Internal Conversion of Gamma-Rays from Co^{60}, Cs^{134}, Zn^{65}

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Using a double-coil, thin-lens magnetic beta-ray spectrometer of transmission 2.40 percent and line width of approximately 3.0 percent, the internal conversion coefficients of the gamma-rays from Co^{60}, Cs^{134}, and Zn^{65} have been measured. Sufficient precision has been attained in several cases to verify the theoretical values and to obtain unambiguous identification of the multipole character of the gamma-rays. Internal conversion coefficients as small as 10^{-5} can be measured with a precision of 5 percent or better.

The results obtained indicate that both of the gamma-rays from Co^{60} are electric quadrupole (*EQ*), the 560-kev gamma-ray from Cs^{134} is either *EQ* or *MD* or a mixture of these, the 602- and 799-kev gamma-rays from Cs^{134} are both *EQ*, the 1.114-Mev gamma-ray from Zn^{65} is either *EQ* or *MD* or a mixture of these and the 1.363-Mev gamma-ray from Cs^{134} may be *EQ*. Further data on the decay scheme of Cs^{134} are given.

The results show that in combination with angular correlation measurements internal conversion data determine the angular momenta and parities of excited nuclear states.

I. INTRODUCTION

OVER the past two decades the theory of internal conversion of gamma-rays has received numerous treatments,[1–12] each author improving or changing the approximations made in previous papers, or extending the treatment to other values of atomic number or atomic shell or gamma-rays energy or multipole order, until finally within the past year or so several papers[1, 2] have appeared which give as the result of rather elaborate calculations the theoretical values of internal conversion coefficients for the *K* shell which are thought to be good to within less than one percent. Similar values for the *L* shell are now being calculated by Rose and his collaborators.[1]

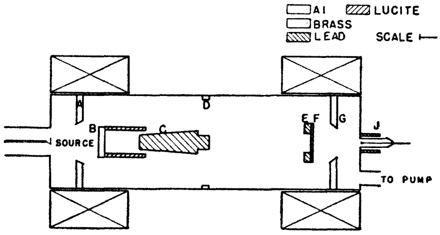

FIG. 1. Schematic diagram of magnetic spectrometer, showing adjustments used in present investigation. All baffles except *C* and *D* are movable from outside the evacuated spectrometer tube. The position of the ring focus as a function of the field pattern and the position and size of the baffles *F* and *G* was determined empirically. The cylindrical part of baffle *B* eliminates higher order focusing of slow electrons. The lead baffles *E* and *J* decrease the background from Compton-scattered radiation from the lens coils. The source is mounted on an "0" ring-sealed shaft and inserted through an air-lock (not shown). With the arrangement shown 660 lbs. of copper take 20 kw to focus 4.5-Mev electrons; with both coils at the center one-fourth as much power is required, but the transmission is decreased. The coils are wound with $1\frac{1}{8}''$ by 0.022" copper strip, each coil containing three pairs of pies separated by water-cooled hollow disks.

Although the present status of the theory of internal conversion seems to be quite good, very few accurate measurements of internal conversion coefficients have been made (in particular for conversion coefficients of less than one percent). It was our purpose in undertaking the present investigation to attain sufficient accuracy in the experimental determination of internal conversion coefficients to provide a significant test of the theory.

II. APPARATUS

Spectrometer

The methods of measuring internal conversion coefficients which we have employed involve the use of a double-coil, thin-lens beta-ray spectrometer in which some care has been taken to eliminate background. The one we have used is shown in Fig. 1. In its essential parts it is patterned after the thin-lens magnetic spectrometer described by Deutsch, Elliott, and Evans[13] except for the modification of ring focusing which Frankel[14] and others[15, 16] have discussed. The particular adjustment of the spectrometer which we have employed in the present investigation is as indicated in Fig. 1. The half-angle of the cone described by baffles *F* and *G* and the counter is approximately 30°. With this adjustment the transmission of the spectrometer is 2.40 percent and the line width (defined below) about 3.0 percent.

The argon- and alcohol-filled Geiger-Mueller counters

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* Now at Vassar College.

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[1] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **76**, 184 (1949).

[2] John R. Reitz, Phys. Rev. **77**, 10 (1950); C. L. Longmire and H. Brown, Phys. Rev. **75**, 264 (1949).

[3] R. Schafroth, Helv. Phys. Acta **21**, 499 (1948).

[4] S. D. Drell, Phys. Rev. **75**, 132 (1949).

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[8] H. M. Taylor and N. F. Mott, Proc. Roy. Soc. **A142**, 215 (1933).

[9] H. M. Taylor and N. F. Mott, Proc. Roy. Soc. **A138**, 665 (1932).

[10] M. H. Hebb and G. E. Uhlenbeck, Physica **5**, 605 (1938).

[11] S. M. Dancoff and P. Morrison, Phys. Rev. **55**, 122 (1939).

[12] M. H. Hebb and E. Nelson, Phys. Rev. **58**, 486 (1940).

[13] Deutsch, Elliot, and Evans, Rev. Sci. Inst. **15**, 178 (1944).

[14] S. Frankel, Phys. Rev. **73**, 804 (1948).

[15] J. W. M. DuMond, Rev. Sci. Inst. **20**, 160 (1949).

[16] E. Persico, Rev. Sci. Inst. **20**, 191 (1949).

used had mica windows which were thick enough to begin affecting the data around 120 kev and to cut off at 50 kev. Although such counters are self-quenching, best results were obtained when a Neher-Pickering quench circuit was used in conjunction with them. Corrections were made for counting losses.

The sources used were mounted on a brass ring, $\frac{1}{64}''$ thick, $\frac{1}{2}''$ o.d. and $\frac{3}{8}''$ i.d., across which was stretched a thin three-ply laminated film (zapon-Formvar-zapon) or a LC-600 film. Some of the sources were covered with a single zapon film. Each of these films was less than 30 μg/cm^2. Care was taken to eliminate any possible effects due to source charging on several of the stronger sources, but no such effects were ever observed. For the external conversion measurements an aluminum absorber ($\frac{1}{16}''$ thick) and lead converter (0.001″ thick) were attached to the brass ring from which the source was supported.

