Nuclear Transitions in Cs^{133}†*

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The characteristics of three nuclear transitions in Cs^{133} have been studied. Observations have been made upon the conversion electrons and/or unconverted quanta emitted in the transitions at 81, 220, and 54 keV. The results may be summarized as follows: (1) The 81-keV ($M1+E2$, $d_{5/2}\rightarrow g_{7/2}$) transition has a measured $K/(L+M)$ ratio of 4.79±0.09. The experimentally determined K-shell conversion coefficient, α_K is 1.35±0.05. For this delayed transition, $\beta_1^K(\lambda)$ is calculated to be 1.33±0.05, and λ to be 5±3. (2) The $K/(L+M)$ ratio of the 220-keV gamma ray has been measured in a semiconducting detector to be 7.4±0.07. (3) The unconverted quanta of the 54-keV transition have been shown to be emitted in only (0.107±0.041)% of the disintegrations. The properties of Cs^{133} seem not to be fully explained by the single-particle model.

INTRODUCTION

BARIUM[133] decays by orbital electron capture to Cs^{133}, which, in turn, de-excites with emission of gamma rays having energies at or near 54, 79, 81, 160, 279, 304, 355, and 385 keV. Examination of the available data[1–7] shows that uncertainties surround the multipole orders of the transitions, the presence or absence of some transitions in detectable intensities, and consequently, values of the total angular momenta of the various excited states. The values of the energies of the reported transitions are summarized in Table I, where the detected particle in each measurement is also indicated. In certain instances of the present investigation, the detectors and techniques employed offered little advantage over those utilized in the earlier studies. For example, the conversion lines of the gamma rays clustered about the intense 355-keV radiation could not be better resolved. Accordingly, specific transitions having critical bearing upon the construction of the disintegration scheme and its associated spin values have been investigated. The unconverted quanta were observed in crystals of NaI-Tl with selected thicknesses, while the charged particles were detected in semiconductor counters.

The conversion-electron spectrum of Ba^{133} is shown in Fig. 1 as recorded by an Ortec-type series SB semiconducting detector. It is seen that conversion lines are present which correspond to most of the known transitions which are summarized in the decay scheme of Fig. 2. This scheme is a synthesis of all known previously reported results.[1–8]

A detailed study of the three transitions at 81, 220, and 54 keV was conducted to remove some of the uncertainties depicted in the decay scheme of Fig. 2. The measurements above cited will be treated in the order given.

THE 81-keV TRANSITION

The $K/(L+M)$ ratio of the 81 keV transition was measured in a gamma-e^- coincidence experiment. In this case, the unconverted quanta of the 355-keV transition supplied the gating pulse for a multichannel analyzer which was actuated by a slow-fast coincidence circuit. The $K/(L+M)$ ratio was obtained by taking the ratio of the areas under the two peaks of Fig. 3. It is calculated to be 4.79±0.09. This value is to be compared with those of Table II, drawn from earlier

TABLE I. Gamma-ray transitions reported in the decay of Ba^{133}. The symbols denote the particle detected for energy determination, γ for unconverted quantum, e^- for conversion electron, and e_p for photoelectron released in an external converter.

Reference	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}
1	57(γ)		82(γ)				300(γ)	357(γ)		
2		79(γ,e^-)	79(γ,e^-)	158(e^-)		276(e^-)	302(γ,e^-)	355(γ,e^-)		
3			79(γ,e^-)	160(e^-)	224(e^-)	277(e^-)	302(γ,e^-)	385(γ,e^-)	383(e^-)	437(e^-)
4	53(γ)	78(γ)	81(γ)	160(γ)		274(γ)	302(γ)	355(γ)	380(γ)	
5	54(γ)	80(γ)	82(γ)	162(γ)	220(γ)	276(γ)	301(γ)	356(γ)	386(γ)	
6	56(γ)	79(γ)	79(γ)			274(γ)	302(γ)	358(γ)	381(γ)	
7	56(γ)	80(γ,e^-)	81(γ,e^-)	161(e^-)		276(γ,e^-,e_p)	302(γ,e^-,e_p)	356(γ,e^-,e_p)	383(γ,e^-,e_p)	

