Decay of K^{43}†

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The decay of K^{43} has been reinvestigated in an attempt to clarify the discrepancies existing in the ordering of the energy levels of Ca^{43}. The external conversion spectrum showed lines corresponding to the following gamma-ray energies: 0.220 ± 0.002, 0.371 ± 0.002, 0.388 ± 0.002, 0.394 ± 0.002, 0.591 ± 0.003, 0.614 ± 0.004 Mev. In addition a γ ray of 1.005 Mev was observed in the scintillation spectrum. β-γ coincidence measurements establish that the gamma transitions to the ground state are the 0.371-Mev and the 0.591-Mev gamma rays and not the 0.614-Mev gamma as believed previously. These results and the γ-γ coincidence measurements indicate only one possible level scheme in Ca^{43}: 0, 0.371, 0.591, 0.985, 1.373 Mev. These energy levels as well as their proposed spin and parity assignments are in good agreement with the results from the Massachusetts Institute of Technology nuclear reaction data. A two-cycle baffle for the solenoid β spectrometer is described. This baffle reduces significantly the background due to scattered gamma radiation from very strong external conversion sources.

INTRODUCTION

THE low-lying nuclear energy levels of Ca^{43} have recently been the object of extensive studies.[1–6] The experimental determination of the level scheme of Ca^{43} has been obtained from studies of the decays of K^{43} [3] and Sc^{43},[4] as well as from studies of the nuclear reactions $Ca^{42}(d,p)Ca^{43}$ and $Ca^{43}(p,p')Ca^{43}$.[6] There were serious discrepancies between the results of the K^{43} and Sc^{43} decay studies. Furthermore, neither of the proposed possible level schemes for Ca^{43} as deduced from β-decay studies was in agreement with that found from the nuclear reaction data. The reaction data of Braams *et al.* on $Ca^{42}(d,p)Ca^{43}$ and $Ca^{43}(p,p')Ca^{43}$ indicated levels in Ca^{43} at 0, 0.373, 0.593, 0.991, 1.394, 1.678 Mev as well as other levels at higher energies that cannot be fed by β decay. A consideration of the possible β and γ transitions from Braams' level ordering indicates that several γ rays differing in energy by only a few percent may be emitted in the radioactive decays of K^{43} and Sc^{43}. It was therefore suggested that the lack of agreement between the β-decay data and the reaction data might be due to the inability to resolve several γ rays in the decay studies.

There has been intense theoretical interest in the level positions and spacing in the region of the Ca isotopes. The isotopes of $_{20}Ca$ are sufficiently close to a doubly magic configuration to facilitate theoretical calculations of level structure. Calculations of the level ordering and spacings for Ca^{43} have been performed by Kurath[7] according to the *j-j* coupling model, by Bohr and Mottelson,[8] who consider possible effects of surface coupling, by Ford and Levinson,[9] who performed a detailed calculation in the weak-coupling approximation, and most recently, by French and Raz,[10] who use a *j-j* coupling model including *j-j* mixed configurations.

In view of the great theoretical interest in the levels of Ca^{43}, it is important to ascertain a reliable energy level scheme for Ca^{43}. It was hoped that a study of the decay of K^{43} with a high-resolution β-ray spectrometer and a selective coincidence scintillation spectrometer would clarify some of the discrepancies mentioned above.

SOURCE PREPARATION

K^{43} was produced from the reaction $A^{40}(\alpha,p)K^{43}$ by bombarding argon gas (99.6% A^{40}) in the external alpha-particle beam of the Brookhaven National Laboratory 60-in. cyclotron. Argon at two atmospheres pressure was contained in a 24-in. long, 6-in. diameter cylindrical brass chamber. The alpha-particle beam entered the container through a 0.002-in. duraluminum foil. After bombardment the argon gas was allowed to escape and the chamber was washed with several hundred cc of distilled water. The potassium activity is readily soluble in the water. Several drops of HCl were added to the water to form KCl and the water could be evaporated leaving the potassium salt behind.

To prepare a source for the measurement of the β spectrum, a 0.008-in. Cu absorber was added to the 0.002-in. Al window in order to reduce the 40-Mev α beam to an energy of about 8 Mev. At this energy there are no significant activities produced other than the

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[10] J. B. French and B. J. Raz, Phys. Rev. **104**, 1411 (1956).

K^{43}. The decay of these sources indicated a half-life of 22 hours in good agreement with that reported in the literature.