Calibration

The constant of the spectrometer, $k \equiv H\rho/i$, was determined by using the internal conversion lines from Co^{60} and the crystal spectroscopy value[17] for the corresponding gamma-ray energies. Appropriate correction was made for the horizontal component of the earth's magnetic field parallel to which the magnetic axis of the spectrometer was aligned. The vertical component of the earth's field was cancelled out to within 1.5 percent throughout the entire volume of the spectrometer by means of two large Helmholtz coils of a design described by Lyddane and Ruark.[18]

The line width of the spectrometer was determined as a function of source size using the highly converted 625-kev internal conversion line of Cs^{137}. For source sizes from 1.5 to 5.5 mm in diameter the increase in line width with diameter was found to be 1.3 percent of the line width per millimeter.

While in principle the transmission could be calculated if the electron orbits were known in detail, we have preferred to measure it experimentally. Consider, for example, a radioactive isotope which has the decay scheme shown in Fig. 2.

Let: t = transmission of spectrometer = fraction of emitted particles of a given energy detected by the counter; N, N_e, N_γ = number of disintegrations, number of internal conversion electrons, and number of gamma-rays, respectively, from the source per unit time; r_α = counting rate at the peak of the conversion line from an infinitely thin source; w = line width = width of a rectangle of height r_α having the same area as the observed internal conversion line; A = area of the momentum plot of the beta-ray spectrum, i.e., number of observed beta-rays per unit time per unit momentum *versus* momentum. It follows from these definitions that

$$t = (A/(Nw)).$$

(This equation is adequate as long as the curvature of the beta-ray spectrum is negligible over the range of w.)

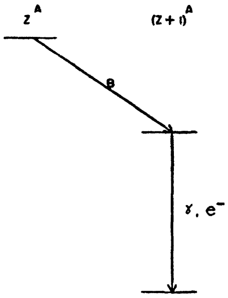

FIG. 2. Hypothetical decay scheme.

The line width being known, in order to determine the transmission of the spectrometer it is necessary to determine A/N as a function of source size. To do this we used three high specific activity Co^{60} sources (approximately two microcuries each) of less than 0.016 mg/cm^2 average thickness and with diameters from 3.0 to 5.0 mm. The absolute strength, N, of each of these sources was obtained by coincidence measurements. The value of A for each of these sources was obtained from a momentum plot of the beta-ray spectrum which had been reconstructed from the Fermi plot of that spectrum. This reconstruction procedure was necessary since the thickness of the counter window did not permit us to obtain valid data below about 120 kev. Thus points for the momentum plot in this energy region were obtained by extrapolating to zero the straight Fermi plot (allowed shape) observed at higher energies. With an exit window 2.0 cm in diameter, the transmission of the spectrometer for sources ranging in diameter from 3.0 to 5.0 mm was found to be constant and equal to 2.40 percent.

After an accurate value of the internal conversion coefficient is obtained for an isotope which can be accurately calibrated, the measurement of the transmission is considerably simplified. Then it is necessary to measure just the strength N of the source and the counting rate r_α at the peak of the internal conversion line for this source. The value of transmission is then given by $t = r_\alpha/(N\alpha)$. [See Eq. (2) below.] The results given in this paper for Co^{60} make this readily possible.

III. METHODS OF MEASURING α

From the definitions given above, it follows[19] that

$$\alpha = N_e/N_\gamma = r_\alpha/(N_\gamma t) = (r_\alpha/Nt)(1+\alpha) = [(Nt/r_\alpha) - 1]^{-1}. \quad (1)$$

For $\alpha \ll 1$ this reduces to

$$\alpha = r_\alpha/(Nt). \quad (2)$$

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[17] Lind, Brown, and DuMond, Phys. Rev. **76**, 591, 1838 (1949).

[18] R. H. Lyddane and A. E. Ruark, Rev. Sci. Inst. **10**, 253 (1939).

[19] We make the assumption that the coefficients of internal pair conversion and all other possible modes of decay are small compared to unity. See M. E. Rose, Phys. Rev. **76**, 678 (1949).

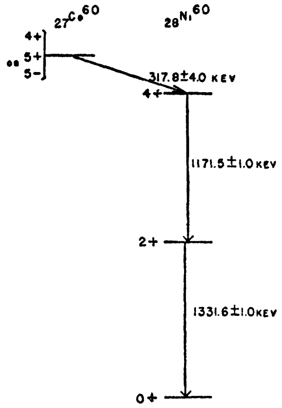

FIG. 3. Decay scheme of Co^{60}; assignment of spins and parities to the nuclear levels involved in the decay of Co^{60}. The assignments are based on polarization and angular correlation measurements, Gamow-Teller selection rules, the allowed shape of the spectrum and the absence of decay to the 2; even level of Ni^{60}. The shell model predicts a $p_{3/2}f_{7/2}$ configuration.

In case the decay scheme is more complex than that shown in Fig. 2 a similar analysis can be made.

The measurement of α can be made by two methods:

(A) If t is known and N can be determined by coincidence measurements or other methods, then α can be obtained directly from the measurement of r_α, the counting rate at the peak of the internal conversion line as observed with the spectrometer using an infinitely thin source.

(B). If the isotope being investigated has a beta-ray spectrum, of known abundance relative to the gamma-ray intensity, the measurement of α does not require a knowledge of t or a determination of absolute source strength. If for the sake of simplicity in illustration we assume $\alpha \ll 1$ and substitute for t in Eq. (2) the expression $t = A/(Nw)$, we obtain

$$\alpha = r_\alpha wN/AN_\alpha. \tag{3}$$

The subscript α indicates that N_α is the strength of the source used in the measurement of r_α, whereas N is the strength of the source used in obtaining A. Thus only the comparison measurement of source strengths, N/N_α, need be made. In addition r_α, the diameter of the source (and thus w) and the area A under the momentum plot of the beta-ray spectrum must be measured.