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[5] M. G. Stewart and D. C. Lu, Phys. Rev. **117**, 1044 (1960).
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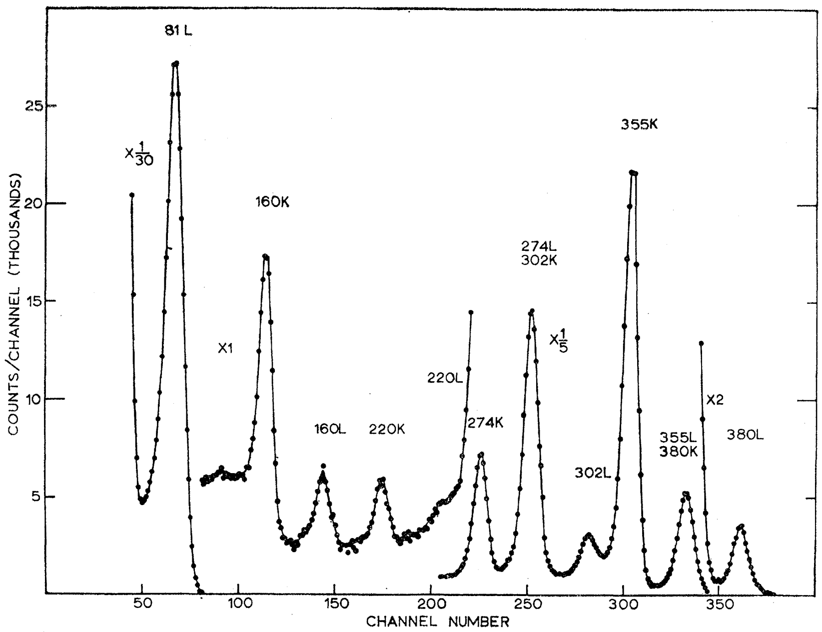

FIG. 1. Spectrum of the conversion electrons emitted in the decay of Ba^{133}, as observed with a semiconducting detector. Lines designated by "L" include contributions from outer lying shells.

investigations.[3,7,9,10] Best agreement is found with the early measurement of Bergstrom[9] who has reported 4.90±0.15 as the value of $K/(L+M)$.

If the 81-keV transition is considered simply as a mixture of $E2$ and $M1$ components, the present measurement of $K/(L+M)$ yields for the percentage of the multiple orders (97±3)%$M1$ and (3±3)%$E2$. These percentages are calculated from the conversion coefficients for pure 81-keV transitions for $Z=55$ which are drawn from the theoretical calculations of Rose[11] and Sliv and Band[12] and presented in Table III.

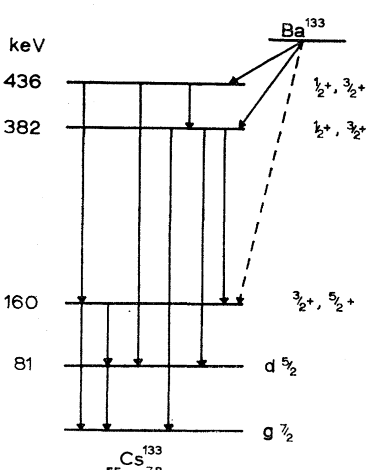

FIG. 2. Disintegration scheme of Ba^{133} as indicated by present results combined with those of the references of this paper.

[9] I. Bergstrom, Arkiv Fysik **5**, 191 (1953).

[10] R. L. Graham and R. E. Bell, Can. J. Phys. **31**, 377 (1953).

[11] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958).

[12] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [English transl.: University of Illinois Report 57 ICC K1 (unpublished)].

The value of α_K was determined directly from the data obtained in an e^--gamma coincidence experiment. Conversion electrons of the 355 keV transition provided the gating pulse and the x rays of Cs and quanta at 81 keV were observed in the multichannel analyzer. The data are presented in Fig. 4. In order to determine

TABLE II. Previously measured $K/(L+M)$ ratios for the 81-keV transition in Cs^{133}.

References	$K/(L+M)$
3	6.9
7	5.38
9	4.90±0.15
10	6.0

from the data the true ratio of K x rays to 81-keV gamma rays involved in the calculation of the value of α_K, corrections must be introduced to take into account fluorescence yield, escape radiation of the K x rays of cesium, absorption of the quantum radiations in the face of the gamma-ray-(x-ray) counter, the fact that each conversion in the K shell can be accompanied by a K x ray, and the fact that K x rays may be emitted in the electron-capture decay of Ba^{133}.