For the external conversion and γ-ray measurements it was necessary to reduce the Cu absorber thickness in front of the gas cylinder in order to produce sufficient activity. For these bombardments the energy of the beam was only reduced to about 20 Mev with the use of a 0.005-in. Cu absorber. At this bombarding energy the activity was found to contain about 20% of the 12-hr K^{42} activity produced by the reaction $A^{40}(\alpha,pn)K^{42}$. However, this contaminant does not interfere significantly with the γ-ray measurements.

TWO CYCLE BAFFLE

The activity of the sources used for external conversion spectra are usually of the order of several millicuries. Measurements of these spectra require very low gamma background. We have constructed a "two-cycle baffle" for the Columbia solenoid spectrometer in order to reduce the γ-ray background from the source. Fortunately, the solenoid is sufficiently long to permit the use of a two-cycle electron trajectory and still maintain an entrance angle of about 45°. A schematic drawing of the two-cycle baffle, showing the sinusoidal electron trajectories, is shown in Fig. 1. The trace of the electron path on the plane perpendicular to the magnetic field consists of two complete superimposed circles. All adjustments for resolution are performed in the first baffle section. The annular openings in the second section are fixed for a resolution of about 2%. We have been able to adjust the second baffle so that the over-all transmission (at ~2% resolution) is reduced by less than 10% by the second baffle compared to the transmission of the first single baffle.

The increased amount of lead between the source and detector in this type baffle, as well as the doubling of the source-to-detector distance, reduced the γ-ray background from a 2-mC γ source to almost zero. All the lead in the baffle system is covered with at least $\frac{1}{16}$-in. aluminum coating to reduce electron scattering.

EXTERNAL CONVERSION SPECTRUM

The K^{43} photoelectron spectra were investigated using both lead and uranium radiators. Sources of about 1 mC were placed in brass capsules thick enough to stop all electrons from both K^{43} and K^{42}. The surface density of the lead and uranium radiators was 11.5 mg/cm² and 19 mg/cm², respectively, and their diameter was 2.5 mm. The resolution of the spectrometer was 1.5%.

Figure 2 shows the momentum distribution of photoelectrons from the Pb radiator. The K line corresponding to six gamma rays were identified. The γ energies corresponding to these photopeaks were calculated from the position of the high-energy edge of the conversion lines. The high-energy edge of the 624-kev Cs^{137}

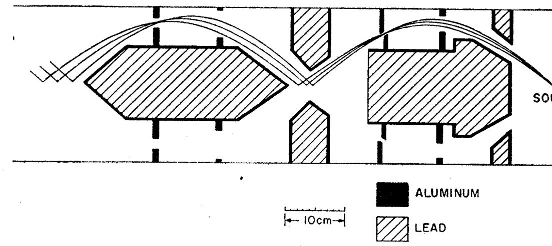


FIG. 1. Schematic diagram of the "two-cycle baffle."

internal conversion line was used for calibration. The γ energies were also calculated from the peak position of the conversion lines using the peak position of the Cs^{137} internal conversion line for calibration and allowing for ~1.7-kev energy loss in the Pb converter. A spectrum was obtained also with U converter. The γ energies determined from the measurements with the U radiator were in excellent agreement with those obtained with the Pb converter.

The energy of the resolved γ rays are: $\gamma_1=0.220\pm0.002$, $\gamma_2=0.371\pm0.003$, $\gamma_3=0.388\pm0.004$, $\gamma_4=0.394\pm0.004$, $\gamma_5=0.591\pm0.006$, and $\gamma_6=0.614\pm0.006$ Mev. The errors quoted are due to the uncertainty in determining the energy lost in the converter and in specifying the exact positions of the high-energy edges of the lines. The 1.000-Mev γ ray reported previously was not seen in external conversion spectra because of its very low intensity and the low photoelectric cross section.

The photoelectric cross section has a strong angular dependence which varies with energy. Because of the complex geometry of our source, converter, and spectrometer trajectories, calculation of the relative efficiencies for photoelectron detection with varying energy is impractical. This dependence is, however, expected to be slowly varying over a small energy interval. By assuming that the efficiency is constant over a small energy interval we have determined the relative intensities $I_{\gamma2}:I_{\gamma3}:I_{\gamma4}=100:7:13$ and independently, $I_{\gamma5}:I_{\gamma6}=16:100$. The ratios $I_{\gamma1}:I_{\gamma2}:I_{\gamma6}$ will be determined from the γ-ray scintillation experiments.

Some important aspects of the level scheme of Ca^{43} are suggested from the accurate determination of the γ-ray energies. It is clear that $E_{\gamma2}+E_{\gamma6}=E_{\gamma4}+E_{\gamma5}=0.985$ Mev. Furthermore, $E_{\gamma5}-E_{\gamma2}=E_{\gamma6}-E_{\gamma4}=E_{\gamma1}=0.220$ Mev. Both these relationships are determined experimentally to within ~5 kev. This information strongly suggests the energy spacing of four levels in Ca^{43}, according to either Fig. 3(a) or Fig. 3(b). However, the ordering of these levels must be determined from coincidence experiments.

