} (keV)	Percent of total decay[a]	$\log ft$[b]	Percent of total decay Present experiment	$\log ft$
0	1.3	8.69 (8.6)	c	c
372	3.5	>7.4 (>7.6)	10.2	7.5
594			3.1	7.8
990	87	5.50 (5.6)	83.0	5.5
1393	8.2	(5.7)	2.4	6.2

[a] Reference 17.
[b] $\log ft$ values in parentheses are taken from Ref. 1.
[c] The results of Ref. 17 were used for the ground-state transition intensity. Intensities for the other transitions were inferred from the measured γ-ray branching.

[19] G. Backstrom and T. Lindqvist, Arkiv Fysik 11, 465 (1957).
[20] T. A. Belote, J. H. Bjerregaard, Ole Hansen, and G. R. Satchler, Phys. Rev. 138, B1067 (1965).

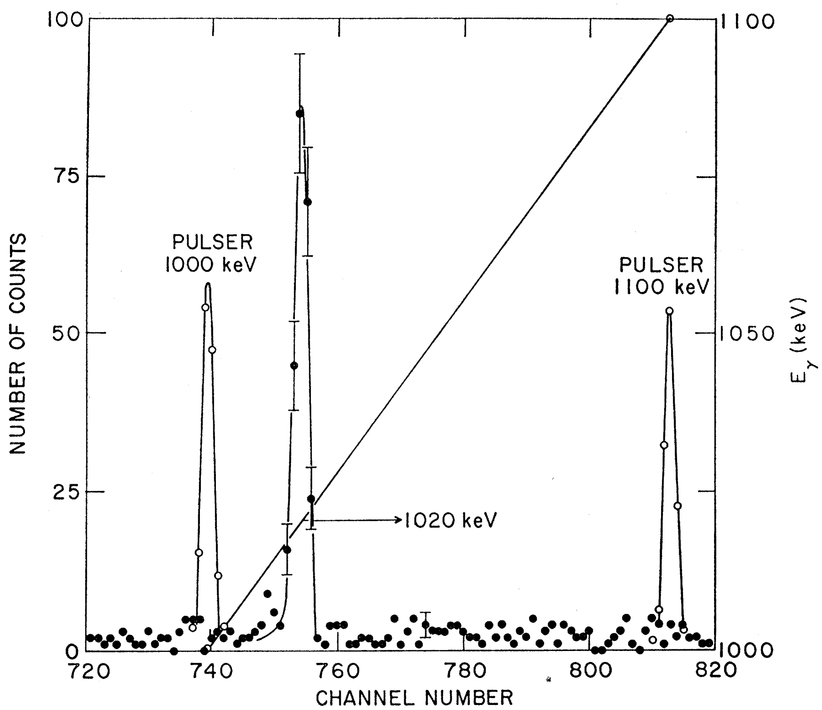

FIG. 6. Portion of a coincidence spectrum from the decay of K^{43}. This shows a portion of the spectrum obtained with the coincidence window placed on the 377–396-keV composite peak. A 1020-keV γ ray is observed which is expected if the decay goes to a state at 1393 keV.

such that they could not be detected. It is known from the stripping work of Dorenbusch *et al.*[18] that the angular distributions for the 990- and 1393-keV states are quite different. Conlon *et al.*,[21] in a study of the $Ca^{44}(p,d)Ca^{43}$ reaction, have identified the 990-keV state as a $d_{3/2}$ hole state and do not observe the 1393-keV state. Thus the branching ratio of the 1676-keV state to the two lower $\frac{3}{2}^+$ states could also differ strongly.

Not too much can be said about the levels between 1.9- and 2.25-MeV excitation. We do not observe transitions which could be definitely assigned to the levels at 1959, 2050, (2109), and 2227 keV which have been seen previously.[1] Dorenbusch *et al.*[18] have made spin-parity assignments of $\frac{1}{2}^+$, $\frac{3}{2}^-$, and $(\frac{1}{2})$ or $\frac{3}{2}^-$ for the 1959-, 2050-, and 2097-keV levels, respectively. Belote *et al.*[20] earlier suggested assignments of $\frac{15}{2}^-$ and $\frac{9}{2}^-$ for the 2071- and 2097-keV levels from inelastic deuteron angular distributions. The assignments for the 2097-keV state disagree, but it is likely that the spin is that suggested by Dorenbusch *et al.*[18] since the analysis of the (d,p) angular distributions is probably more reliable than that for the inelastic deuteron angular distributions. Aside from the level at 2250 keV, we have observed only ground-state transitions. Thus any level of the group between 1.9 and 2.25 MeV would be a candidate for the high spin levels predicted by theory, although we cannot place a very stringent limit on the strengths of cascade transitions from these states. At best we would estimate that the strengths of possible cascade transitions with energies greater than a few hundred keV are less than 20% of the ground-state transitions.

CONCLUSIONS

Our results confirm past energies, γ-ray branching ratios, and $\log ft$ values for K^{43} decay to states in Ca^{43} below 993 keV. The $\log ft$ value for K^{43} decay to the 1393-keV state was found to be 6.2. The energy and γ-ray branching ratios for this state are in disagreement with the results of Benczer-Koller *et al.*[17] The observation of a cascade transition from the 1676-keV state to the 1393-keV state shows that the spin of the 1676-keV state is probably not $\frac{11}{2}^-$ as was previously argued.[20] Consideration of the branching and single-particle strengths make an assignment of $\frac{3}{2}^-$, $\frac{5}{2}^-$, or $\frac{7}{2}^-$ plausible. γ-ray transitions from other states up to 2.25 MeV are given as found by the inelastic scattering studies. No evidence was found in this data for a $\frac{9}{2}^-$ or higher spin state at an excitation energy below 1.7 MeV.

ACKNOWLEDGMENT

We are indebted to Professor L. L. Lee, Jr., for several helpful discussions on this experiment.

[21] T. W. Conlon, B. F. Bayman, and E. Kashy, Phys. Rev. 144, 941 (1966).