TABLE III. Values of β_1^K, β_1^{L+M}, α_2^K, α_2^{L+M}, and $K/(L+M)$ for an 81-keV transition as taken from Rose (Ref. 11) and Sliv and Band (Ref. 12). $Z=55$.

Reference	$M1$			$E2$		
	β_1^K	β_1^{L+M}	$K/(L+M)$	α_2^K	α_2^{L+M}	$K/(L+M)$
11	1.41	0.25	5.64	2.25	1.90	1.18
12	1.41			2.25		

TABLE IV. Previously measured values of the K-shell conversion coefficient of the 81-keV transition in Cs^{133}.

Reference	α_K
2	1.3 ±0.5
9	1.51±0.15
10	1.77±0.15
13	1.47±0.05
14	1.39±0.06

This last correction requires consideration of the ratio of the probability of electron capture from outer shells to the probability of capture from the K shell. This ratio has been measured[3] as $1.7_{-0.20}^{+0.26}$. The experimental value of α_K so obtained is 1.35±0.05. This result is to be compared with 1.44±0.08 calculated from the $K/(L+M)$ ratios of Rose[11] in Table III, and the previously indicated percentages of mixture. Other values of α_K, obtained by direct measurement, are shown in Table IV.[2,9,10,13,14] Percentages of the $E2$–$M1$ mixture have also been obtained from gamma-gamma angular correlation studies.[15–18] Reported values of the measured $M1$ intensity are given in Table V.

TABLE V. Intensity of the $M1$ component of the 81-keV gamma transition in Cs^{133}.

Reference	$M1$ (%)
15	97.5
16	98.1
17	96.5±0.5
18	97.6±0.4

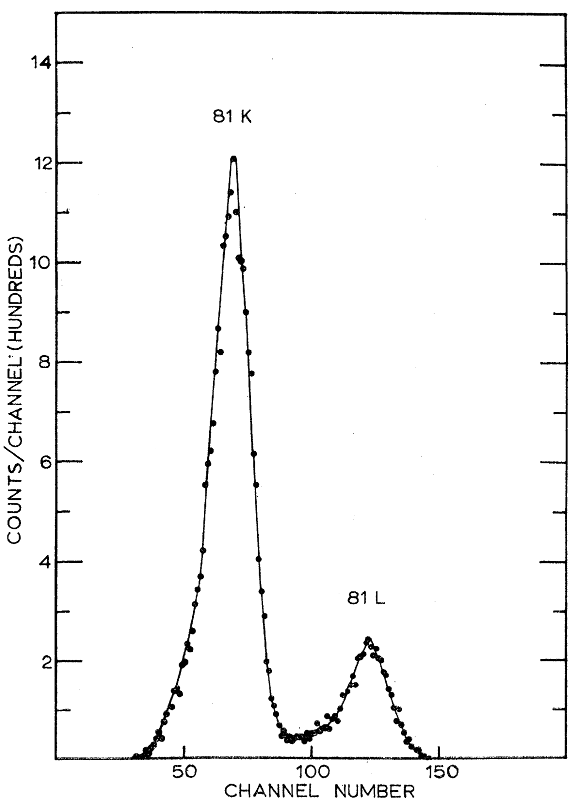

FIG. 3. Conversion electrons of the 81-keV transition coincident with 355-keV gamma rays. The peak labeled "L" includes M-shell contributions.

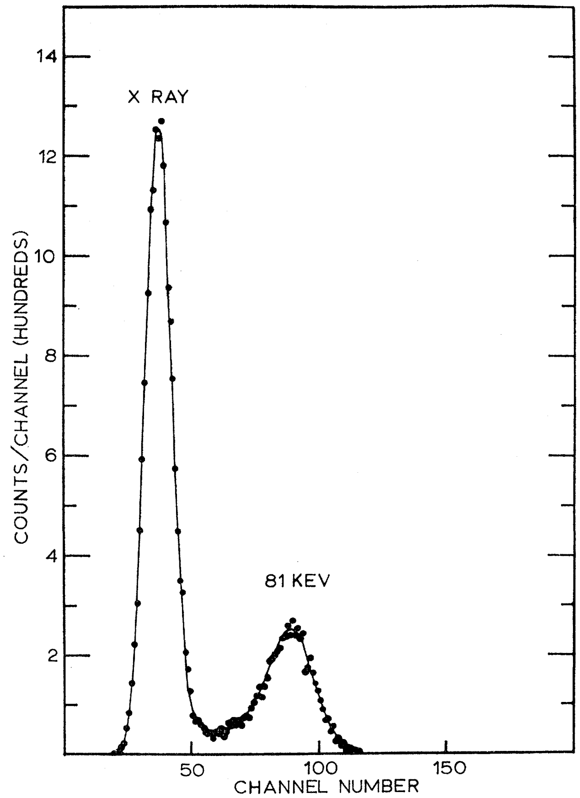

FIG. 4. X rays and 81-keV gamma rays coincident with 355-keV gamma rays.