SCINTILLATION SPECTROSCOPY

1. Single Gamma-Ray Analysis

The spectrum of photons emitted in the decay of K^{43} was studied in a 2-in.×2-in. NaI(Tl) scintillation spectrometer with a 20-channel pulse-height analyzer. The

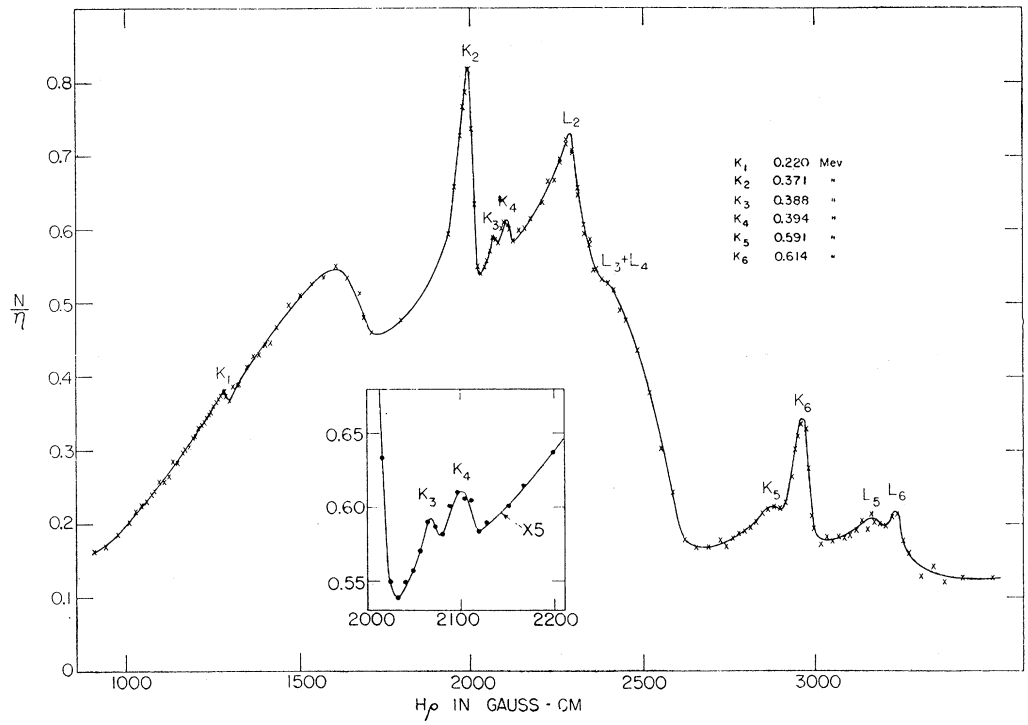


FIG. 2. External conversion spectrum from a lead converter. The energy corresponding to the gamma rays whose K lines were observed is indicated. The region between 0.375 and 0.400 Mev is amplified 5 times and shown in the insert.

spectrum is plotted in Fig. 4. Three gamma rays were identified at the energies of 0.375, 0.615, 1.005 Mev. When a 5-in.×2-in. lead block was placed behind the source, a line previously reported[4] at 0.810 Mev was observed, but it disappeared when the lead was removed. This peak may be explained as a pile-up of the back-scattered radiation and the 0.615-Mev peak.

The 0.220-Mev gamma radiation seen in the external conversion spectrum was hidden in the scintillation spectrum by the back-scattered radiation from higher-energy gammas.

Since the resolution of the detector is only 9% at 661 kev, the 0.371-, 0.388-, and 0.394-Mev and the 0.591-Mev and 0.614-Mev γ rays form two compound peaks. The relative intensities $I_{\gamma 2}:I_{\gamma 3}:I_{\gamma 4}$ and $I_{\gamma 5}:I_{\gamma 6}$ are known from the external conversion data. The intensities $I_{\gamma 2}+I_{\gamma 3}+I_{\gamma 4}:I_{\gamma 5}+I_{\gamma 6}$ can be obtained from the scintillation spectrum. It is therefore possible to calculate the relative abundance of these five γ rays. The results are shown in Table I. The over-all efficiency of the scintillation detector as a function of energy was estimated to within 10% by a method outlined previously.[11]