When the value of N_γ needed in the calculation of internal conversion coefficients cannot be determined by means of coincidence measurements or integration of a beta-ray spectrum, the value of N_γ must be determined by some other method. One such method is by comparing the photoelectric conversion line of the gamma-ray of unknown intensity with that of a gamma-ray of known intensity, using identical radiators. In practice, however, this method encounters at least two difficulties: uncertainty as to the correct dependence of the photoelectric cross section on energy, and of the effects of the anisotropy and scattering of the photoelectrons. In the cases discussed in this paper, wherever the method of external conversion comparison has been used to determine N_γ the energies of the gammas being compared are sufficiently alike that the errors due to the above difficulties are quite small. We have therefore neglected the effect of anisotropy and used Gray's[20] empirical formula, which seems to be the best available, for the photoelectric cross-section ratios. We intend to publish in a subsequent paper other results which are more seriously affected by the above mentioned difficulties with the method of external conversion comparison.

IV. EXPERIMENTAL RESULTS

A. Cobalt 60

The decay scheme[21] for Co^{60} is shown in Fig. 3. The gamma-ray energies have been measured accurately by Lind, Brown, and DuMond[17] using a crystal spectrograph. The value given for the end point of the beta-ray spectrum is the one we have determined from the Fermi plots of data on three different Co^{60} sources (same sources and data used in obtaining A/N in the measurement of the transmission of the spectrometer). Previous work[21] had indicated the beta-ray spectrum to have an allowed shape and our results are in agreement with this. The order of emission of the two gamma-rays is known from the work of Peacock.[22]

Brady and Deutsch[23] have studied the angular correlation of the gamma-rays of Co^{60} and found them both to be quadrupole with the spins of the three nuclear levels involved having the values 0, 2, 4. Angular correlation measurements, however, cannot distinguish between electric and magnetic radiation and therefore the parities of the nuclear levels cannot be fixed from these results. Measurement of the internal conversion coefficients for these two gamma-rays will determine the exact type of radiation and thus fix the parities of these nuclear levels relative to each other (as well as checking on the spin assignments). Recent measurements of Metzger and Deutsch[24] of the polarization-directional correlation of the gamma-rays indicate that the levels all have the same parity.

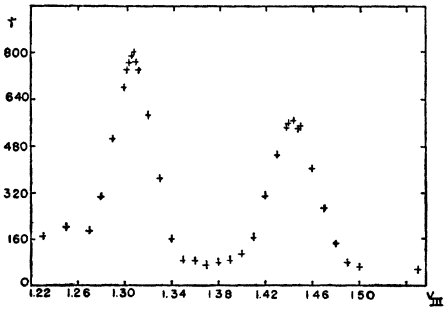

FIG. 4. Internal conversion lines of 1.17- and 1.33-Mev gamma-rays of Co^{60}. The K, L, and M conversion lines for each gamma-ray differ by less than one percent in momentum and are unresolved. The background has not been subtracted.

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[20] L. H. Gray, Proc. Cam. Phil. Soc. **27**, 103 (1931).

[21] Deutsch, Elliot, and Roberts, Phys. Rev. **68**, 193 (1945).

[22] E. Segrè and A. C. Helmholz, Rev. Mod. Phys. **21**, 294 (1949).

[23] E. L. Brady and M. Deutsch, Phys. Rev. **74**, 1541 (1948); **78**, 558 (1950).

[24] F. Metzger and M. Deutsch, Phys. Rev. **78**, 551 (1950).

TABLE I. Internal conversion in excited states of $_{28}\mathrm{Ni}^{60}$.*

Gamma-ray energy in Mev	$\alpha\times10^4$ exp	Theoretical values of internal conversion coefficients EQ	MD	Classification of radiation
1.1715	1.733 ± 0.061	1.545×10^{-4}	1.387×10^{-4}	EQ
1.3316	1.286 ± 0.035	1.175×10^{-4}	1.034×10^{-4}	EQ

* The experimental values are for the $K+L+M$ conversion, unresolved. The theoretical values given are obtained by interpolation from the results given by Rose and his collaborators (see reference 1). The internal conversion coefficients for all types of radiation except magnetic dipole differ from that of electric quadrupole by a factor two or more and are therefore not given in this table.

The internal conversion coefficients in this case can be measured[25] by method B; i.e., using Eq. (3). In this case A and r_α cannot be measured with the same source since α is of the order of 10^{-4}. Therefore r_α was measured for three different Co^{60} sources of strengths varying from 60.5 to 85.8 microcuries and average thickness less than 0.20 mg/cm^2. A plot of a typical set of the data obtained for r_α is shown in Fig. 4. The rising background on the left is due to Compton electrons from the source which have end points at the potentiometer readings $V_{III}=1.128$ and 1.274 for the 1.17- and 1.33-Mev gamma-rays, respectively. A was measured for three different Co^{60} sources of strengths varying from 2.5 to 3.9 microcuries and average thickness less than 0.016 mg/cm^2 in the manner described above. The line width, w, was already known as a function of source size and the values of N/N_α were obtained by comparison of gamma-intensities.

The values we have obtained for the coefficients of conversion in the K, L, and M shells together (unresolved) for the two gamma-rays involved in the decay of Co^{60} and the theoretical[1] values of the conversion coefficients for the K shell for electric quadrupole (EQ) and magnetic dipole (MD) radiation are given in Table I. The conversion coefficients for all types of radiation except MD differ from that for EQ by a factor two or more. Supposing $L+M$ conversion[11] and screening[2] effects to contribute about 10 percent, our results classify both gamma-rays as EQ radiation. Since the selection rules for EQ radiation are $|I+I'|\geqslant2\geqslant|I-I'|$; no parity change, comparison of our results with angular correlation and polarization measurements fixes the spins and parities of the three Ni^{60} nuclear levels involved in the decay of Co^{60} as 0, 2, 4; same. If we assume the ground state of $_{28}\mathrm{Ni}^{60}$ has even parity, then all three levels have even parity.