The results of Table V show that, since the $E2$ contribution to the transition is appreciable, the $M1$ portion is delayed. Thus, the experimental results and shell model considerations require that the 81-keV transition be l-forbidden, delayed, and in large measure $M1$. In this case, use of the tabulated conversion coefficients[11,12] is not recommended.[19] Instead, $\beta_1^K(\lambda)$ must be calculated to take into account penetration effects and nuclear structure factors.[19] This value is

$$\beta_1^K(\lambda) \approx \beta_1^K[1-C(Z,k)(\lambda-1)]^2, \quad (1)$$

where $\lambda = M_e/M_\lambda$ and values of the weighting factor, $C(Z,k)$, are given.[19,20] The value of $\beta_1^K(\lambda)$ is calculated

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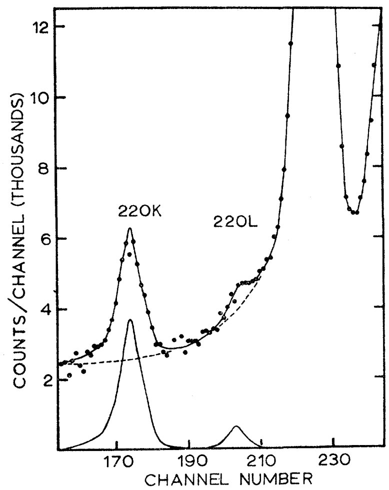

FIG. 5. K-shell and $(L+M)$-shell conversion electrons of the 220-keV transition.

from the equation

$$\alpha_K=[\beta_1{}^K(\lambda)+\delta^2\alpha_2{}^K]/(1+\delta^2)\,, \tag{2}$$

where α_K has the presently measured value of 1.35 ± 0.05; δ^2 is taken from Ref. 18, and $\alpha_2{}^K$ is 2.25.[11,12] The calculated value of $\beta_1{}^K(\lambda)$ is 1.33 ± 0.05. This result in turn yields for λ values of 5 ± 3 and 251 ± 3. For the l-forbidden $M1$ transitions, λ has been found to lie generally[19] between 5 and 10, as indicated by the present measurements. The larger solution is excluded by the experimental measurements.

THE 220-keV TRANSITION

This transition has been previously reported.[3,5] In other cases, it has not been observed.[1,2,4,6,7] In one measurement,[5] unconverted quanta are reported, but the statement is made that the statistics are not good enough to definitely establish the presence of the gamma ray. The K and $(L+M)$-shell conversion lines are apparent in Fig. 1, better shown in Fig. 5, where the K and $L+M$ conversion lines are given in greater detail. $K/(L+M)$ is calculated from the areas under the peaks to be 7.4 ± 0.7. This value is not inconsistent with that given for an $E0$ transition[21] or an $M1$ transition,[11] or a mixture of both. Calculations show that the unconverted gamma rays of an $M1$ transition would be of far too low intensity for detection. If the relative intensities of the K-shell conversion lines of the 220- and 355-keV quanta are taken to be those of Fig. 1, and if the 220-keV transition is taken to be pure $M1$ and that at 355 keV pure $E2$, the intensity of any unconverted quanta at 220 keV is found to be 4×10^{-3} quantum per disintegration, in reasonable agreement with an earlier estimate.[5] On the basis of present data, it is impossible to conclude whether the 220-keV transition contains an $E0$ component. Furthermore, no definite conclusions can be reached as to whether the spins and parities of the 160- and 382-keV states are the same or different.

[21] E. L. Church and J. Weneser, Phys. Rev. 103, 1035 (1956).