Special measurements were required to determine the relative intensity of the two fractions of the apparent 1.005-Mev line. The peak seen in the scintillation spectrum actually consists of two parts: the first is due to a real 1.005-Mev line in K^{43}; the second comes from the pile-up peak at 0.985 Mev due to the two very strong lines at 0.371 and 0.614 Mev, a peak which

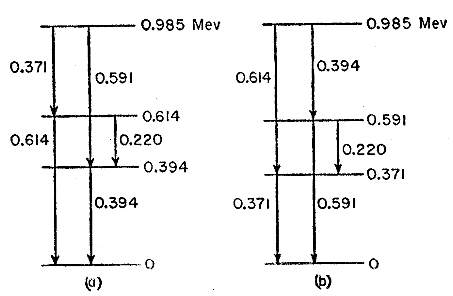


FIG. 3. Two probable schemes for the four low-lying levels of K^{43} as suggested by the analysis of the gamma-ray external conversion spectrum.

TABLE I. Relative intensities of the gamma radiations of K^{43}.

Energy (Mev)	Percent of total decay
γ_1 0.220±0.002	3±1
γ_2 0.371±0.003	85±8
γ_3 0.388±0.004	7±1
γ_4 0.394±0.004	11±1
γ_5 0.591±0.006	13±1
γ_6 0.614±0.006	81±8
γ_7 1.005±0.020	2±0.2

[11] Koerts, Macklin, Farrelly, Van Lieshout, and Wu, Phys. Rev. 98, 1230 (1955).

cannot be resolved from a 1.005-Mev line. (It will be shown below that the intense 0.371- and the 0.614-Mev lines are in true time coincidence.) Two methods were used to obtain the relative contributions of these two effects.

(*a*) A 2-mm lead absorber was placed between the source and detector, and the spectrum thus obtained was compared to the spectrum seen with the source in the same position but without Pb absorber. Let N be the source strength; k_1, k_2, k_3 the relative intensities of the 0.371-, 0.614-, and 1.005-Mev transitions; ϵ_1, ϵ_2, ϵ_3 the relative efficiencies of the counter for detection of these gamma rays; and let N_1, N_2, N_3 be the number of counts in the spectrum corresponding to these energies, and ω the solid angle subtended by the crystal: then

$$N_1 = Nk_1\epsilon_1\omega, \quad (1a)$$

$$N_2 = Nk_2\epsilon_2\omega, \quad (1b)$$

$$N_3 = Nk_3\epsilon_3\omega + Nk_1k_2\epsilon_1\epsilon_2\omega^2, \quad (1c)$$

where the last term in (1c) gives the pile-up counting rate of the 0.614+0.371(=0.985-Mev) γ rays. With an absorber between the source and the detector the number N' of counts corresponding to the three gamma rays considered becomes

$$N_1' = Nk_1\epsilon_1\omega e^{-\mu_1 d}, \quad (2a)$$

$$N_2' = Nk_2\epsilon_2\omega e^{-\mu_2 d}, \quad (2b)$$

$$N_3' = Nk_3\epsilon_3\omega e^{-\mu_3 d} + Nk_1k_2\epsilon_1\epsilon_2\omega^2 e^{-(\mu_1+\mu_2)d}, \quad (2c)$$

where μ_1, μ_2, and μ_3 are the absorption coefficients in cm^{-1} for each of the three gammas and d is the absorber thickness. The solution of Eqs. (1) and (2) yields the relative intensity of the true 1.005-Mev line:

$$k_3/k_1 = (2.8 \pm 0.3)\%.$$

(*b*) Several single gamma-ray spectra were taken

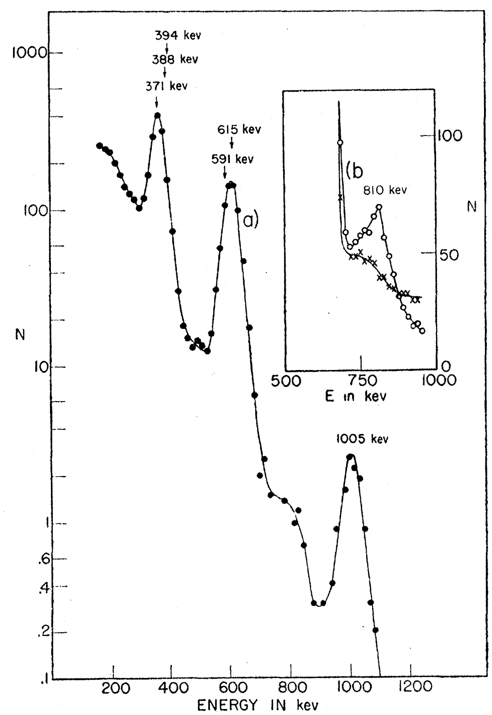


FIG. 4. (a) K^{43} gamma-ray scintillation spectrum using a 2-in.×2-in. NaI(Tl) crystal mounted on a 6292 Dumont photomultiplier. The source detector distance was 10 cm. (b) Gamma-ray scintillation spectrum in the 0.800-Mev region with a block of lead placed behind the source. The 0.810-Mev peak is the pile-up of the 0.614-Mev gamma and back-scattered radiation.