Once having assigned these spins and parities to the three Ni^{60} levels the fact that the beta-decay to the 4; even level has an allowed shape and no beta-decay to the 2; even or 0; even level is observed permits us to draw some tentative conclusions as to the spin and parity of the Co^{60} nuclear level. The present experiment permits us to place an upper limit of 0.1 percent on beta-decay to the 2; even level. Assuming that decay to the 2; even level must be at least once more forbidden than the observed decay and using Gamow-Teller selection rules, possible assignments to the Co^{60} level would be 4; even, 5; even or 5; odd. Thus the assignment of spins and parities to the nuclear levels involved in the decay of Co^{60} would be as shown in Fig. 3.

Although the agreement between theoretical and experimental values of the internal conversion coefficients seems quite good, more exact comparison cannot be made until the theoretical values for the effects of $L+M$ conversion and screening have been calculated. The present results are in agreement with those of Deutsch and Siegbahn[26] within the relatively large error (approximately 30 percent) of the latter. The classification of both gamma-rays as EQ now seems unambiguous.

B. Cesium 134

The decay scheme of Cs^{134} has been investigated by Siegbahn and Deutsch[27,28] and Elliot and Bell[29] with coincidence and spectrometer techniques. They found gamma-rays of energies 568, 602, 799, and 1350 kev and beta-rays with endpoints of 658 kev and approximately 90 kev. Coincidence and intensity measurements indicated that the three lowest energy gammas were in cascade and the 568-kev gamma-ray was first, but the order of the 799- and 602-kev gamma-rays was not determined. The 1.35-Mev gamma-ray was not definitely located in the decay scheme.

Elliot and Bell[29] obtained a straight (allowed shape) Fermi plot for both beta-spectra and determined the branching ratio of the beta-decay by two different methods. The values they obtained for the ratio of the number of 90 kev to the number of 658-kev beta-rays were about 0.25 and 0.28. Siegbahn and Deutsch[28] also measured this ratio by two methods and obtained the values 0.26 ± 0.08 and 0.32 ± 0.08. Meem and Maienschein[30] give the value 0.34 ± 0.05. Siegbahn and

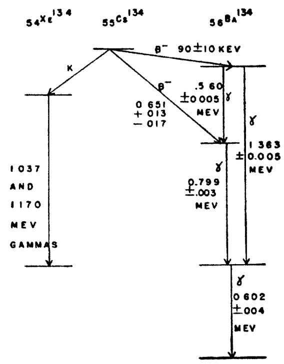

FIG. 5. Tentative decay scheme for Cs^{134}.

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[25] Our results for Co^{60} have already been reported in a letter, Phys. Rev. **78**, 295 (1950).

[26] M. Deutsch and K. Siegbahn, Phys. Rev. **77**, 680 (1950).

[27] K. Siegbahn and M. Deutsch, Phys. Rev. **71**, 483 (1947).

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[30] J. L. Meem, Jr. and F. Maienschein, Phys. Rev. **76**, 328 (1949).

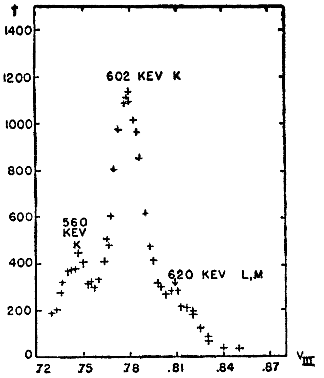

FIG. 6. Internal conversion lines of 560- and 602-kev gamma-rays of Cs^{134}. Fermi plot *II* (Fig. 9) has been subtracted as background. Note the incomplete resolution of the two *K* conversion lines and the partial resolution of the *L* conversion line of the 602-kev gamma-ray.

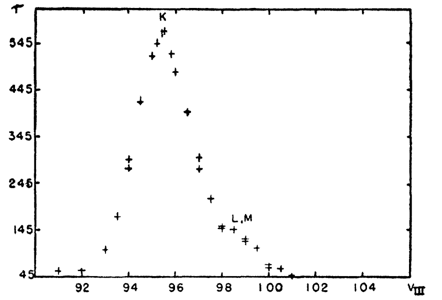

FIG. 7. Internal conversion line of 799-kev gamma-ray of Cs^{134}.

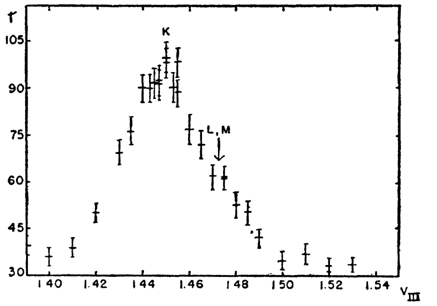

FIG. 8. Internal conversion line of 1.363-Mev gamma-ray of Cs^{134}.

Deutsch found no indication of *K*-capture and placed an upper limit of 5 percent on it.

Decay scheme

We have measured the energies of the gamma-rays and the high energy beta-ray involved in the decay of Cs^{134}. The values obtained are shown in Fig. 5. The low energy beta-ray spectrum was not investigated but previous measurements[29, 30] are in agreement with the present value for the difference in energy of the 651-kev beta-ray and the 560-kev gamma-ray. If the 1.363-Mev gamma-ray belongs in the decay scheme as a cross-over transition, the energies indicate it to be a cross-over of the 560- and 799-kev gamma-rays. The fact that the energies add up correctly is not conclusive evidence for so assigning it, of course. Dr. R. Holland of this department has observed coincidences between the 90-kev beta-ray and the 1.363-Mev gamma-ray. His results indicate that 80±20 percent of the 1.363-Mev gamma-rays coincide with the 90-kev beta-rays. Thus we feel justified in saying that at least part of the 1.363-Mev gamma-rays belong in the decay scheme as an alternate transition to the 560, 799-kev cascade.