THE 54-keV TRANSITION: MEASUREMENTS

The previously reported values of the intensity of the 54-keV gamma ray relative to that of the gamma rays of the 79–81-keV cascade are 4.5[1], <5[2], 16[3], (5.6–6.5)[4], 4.7[5], 5.7[6], and (5 ± 2)[7]%. The region of 54 keV has been cited[2] as one containing a multiplicity of events, including (x-ray)–(x-ray) summing, and backscattered radiation and escape radiation of the gamma rays of the 79–81-keV cascade. Because of the effects aforementioned, detection of a gamma ray emitted in a radiative transition at 54 keV is rendered difficult.

A beam of gamma rays from Ba^{133} was passed through a lead collimator, which was lined with cadmium and copper, falling upon a crystal of NaI-Tl having a thickness of 4 mm. Intervening absorbers of copper were employed to reduce the intensity of 30.85-keV x rays of Cs^{133}. Two thicknesses of absorber were employed in observing the spectrum of single counts in the vicinity of the 80-keV full energy peak and its associated escape peak. The data are shown in Fig. 6 for copper thicknesses of $t_1=0.040$ cm and $t_2=0.110$ cm. The energy calibration of the counting equipment showed the peak of interest to occur at 51.4 keV, at the expected escape peak energy. In the case of Fig. 6, the points for the curve at greater absorber thickness have been multiplied by a normalization factor required to make the areas under the 80-keV peak equivalent. If any 54-keV radiation present be denoted by the subscript "a" and the 80-keV radiation by subscript "b," the difference of the areas under the two peaks at 51.4 keV after normalization would be given by

$$\Delta A={}_0I_a(e^{-\mu_at_1}-Fe^{-\mu_bt_2}), \tag{3}$$

where F is the experimentally determined value of $(e^{-\mu_bt_1})/(e^{-\mu_bt_2})$, the normalization factor, and ${}_0I_a$ is the intensity of any 54-keV radiation present at zero absorber thickness. ΔA is readily calculated from the data themselves, so that ${}_0I_a$ is easily computed. When the area under the composite peak at 80 keV and its escape peak are corrected likewise to zero absorber thickness, any radiation of quantum energy 54 keV is found to be only (0.28 ± 0.11) % in intensity of the gamma rays of the 79- to 81-keV cascade. This estimate includes an increment which takes into account the added contribution of an escape peak associated with any 54-keV radiation. To compute the percentage of disintegrations in which the 54-keV gamma ray is emitted, the average[4–6] in percent of disintegrations of the intensity of the gamma rays of the 79- to 81-keV cascade was calculated to be 37.7. From this average, the 54-keV gamma ray can be estimated to be emitted in (0.107 ± 0.041) % of the disintegrations.

Examination of the decay scheme of Fig. 1 shows the presence of a (355- to 81-keV) cascade and a (54- to 304- to 81-keV) cascade. Employing the slow-fast coincidence circuit ($\tau=10^{-7}$ sec), gamma rays in

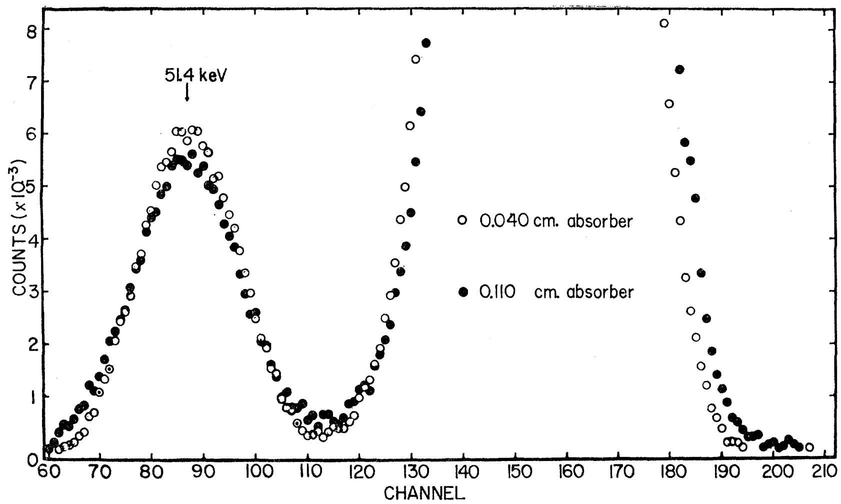

FIG. 6. Full energy peak and escape peak of the gamma rays of the 79- to 81-keV cascade, as observed with two different intervening thicknesses of absorber.