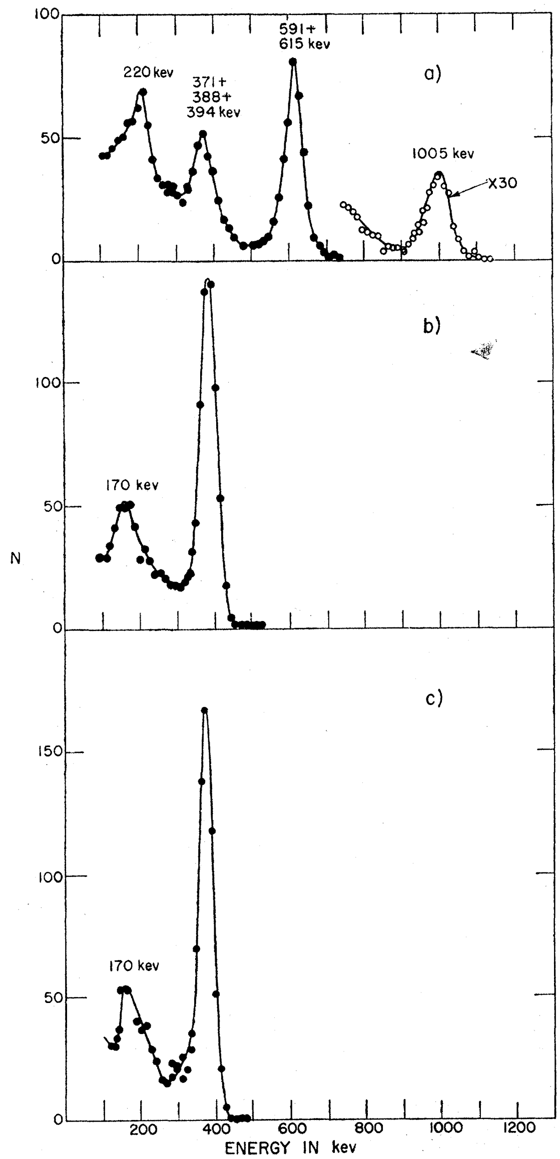


FIG. 5. (a) Gamma-ray spectrum in coincidence with the 0.371-, 0.388-, and 0.394-Mev lines. (b) Gamma-ray spectrum in coincidence with the 0.591- and 0.614-Mev lines. (c) Gamma-ray spectrum in coincidence with the 1.005-Mev line.

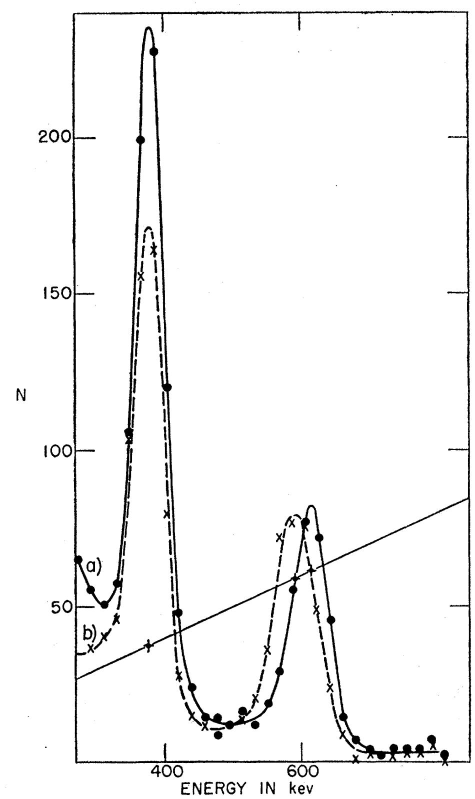


FIG. 6. (a) Gamma-ray spectrum in coincidence with electrons with $E_\beta<0.820$ Mev. (b) Gamma-ray spectrum in coincidence with electrons with $E_\beta>0.820$ Mev.

varying the source-detector distance; the relative intensities of the gamma rays were compared as a function of the solid angle.