In our investigation of Cs^{134} we found, in addition to the internal conversion lines corresponding to the four gamma-rays previously observed, two conversion lines of energies 1.002 and 1.135 Mev of intensities about half of that of the 1.363-Mev gamma-ray conversion line. Sufficient evidence is not available to permit us to say definitely whether these are perhaps due to impurities or belong to a *K*-capture branch. The intensities and energies of these gamma-rays do not permit us to place them in the beta-ray decay branch. The height of the conversion lines of these gamma-rays were watched over a period of four months and there was no significant change of these lines with respect to that of the 1.363-Mev gamma-ray. Thus the assignment of these gamma-rays to an impurity seems unlikely. If they do belong to a *K*-capture branch, the corresponding gamma-ray energies would be 1.03 and 1.17 Mev and their intensities indicate that less than 4 percent of the disintegrations proceed in this manner. All of the experimental results discussed here are independent of the origin and assignment of these gamma-rays.

We thus *tentatively* propose as the decay scheme of Cs^{134} the one shown in Fig. 5.

Angular correlation[23] measurements for the 602- and 799-kev gamma-rays indicate that the spins of the first three $_{56}Ba^{134}$ nuclear levels are probably 0, 2, 4. These results are not completely unambiguous, but they do show definitely that the spin assignments cannot be anything which give rise to a very great anisotropy such as 0, 2, 0, for example. The polarization-directional correlation measurements[24] indicate that if the 0, 2, 4 spin assignment is correct, the levels all have the same parity.

It is clear that the measurement of internal conversion coefficients in the case of Cs^{134} involves some practical difficulties. Not only is the decay scheme somewhat in doubt, which presents a very serious problem, but there are also other difficulties. The 560- and 602-kev

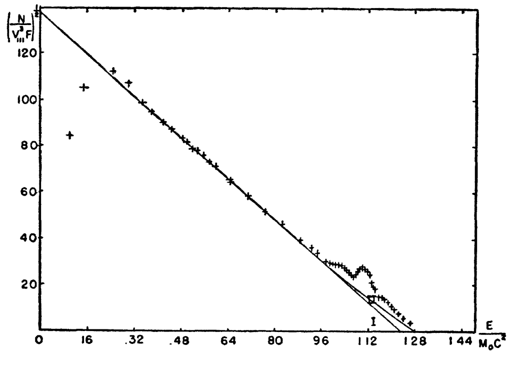

FIG. 9. Fermi plot of 651-kev beta-ray spectrum of Cs^{134}.

TABLE II. Internal conversion in excited states of $_{56}Ba^{134}$, calculated for two values of the beta-branching ratio, b, and for a relative abundance, z, of the 1.363-Mev gamma-ray to the 651-kev beta-ray of 0.058 (see reference 32).

	$\alpha_{560}\times10^3$	$\alpha_{602}\times10^3$	$\alpha_{799}\times10^3$	$\alpha_{1363}\times10^4$
Experimental values for				
b 265/735	8.2±1.0	5.31±0.23	2.55±0.06	6.20±0.34
b 30/70	6.7±0.8	5.06±0.22	2.41±0.06	6.20±0.34
Theoretical values				
ED	2.25	~2	1.06	3.87
EQ	6.17	5.25	2.63	8.5
MD	9.75	8.13	4.12	13
EO	15.40	12	6	18
MQ	20	20		
Classification of radiation				
	EQ and/ or *MD*	*EQ*	EQ	?

gamma-rays do not differ sufficiently in energy to be completely resolved (the L line of the 560 and the K line of the 602-kev gamma-ray will not be resolved at all). Both the 560- and 602-kev lines are superimposed on the high energy beta spectrum and near its end point. The 90-kev beta-spectrum is of such low energy that it is difficult to investigate. The branching ratios are not accurately known. The decay scheme is sufficiently complicated to make determination of source strengths by coincidence methods difficult. Consequently our results for Cs^{134} are not complete. We have taken as the basis of our calculations the decay scheme indicated in Fig. 5. The calculations have been carried through for two different values of the beta-ray branching ratio, namely, 265/735 and 30/70.

1.363-Mev gamma-ray

The number of 1.363-Mev gamma-ray transitions was determined by comparison with the external conversion line of the 1.332-Mev gamma-ray of a Co^{60} source of known strength, appropriate allowance being made for the change in photoelectric cross section with energy.[31] The conversion coefficient could then be obtained by determining the value of r_α for the 1.363-Mev line since $\alpha = r_\alpha/(N_\gamma t)$. Thus the value of the internal conversion coefficient for the 1.363-Mev gamma-ray is independent of all the difficulties with branching ratios and so forth.

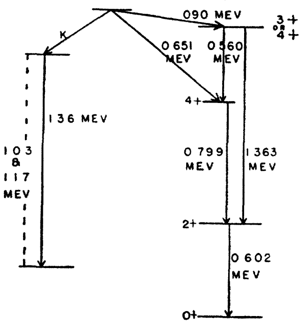

FIG. 10. Tentative assignment of spins and parities to the nuclear levels involved in the decay of Cs^{134}. We have assumed the 0, 2, 4 spin assignment to the first three Ba^{134} levels as indicated by angular correlation measurements to be correct. The shell model predicts a $g_{7/2}d_{3/2}$ configuration. Decay to the 2; even level of Ba^{134} is not present to as much as 0.1 percent.

560-, 602- and 799-kev gamma-rays

The measurement of the internal conversion coefficients for the other gamma-rays can be made by either of the methods previously discussed. Because of the difficulties with the decay scheme we have found it convenient to use the second method, i.e., Eq. (3), and express our results in terms of two parameters:

$b \equiv$ the beta-branching ratio $\equiv$ number of 90-kev beta-rays divided by the number of 651-kev beta-rays,

$z \equiv$ the ratio of the number of 1.363-Mev gamma-rays to the number of 651-kev beta-rays.