coincidence with the 355-keV gamma ray (Fig. 7) and the 304-keV gamma ray (Fig. 8) were displayed upon a multichannel analyzer. The exact shapes of the various peaks obtained in the aforementioned coincidence experiments were determined in the following manner. The high-energy side of the 81-keV peak was folded about the center to determine the shape of its low-energy side. In a similar manner, the low-energy side of the 31-keV x-ray peak was folded about its center to give the shape of its high-energy side. When the peaks so determined were subtracted from the experimentally observed data of Figs. 7 and 8, the shape of the curve at about 54 keV was obtained. The peak so constructed has the proper full width at half-maximum for a gamma ray at ~54 keV when compared with the full width at half-maximum of the 81-keV peak. The shape of the peak near 54 keV also compared favorably with that of the escape peak of the 87-keV gamma ray of Cd^{109}, as measured in the same geometry.

In Fig. 7, the peak near 54 keV is (10.50±0.13) % of that at 81 keV, and in Fig. 8 the percentage is (11.90±0.18) %. The difference, (1.40±0.22) % is, for the purpose of calculation, assigned to the presence of 54-keV radiation. If two gamma rays in cascade are represented respectively by the symbols γ_1 and γ_2, the gamma-gamma coincidence rate is given by

$$N_{\gamma_1\gamma_2}=N_{\gamma_1}[e^{-\mu_1 t}e^{-\mu_2 t}/(1+\alpha_2)]\epsilon_1\epsilon_2\omega_1\omega_2. \qquad (4)$$

Taking γ_1 and γ_2 to be the 304-keV gamma ray and the 81-keV gamma ray, the coincidence rate is calculated, using an average value,[4-6] of 20.2 as the percentage of disintegrations in which unconverted gamma rays at 304 keV are emitted. Of this amount, (1.40±0.22) % are then set equal to one side of Eq. (4), now taking γ_1 to have an energy of 54 keV and γ_2 to have an energy of 304 keV. The quantity t is the thickness of copper which was inserted before the counter recording the soft-coincident gamma rays, being 0.040 cm, an amount reducing the intensity of the 54-keV radiation to 46.7% of its intensity at zero absorber thickness. Again, it should be remarked that in examining the softer gamma rays of Ba^{133}, absorbers are essential for reduction of the overshadowing intensity of the x radiation. Calculation shows the 54-keV gamma ray to participate

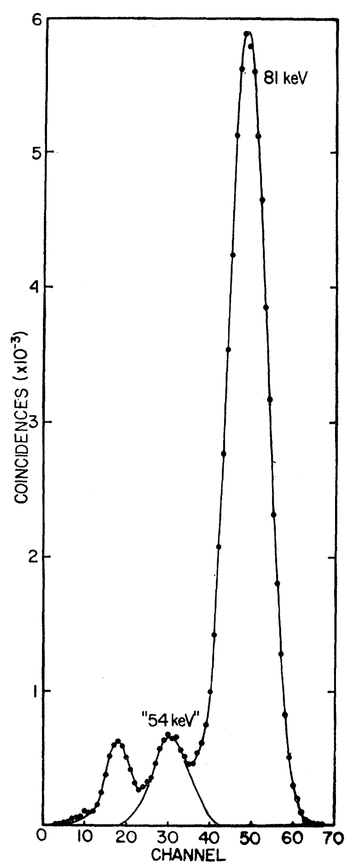

FIG. 7. Coincidences between the 355-keV gamma rays and 81-keV gamma rays.