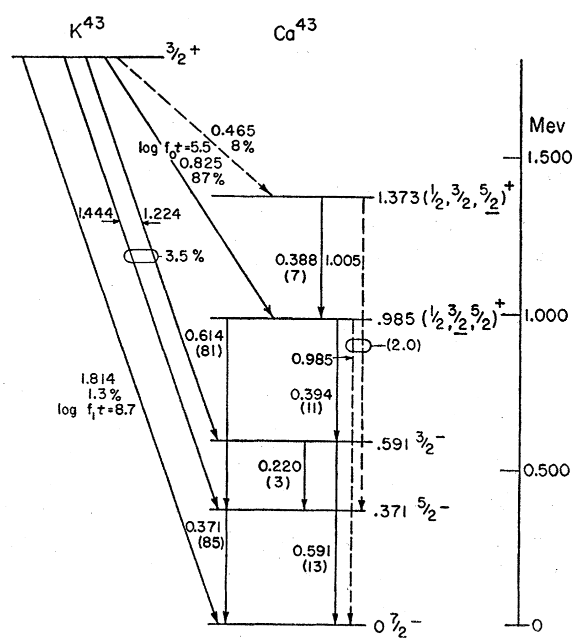


FIG. 7. Decay scheme of K^{43}.

Using the same notation as in case (*a*), we can write

$$\frac{N_3}{N_1} \equiv M = \left(\frac{k_3}{k_1}\frac{\epsilon_3}{\epsilon_1}\right) + k_2\epsilon_2\omega.$$

If now M is plotted *versus* the solid angle ω, then the intercept of the straight line with the M axis gives $k_3\epsilon_3/k_1\epsilon_1$, and therefrom k_3/k_1 since the relative efficiencies are known. The value of k_3/k_1 obtained by this method is $(2.3\pm0.5)\%$, which is in good agreement with that obtained from the lead absorption method.

2. Coincidence Measurements

(*a*) *γ-γ coincidence.*—The selective coincidence spectrometer used was described in detail in a previous paper.[11] The spectra of γ rays in coincidence with the composite lines at 0.375, 0.615, and 1.005 Mev are shown in Fig. 5(a), (b), (c). An important feature is the fact that the 0.220-Mev line is seen in coincidence only with lines from the 0.371+0.388+0.394-Mev compound peak. The intensity of the 0.220-Mev lines can be estimated from Fig. 5(c). The estimate is made with an uncertainty of $\sim30\%$ due to the large background in the peak region.

(*b*) *β-γ coincidence.*—Anthracene and NaI(Tl) scintillators were used for the β-γ coincidence experiments. The γ-rays spectrum in coincidence with the β rays within a certain energy interval were displayed on the 20-channel analyzer. When β^- rays of energy less than 0.812 Mev are selected, the coincident gamma spectrum is identical to the single gamma spectrum. But when β^- rays of energy higher than 0.820 Mev are selected, the peak at 0.615 Mev shifts to lower energy (Fig. 6). This effect is in agreement with the decay scheme of Fig. 3(b) and not with Fig. 3(a). The relative intensity of the 0.371- and 0.591-Mev lines in coincidence with β^- rays above 0.812 Mev are in agreement with the finally proposed decay scheme of Fig. 7.

β SPECTRUM

The β^- spectrum was measured with the solenoid spectrometer. The momentum distribution obtained is shown in Fig. 8. Kurie analysis of the upper 0.300 Mev indicates that the ground-state transition has unique first-forbidden shape. The shape-corrected Kurie plot is shown in Fig. 9(a). Analysis of the lower groups was

TABLE II. Relative intensities and logft values of the various β-ray transitions in the decay of K^{43}.

	Energy (Mev)	Percent of total decay	
β_1	1.814±0.025	1.3	$\log f_1t=8.69$
β_2	(1.444)[a]	3.5	$\log ft>7.4$
β_3	(1.224)[a]		
β_4	0.825±0.010	87	$\log f_0t=5.50$
β_5	0.465±0.050	8.2	

[a] Unresolved groups.

performed by successive subtraction methods. The results are shown in Fig. 9(b), (c), (d). The relative intensities and log ft values are given in Table II.

The decay scheme of Fig. 7 suggests possible β^- groups with end points of 1.444 and 1.224 Mev. The Kurie analysis results in a group with intermediate end point $\sim$1.24 Mev. This suggests that the two β^- groups are present and that the sum of their intensities is $\sim$3.5%.

The end point of the most intense group is 0.825 Mev. Deviations from the linear shape of the Kurie plot begin below 0.465 Mev. Kurie analysis below 0.465 indicates a group with end point $\sim$0.465 Mev. The analysis is extremely sensitive to the successive subtractions and we therefore assign an error of 0.050 Mev to the lowest end point. The intensity of the lowest group has been determined from γ-ray intensities since the effects of scattering in the spectrometer baffle and source are very likely to distort the spectrum in the low-energy region.