This will permit the calculations to be repeated when more accurate values of the beta-branching ratio are obtained as well as making it clear just how the various internal conversion coefficients are affected by the 1.363-Mev gamma-cross-over transition.

The internal conversion coefficients can also be determined by the first method, i.e., $\alpha = r_\alpha/(N_\gamma t)$, if an absolute value for N_γ can be obtained. We have done this by determining the number of 651-kev beta-rays by coincidence techniques. The results obtained are entirely consistent with those obtained from Eq. (3).

In the determination of the internal conversion coefficients by Eq. (3) we have used the 651-kev beta-spectrum to obtain the value of A. The value of r_α for all the gamma-rays (except the 1.363 Mev) could be obtained from the same source. Thus N/N_α was simply an expression in terms of z and b which gave the ratio of the number of gamma-rays of the particular energy concerned to the number of 651-kev beta-rays in the assumed decay scheme.

The Cs^{134} sources used in obtaining A and the value of r_α for all except the 1.363-Mev gamma-ray were approximately 4 microcuries, 4 mm in diameter, and had an average thickness of less than 0.3 mg/cm^2. The sources

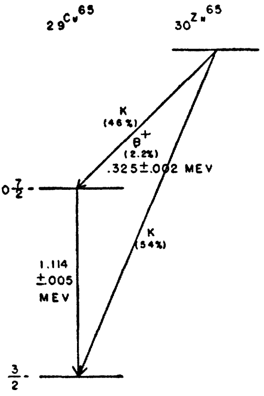

FIG. 11. Decay scheme of Zn^{65} according to previous work (references 34–38). The branching ratios are not relevant to the measurement of the conversion coefficient.

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[31] The method of external conversion comparison will be quite accurate in this case since we are comparing gamma-rays of very nearly the same energy.

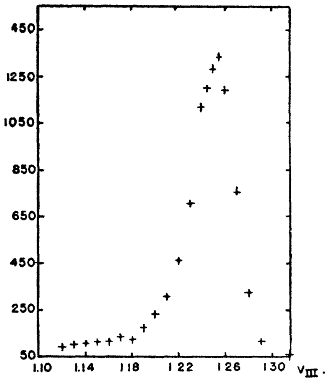

FIG. 12. Internal conversion line of 1.114-Mev gamma-ray of Zn^{65}. The distortion of the line is caused by finite source thickness.

used in obtaining r_α for the 1.363-Mev gamma-ray were about 10 times stronger and 4.5 mm in diameter.

Typical experimental data on the internal conversion lines of Cs^{134} are shown in Figs. 6–8.

Beta-Ray Spectrum Shape

In addition to the above mentioned difficulties another was encountered. In order to obtain A it was necessary to reconstruct the momentum plot of the 651-kev beta-ray spectrum from the Fermi plot by extrapolating the latter to zero. Contrary to the results of Elliot and Bell[29] we did not obtain a straight Fermi plot for this spectrum, but one slightly convex toward the energy axis at the high energy end. This curvature, found for two sources, was more than could be accounted for on the basis of the effect of the internal conversion lines which occur in this region. The Fermi plot for one of the sources is shown in Fig. 9. We have drawn two different curves through the data: I is a straight line and II is a smooth curve which coincides with I at lower energies but which is so chosen at the high energy end that the internal conversion lines of the 560- and 602-kev gamma-rays have the correct widths. Although the value of A (and consequently the value of z) is changed only about 0.3 percent by this difference in the shape of the Fermi plot at the high energy end, the values of r_α for the 560- and 602-kev gamma-rays are very sensitive to this shape since the beta-ray spectrum must be subtracted as background from these lines. The results given here are based on Fermi plot II. No attempt to find a correction factor to straighten this plot has been made.

The number of 651-kev beta-rays was also determined by coincidence methods. Although the results obtained were consistent with those obtained by integration of the beta-ray spectrum, they do not permit one to choose between the two Fermi plots since the coincidence method requires the use of the beta-branching ratio which is rather inaccurately known at the present time.

The average value of z obtained from two separate measurements is 0.0582 ± 0.0012.

Results

Expressed in terms of b and z the values obtained for the internal conversion coefficients are[32] as follows:

$$\alpha_{560} = (2.46 \pm 0.30) \times 10^{-3}/(b-z),$$
$$\alpha_{602} = (7.22 \pm 0.13) \times 10^{-3}/(1+b),$$
$$\alpha_{799} = (3.32 \pm 0.08) \times 10^{-3}/(1+b-z),$$
$$\alpha_{1363} = (6.20 \pm 0.34) \times 10^{-4}.$$

A summary of the calculations of the experimental values for the internal conversion coefficients of Cs^{134} and comparable theoretical values[1] is given in Table II. All of the experimental values are for the K shell only.

These results indicate that the 600- and 799-kev gamma-rays are both EQ. Comparison of these results with angular[33] correlation and polarization-directional correlation measurements fixes the spins and parities of the first three ${}_{56}Ba^{134}$ levels as 0, 2, 4; same. If we assume the ground level of ${}_{56}Ba^{134}$ to be 0; even, then the spins and parities of the first three Ba^{134} nuclear levels are as shown in Fig. 10.

The dependence of α_{560} on both b and the shape of the Fermi plot does not permit us to say whether the 560-kev gamma-ray is EQ, MD or a mixture of these. In any case, however, it seems clear that the selection rules obeyed by this transition are $|I+I'| \geqslant 2 \geqslant |I-I'|$; no parity change. Thus we would assign a spin between 2 and 6 and an even parity to the highest excited level of Ba^{134}. We shall return to the discussion of this assignment later.