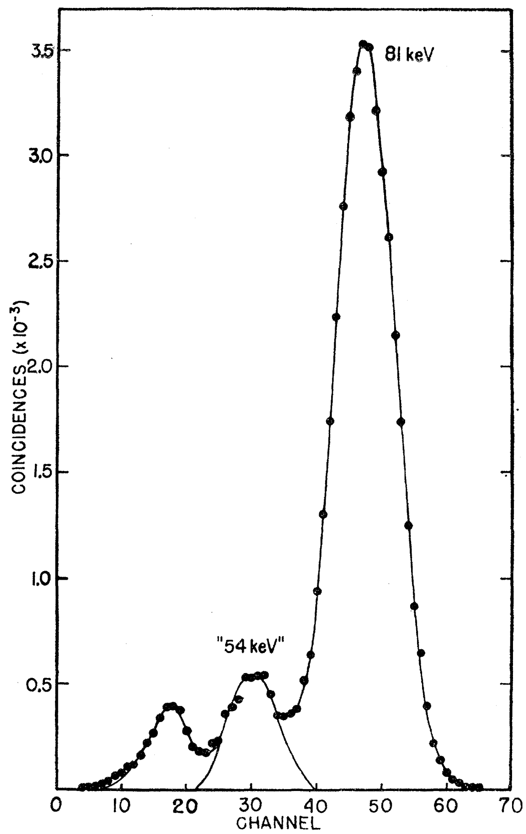

FIG. 8. Coincidences between the 304-keV gamma rays and 81-keV gamma rays.

in the 54- to 304-keV cascade in (0.155±0.025) % of the disintegrations. When this result is corrected for escape radiation associated with the 54-keV gamma ray itself, the 54- to 304-keV cascade is finally computed to occur in (0.182±0.029) % of the disintegrations. This result must be corrected for the fact that not all the disintegrations of Ba^{133} terminate at the 436-keV level of Cs^{133}. If only 70% of the disintegrations so terminate, the 54-keV gamma ray is emitted in (0.260±0.041) % of the disintegrations. Because of the possibility of fewer systematic errors and the ready determination of the intensity of the gamma rays of the 79- to 81-keV cascade, the percentage of intensity of the 54-keV transition, (0.107±0.041), as determined from the spectrum of single counts, is preferred.

THE 54-keV TRANSITION: DISCUSSION OF RESULTS

Gamma-gamma angular correlation studies[15–18] of the 355- to 81-keV cascade have shown the spin sequence to be $\frac{1}{2}\rightarrow\frac{5}{2}\rightarrow\frac{7}{2}$. However, gamma-gamma correlation measurements supplemented by γ-e^- correlation observations[8] favor spins of $\frac{3}{2}\rightarrow\frac{5}{2}\rightarrow\frac{7}{2}$, and indicate the 355-keV transition to be an admixture, $0.7M1+0.3E2$. Retardation factors for the 54-keV transition have been calculated by comparison of its observed lifetime under various assumed sets of conditions with the Weisskopf units. The Weisskopf single-particle lifetime estimates are taken to be

$$\tau_{1/2}(M1)=2.24AE_\gamma^{-3}\times10^{-14}\text{ sec}$$

and

$$\tau_{1/2}(E2)=9.37A^{-4/3}E_\gamma^{-5}\times10^{-9}\text{ sec}.$$

The two possibilities cited above of the spin value of the 436-keV level lead to several different possible values for the retardation factor of the 54-keV transition. The 355-keV gamma ray has been taken to be emitted in 58.8±6.0%[4–6] of the disintegrations, and the 54-keV transition has been assumed to indeed be emitted in 0.107±0.041% of the disintegrations. Some calculated possibilities are as follows:

(1) If the 54-keV transition is pure $M1$ and the 355 transition ($\frac{1}{2}+\rightarrow\frac{5}{2}+$) is unenhanced, the retardation factor is 9010±3600.

(2) If the 54-keV transition is pure $M1$ and the 355-keV transition ($\frac{1}{2}+\rightarrow\frac{5}{2}+$) is enhanced by 100, the retardation factor is 90.1±36.

(3) If the 54-keV transition is $M1+E2$, with its $E2$ component enhanced by 100, and the 355-keV transition ($\frac{1}{2}+\rightarrow\frac{5}{2}+$) pure $E2$, enhanced by 100, the $M1$ component of the 54-keV transition is retarded by a factor 94.3±38.4.

(4) If the 54-keV transition is pure $M1$, and the 355-keV transition ($\frac{3}{2}+\rightarrow\frac{5}{2}+$) is $0.7\,M1+0.3\,E2$, with the $E2$ component enhanced by 100, the retardation factor is 27.4±10.8.

(5) If the 54-keV transition is pure $E2$, and the 355-keV transition ($\frac{1}{2}+\rightarrow\frac{5}{2}+$) is pure $E2$, the enhancement factor for the 54-keV transition is 24.2±9.6.

The possibilities above and other assumed sets of conditions too numerous to detail lead to such values of retardation and enhancement that the behavior of Cs^{133} appears not to be fully explained by single-particle calculations.