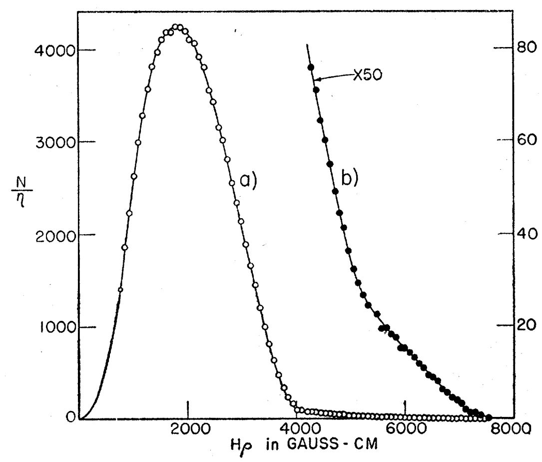


FIG. 8. Momentum distribution of the composite electron spectrum of K^{43}.

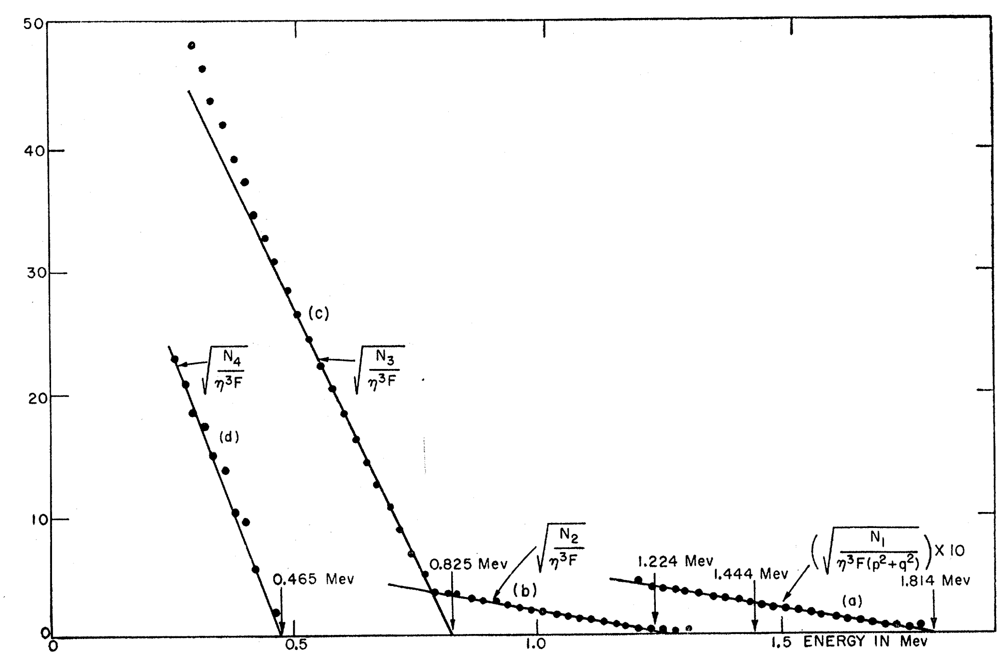
0.388- AND 1.000-MEV γ RAYS

It is suspected from the β^- decay data that the 0.388-Mev line is due to the decay of a level above the 0.985-Mev state. Experiments with a well-type crystal have confirmed this assumption.

A K^{43} source surrounded by a brass cylinder for absorption of all β^- rays was placed centrally in a $1\frac{3}{4}$-in.$\times$2-in. NaI(Tl) well-type crystal. The pulse-height spectrum obtained is shown in Fig. 10. In the 4π geometry of this experimental arrangement, γ rays in coincidence are seen as a sum peak. The 1.000-Mev line seen in the figure is practically due to the sum peak of the 0.371- and 0.614-Mev and the 0.394- and 0.591-Mev γ-rays. The peak at 1.375 Mev can be interpreted as the sum of the $0.388+0.371+0.614=1.373$- and $0.388+0.394+0.591=1.373$-Mev γ-rays. However, the intensity of the 1.375-Mev peak is well above the expected accidental coincidence rate. This evidence indicates a level at 1.375 Mev. The intensity of the sum peak is in agreement with this conclusion and the relative intensity of the 0.388-Mev peak from the conversion spectrum.