As previously noted, the value of the internal conversion coefficient for the 1.363-Mev gamma-ray is quite independent of errors in the branching ratio and Fermi plot. Yet if we accept the theoretical values, the value

TABLE III. Internal conversion in excited state of ${}_{29}Cu^{65}$

α_K(exp)*	Theoretical values† of internal conversion coefficients for K shell				
	ED	EQ	EO	MD	MQ
$(2.28 \pm 0.26) \times 10^{-4}$	1.2×10^{-4}	1.84×10^{-4}	5.4×10^{-4}	1.74×10^{-4}	5.0×10^{-4}

* The probable error given does not include error in value used for the ratio of the photoelectric cross sections for 1.114- and 1.172-Mev gamma-rays, 1.10, nor possible error due to external conversion in the source.

† See reference 1.

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[32] The probable error given for the internal conversion coefficient of the 560- and 602-kev gamma-rays does not include error in r_α due to error in background, i.e., error in Fermi plot. The error given for the internal conversion coefficient of the 1.363-Mev gamma-ray does not include any error in the value taken for the ratio of the photoelectric cross sections for 1.332- and 1.363-Mev gamma-rays, 1.046.

[33] We assume here that the 0, 2, 4 spin assignment indicated by angular correlation measurements (but not unambiguously) is correct. See the text.

TABLE IV. Complete tabulation of experimental results.

Isotope	$E\gamma$(Mev)	Source number	
Co^{60}	1.1715	6	1.745×10^{-4}
		10	1.795×10^{-4}
		11	1.658×10^{-4}
			Av. 1.733×10^{-4}
	1.3315	6	1.290×10^{-4}
		10	1.283×10^{-4}
		11	1.286×10^{-4}
			Av. 1.286×10^{-4}
Cs^{134}	0.560	1	$\frac{2.44}{b-z}\times10^{-3}$
		6	$\frac{2.48}{b-z}\times10^{-3}$
			Av. $\frac{2.46}{b-z}\times10^{-3}$
	0.602	1	$\frac{7.19}{1+b}\pm10^{-3}$
		6	$\frac{7.24}{1+b}\times10^{-3}$
			Av. $\frac{7.22}{1+b}\times10^{-3}$
	0.799	1	$\frac{3.37}{1+b-z}\times10^{-3}$
		11	$\frac{3.34}{1+b-z}\times10^{-3}$
			Av. $\frac{3.32}{1+b-z}\times10^{-3}$
Cs^{134}	1.363	5	5.94×10^{-4}
		9	6.45×10^{-4}
			Av. 6.20×10^{-4}
Zn^{65}	1.114	11	2.38×10^{-4}
		12	2.18×10^{-4}
			Av. 2.28×10^{-4}

$(6.20\pm0.34)\times10^{-4}$ which was obtained is not plausible for a single gamma-ray. According to the theoretical values α_{1363} cannot have a value between 3.87 and 8.5×10^{-4} unless we wish to consider the possibility of combining *ED* and *EO* radiation. The large difference in the theoretical half-lives of these types of radiation makes such a combination very unlikely, however.

There are at least five possible explanations of this anomalous conversion coefficient. First, the sources used were not extremely thin and as a result perhaps the conversion line is spread out and the peak value r_α is smaller than it should be. From a careful study of the conversion lines from three different Cs^{134} sources this effect was found to be small, however. (See Fig. 8.) This small correction has been made. (The value of r_α used in obtaining α_{1363} is that obtained by dividing the area under the observed conversion line by the appropriate line width, allowance being made for the effect of the *L* line on the line width.)

Second would be the possible effect of external conversion of the gamma-rays in the source itself. (See discussion with regard to this point under the results for Zn^{65}.) This would cause the observed value to be at most about 3 percent too high.

Third, perhaps the value used for the ratio of photoelectric cross sections for the 1.332- and 1.363-Mev gamma-rays is not correct. These two energies are close enough, however, that any error in this ratio, 1.046, cannot be large.

Fourth, perhaps the 1.363-Mev gamma-ray does not belong to Ba^{134} at all, but to some other isotope. This explanation is ruled out, however, on the basis of Holland's results that 80 ± 20 percent of the 1.363-Mev gamma-rays coincide with the 90-kev beta-rays.

Fifth, perhaps not *all* of the 1.363-Mev gamma-rays belong in the decay scheme as assumed, but part of them belong to a *K*-capture branch or even to another isotope.

Of these proposed explanations it is only the last one that the present evidence does not rule out. If about 40 percent of these conversion electrons belong to an *ED* gamma-ray in a *K*-capture branch (the gamma-ray energy would be 1.360 Mev), the conversion coefficient would be as observed provided the cross-over transition in the beta-decay branch is *EQ*. This would mean a spin of 2, 3, or 4 (and even parity) for the highest excited nuclear level of Ba^{134}. The absence of beta-decay to the first excited level (2; even) of Ba^{134} would rule out the assignment of 2; even to the highest excited level, assuming the existence of only the Gamow-Teller selection rules.

Thus if the above explanation is correct the assignment of spins and parities to the Ba^{134} nuclear levels would be as shown in Fig. 10. Whether this is the correct explanation or not present evidence does not permit us to decide.

C. Zinc 65

The decay scheme[34–38] of Zn^{65} is shown in Fig. 11. The energies given there are those reported by Mann, Rankin, and Daykin.[35] The value of the gamma-ray energy obtained in the present experiment is 1.112 ± 0.007 Mev. The positron spectrum was not investigated, but previous work[35,36] indicates that it has an allowed shape. None of the branching ratios are relevant to the present investigation. In the case of Zn^{65} the internal conversion coefficient of its 1.11-Mev gamma-ray can be measured by either of the methods previously discussed. However, since the number of disintegrations leading to the 1.11 Mev excited state is easily measured whereas the *fraction* of disintegrations occurring by positron decay and leading to the 1.11-Mev excited state is not accurately known, we have used the first method, i.e., $\alpha=r_\alpha/(N_\gamma t)$.