The position of the 2.0% 1.00-Mev peak has not been definitely ascertained. It may be at either or both positions indicated in the decay scheme of Fig. 7. The relatively poor resolutions of scintillation spectrometers

FIG. 9. (a) Fermi-Kurie analysis of the high-energy group corrected with the unique-shape correction factor $1/(p^2+q^2)^{\frac{1}{2}}$. (b) Fermi-Kurie plot of the unresolved second and third groups obtained by the subtraction method. (c) Fermi-Kurie analysis of the most intense β group in the decay of K^{43}. (d) Fermi-Kurie plot of the fifth β group obtained from three successive subtractions. Both the end-point determination and the relative intensity of this group have large errors in view of the indeterminate scattering of electrons in the source and spectrometer.



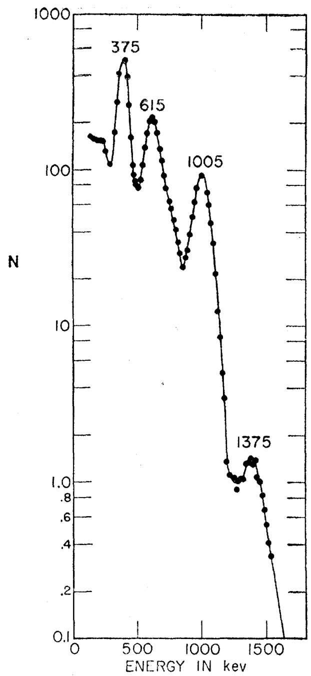


FIG. 10. Gamma-ray scintillation spectrum taken with a $1\frac{3}{4}$-in.×2-in. well-type NaI(Tl) crystal and a 6292 Dumont photomultiplier.

obviates the possibility of determining its position by coincidence methods.

DISCUSSION

The final proposed decay scheme of K^{43}, as presented at the New York American Physical Society Meeting of January, 1957,[12] is shown in Fig. 7. The energies of the Ca^{43} levels are essentially in agreement with the reaction data of Braams, and the recent K^{43} decay scheme of Bäckström and Lindqvist.[13] The discrepancy in energy between our 1.371-Mev level and Braams' level at 1.394 Mev does, however, seem outside the limit of our experimental accuracy. If we assume that we have a small systematic error in determination of the photoelectron energy loss in passing through the Pb or U converter, which may accumulate by addition of several γ-ray energies, we can still not explain this discrepancy. Braams' level spacing between the 0.991- and 1.394-Mev levels would suggest that there should be a γ ray of 0.403 Mev rather than 0.388 Mev. The proximity of the 0.388-Mev to the 0.371-Mev photoelectrons lines in our spectra, coupled with the excellent agreement between our 0.371-Mev γ-ray energy and Braams' 0.373-Mev first excited state strongly indicates that our 0.388-Mev γ-energy determination is correct.

Shell model predictions and the ft values of the β transitions of K^{43} suggest the spin assignment indicated in our level diagram. The ground-state configuration $f_{7/2}$ of Ca^{43} is based on the spin and magnetic moment measurement of Jeffries.[14] The unique first-forbidden ($\Delta J=2$, yes) character of the ground-state β^- transition indicates that the spin and parity of K^{43} is $3/2^+$ in agreement with the shell model predictions. The β^- transitions to the 0.371- and 0.591-Mev states have large $\log ft$ value, implying negative parity for these states. Since the β transitions to both the 0.991- and 1.371-Mev levels are allowed, they each will have positive parities and possible spin assignments as indicated in the decay scheme. The underlined spin values are those favored by Lindqvist from γ-γ angular correlation measurements.[15]

The spin and parity assignments could also be made by analyzing the angular distribution of protons in the $Ca^{42}(d,p)Ca^{43}$ stripping reaction.[16] Unfortunately, the angular distribution measurements cannot be interpreted uniquely. Nevertheless, the experimental data can be fitted by theoretical curves corresponding to the set of spins and parities for the levels involved which is not in disagreement with the predictions from the β decay.

There have been theoretical speculations regarding a possible high-spin state (9/2, 11/2, or 13/2) below 1.5 Mev in Ca^{43}. Such a level could not be found in the β decay of K^{43} due to the high degree of forbiddenness for such a transition. The evidence for a 0.810-Mev state as observed in the decay of Sc^{43},[4] which was assigned spin 9/2 by Lindqvist and Mitchell, is weak. Furthermore, no such level has been observed in any of the nuclear reaction work. It should be noted that the recent theoretical analysis of Ca^{43} levels by French and Raz does not require such a level in this energy region.

The very successful analysis using j-j coupling with mixed configurations by French and Raz[10] is in excellent agreement with our experimental results. The spin and parity assignments, as well as the level energies calculated by them, are in agreement with our decay scheme.

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