The value of r_α was obtained for two Zn^{65} sources of diameters 4.45 mm and average thicknesses 2.2 and 2.6 mg/cm². The corresponding values of N_γ were obtained by means of gamma-comparison measurements with three other Zn^{65} sources for which the external conversion lines of the 1.11-Mev gamma-ray were compared with the external conversion lines of the 1.17-Mev gamma-ray of two Co^{60} sources of known strengths,

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[34] Deutsch, Roberts, and Elliot, Phys. Rev. **71**, 389 (1942).

[35] Mann, Rankin, and Daykin, Phys. Rev. **76**, 1719 (1949).

[36] W. C. Peacock, Plut. Proj. Rep., Mon. N-432, **56** (Dec. 1947).

[37] Jensen, Laslett, and Pratt, Phys. Rev. **75**, 458 (1949).

[38] W. M. Good and W. C. Peacock, Phys. Rev. **69**, 680 (1946).

appropriate allowance being made for the dependence of the photoelectric cross section on energy. The error due to the inaccuracy in the knowledge of the variation of the photoelectric cross section with energy and the effect of anisotropy will be small here if we compare the 1.11- and 1.17-Mev gamma-rays since the difference in energy is small.

A typical example of the data obtained for r_α is shown in Fig. 12. Because of the thickness of the Zn^{65} sources used in obtaining the internal conversion line, these lines were spread over a wider energy range than that due to the finite resolution of the spectrometer. As a result the value of r at the peak of the conversion line is not the actual value of r_α, but is too small.[39] The actual value of r_α is obtained by determining the area under the internal conversion line and dividing by the line width (due to the finite resolution of the spectrometer) corresponding to that particular diameter source. Appropriate allowance must, of course, be made for the effect of the L and M lines on the line width.

The experimental values obtained and the relevant theoretical values[1] of the conversion coefficients for the K shell are given in Table III.

The experimental accuracy attainable with the relatively low specific activity Zn^{65} available and the uncertainty concerning the dependence of the photoelectric cross section on energy and the effect of anisotropy in the emission of the photo-electrons do not permit us to classify the gamma-radiation unambiguously. However, the above results seem to indicate that the radiation is *EQ* or *MD* or a mixture of these. Thus the parity of the excited state in Cu^{65} is the same as that of the ground state.

The theoretical values for *EQ* and *MD* radiation lie outside the experimental error by an amount which is of doubtful significance. One cannot account for the large observed coefficient on the basis of the effect of photo-electrons produced in the relatively thick source. These photo-electrons would add to the height of the external conversion line observed and the corresponding absorption would decrease the height of the observed external conversion line. Since $\alpha = r_\alpha/(N_\gamma t)$, the effect on α could be rather large if the product of the effective thickness of the source and the photoelectric absorption coefficient for this energy gamma-ray in Zn^{65} were appreciable compared to α. Using the values of photoelectric cross sections given by Hulme and collaborators[40] and supposing the effective path length in the approximately 2.5 mg/cm^2 ZnS source to be less than 10^{-3} cm, one would estimate as an upper limit on the value of (μx) about 3×10^{-6}. This would cause the observed internal conversion coefficient to be about 2 percent too high. This effect alone is thus not enough to account for the large coefficient observed. (See Table III.)

V. CONCLUSIONS

Of the seven gamma-rays reported on here (see Table IV) the measured internal conversion coefficients of four (the 1.17 and 1.33 Mev of Co^{60} and the 602 and 799 kev of Cs^{134}) agree very well both with the angular correlation and polarization measurements and with the theoretical values obtained by careful interpolations from the calculations of Rose and collaborators,[1] one value (that for the 1.11 Mev of Zn^{65}) is slightly too high and the experimental accuracy on another (the 560 kev of Cs^{134}) is not good enough to permit an accurate comparison with theory. The observed value for the 1.363-Mev gamma-ray of Cs^{134} does not agree with the theoretical results if the experimental calculations are based on the decay scheme for Cs^{134} shown in Fig. 5. Thus in the majority of the cases the agreement between experiment and theory is quite satisfactory. Further work must be done on the decay scheme of Cs^{134} to check the proposed explanation for the disagreement between experiment and theory in the case of the 1.363-Mev gamma-ray of Cs^{134}. It is noteworthy that all six of the excited nuclear levels observed in the present experiment have the same parity as their respective ground states.

In conclusion we may note the following:

(1) The results for Co^{60} and the two abundant gamma-rays of Cs^{134} are in excellent agreement with the theoretical values of Rose *et al.* and may be taken as verifying the theory, since independent evidence of the nature of these gamma-rays is available. Accordingly, the results of internal conversion measurements can be taken as positive identification of the multipole character of the gamma-ray, except in those cases in which different multipoles give indistinguishable coefficients.

(2) Internal conversion coefficients of 10^{-5} or even less can be measured with a precision of 5 percent or better. The 1.363-Mev gamma-ray of Cs^{134} gives one conversion electron for every 40,000 disintegrations and does not by any means represent the limits of the instrumental technique.

(3) In combination with angular correlation measurements, internal conversion coefficients can establish uniquely both the angular momenta and parities of excited nuclear states; in this respect they are probably more useful than the often ambiguous polarization correlations.

The radioactive materials used in this investigation were obtained from the Oak Ridge National Laboratory, Union Carbide and Carbon Corp. We should like to express our appreciation to Dr. R. Holland of this department for the coincidence measurements with the Cs^{134}, to Dr. A. Popov of the University's chemistry department for valuable aid and advice in the preparation of the radioactive sources, to Mr. J. G. Sentinella and the physics shop who fabricated the spectrometer for us, and to Dr. W. R. Arnold and Mr. P. Malmberg who assisted in the construction of the spectrometer and associated equipment.

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[39] This is similar to the dependence of the height of an external conversion line on the thickness of the converter. See Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).

[40] Hulme, McDougall, Buckingham, and Fowler, Proc. Roy. Soc. **A149**, 131 (1935).