Radioactive Decay of Cs^{137}

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The spins of the ground states of Cs^{137} and Ba^{137} are known to be 7/2 and 3/2, respectively. The shape of the 518-kev beta-ray spectrum has been measured and found to correspond to the correction factor $G'=(W_0-W)^2+A(W^2-1)$ in agreement with previous work. This is the shape predicted by the Fermi theory of beta-ray decay and the Gamow-Teller selection rules for a transition for which $\Delta I=\pm 2$ and there is a parity change. The internal conversion coefficient of the 663-kev gamma-ray has been measured and found to be 0.097, which is in agreement with the theoretical value for magnetic 2^4-pole radiation.

IN the isotope Cs^{137} we have a means of testing the Fermi theory of beta-ray decay and the selection rules involved therein as well as the theory of internal conversion and the recent calculations of internal conversion coefficients.

An experiment designed for these purposes is as follows.

I. KNOWN

It is known that the spins[1] of the ground states of Cs^{137} and Ba^{137} are 7/2 and 3/2, respectively, and that the Cs^{137} isotope decays by beta-ray emission either to the ground state of Ba^{137} or to a metastable excited state of Ba^{137}, which then decays by single gamma-ray emission to the ground state of Ba^{137}. This gamma-ray is highly internally converted.

The decay scheme of Cs^{137} is shown in Fig. 1. For convenience we assume that the ground state of Ba^{137} has even parity as predicted by the nuclear shell model.[2] The energy of the high energy beta-ray given in Fig. 1 is that given by Osaba,[3] whose results indicate

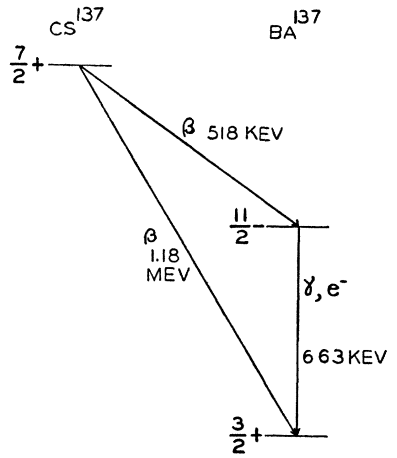

FIG. 1. Decay scheme of Cs^{137} and assignment of spins and parities to the nuclear levels involved in its decay.

that two to five percent of the decay processes proceed in this manner. All other energy values given in Fig. 1 are those obtained in the present experiment and are in agreement with previous results.[3] The half-life of the metastable excited state of Ba^{137} is known to be 158 ± 5 seconds.[4]

Langer and Moffat[5] have recently investigated the shape of the high energy beta-ray spectrum in detail and found that it is the shape predicted by the Fermi theory of beta-ray decay and the Gamow-Teller selection rules for a transition for which $\Delta I=\pm 2$ and there is no parity change. The shape of the low energy beta-ray spectrum has been investigated carefully by several different research groups[3,6,7] and found to have the shape predicted by the Fermi theory of beta-ray decay and the Gamow-Teller selection rules for a transition for which $\Delta I=\pm 2$ and there is a parity change. (Correction factor G'.)

The internal conversion coefficient for the K shell (α_K) and the α_K/α_L ratio for the 663-kev gamma-ray have been measured by Osaba[3] and by Mitchell and Peacock.[8] Their results were $\alpha_K=0.081$, $\alpha_K/\alpha_L=5.0$ and $\alpha_K=0.118$, $\alpha_K/\alpha_L=4.8$, respectively. These results do not permit an unambiguous classification of the multipole order of the gamma-ray.

II. APPARATUS

The beta-ray spectrometer used in this experiment is the double-coil thin-lens magnetic spectrometer described in a recent paper by Waggoner, Moon, and Roberts.[9] The adjustment of the spectrometer for this experiment is the same as that described in the paper referred to, namely, 2.40 percent transmission, line width of about 3.0 percent, energy calibration with respect to the Co^{60} internal conversion lines, and the crystal spectroscopy values for the energies of these lines.[10] The source mounting, counters, and external conversion absorbers and converters used in this experiment are as described in that paper.

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[4] Townsend, Cleland, and Hughes, Phys. Rev. **74**, 499 (1948).

[5] L. M. Langer and R. J. D. Moffat, Phys. Rev. **82**, 333 (1951).

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III. MEASUREMENTS

A. Shape of the 518-kev Beta-Ray Spectrum

The uncorrected Fermi plot of the 518-kev beta-ray spectrum is shown in Fig. 2, curve A. Curve B of Fig. 2 shows the Fermi plot of the same spectrum when corrected with the correction factor[11] $G'=(W_0-W)^2+A(W^2-1)$, where W is the electron energy in units of m_0c^2, W_0 is the total energy available for the beta-ray transition in units of m_0c^2, and A is a function of the atomic number and the electron energy W.

The fit of the correction factor G' is in agreement with previous results[3,6,7] and indicates that the interaction is of either the tensor or axial vector form and that the selection rule obeyed in this beta-ray transition is

$$\Delta I=\pm 2;\ \text{change in parity.}$$

B. Internal Conversion Coefficient of the Cs^{137} Gamma-Ray First Method

The methods by which the internal conversion coefficient can be measured have been discussed fully in the paper by Waggoner, Moon, and Roberts.[9] The first method which we used to measure the internal conversion coefficient of the Cs^{137} gamma-ray is method A of that paper, i.e.,

$$\alpha=r_\alpha/(N_\gamma t), \tag{1}$$

where α = internal conversion coefficient of the gamma-ray ≡ number of internal conversion electrons/number of gamma-rays, $N\gamma$ = number of gamma-rays per minute from the source, and r_α = counting rate per minute at the peak of the internal conversion line as observed with a spectrometer of transmission t when using an infinitely thin source.

Owing to the fact that the excited state of Ba^{137} is metastable with a half-life of 158 seconds, the number of gamma-rays could not be determined by coincidence counting techniques, and we determined N_γ by means of external conversion comparison methods. That is, using identical converters, we compared the external conversion line of a source of Cs^{137} with the external conversion line of a source which could be calibrated by coincidence counting techniques. The converter used consisted of an aluminum absorber ($\frac{1}{16}$″ thick) and a lead converter (0.001″ thick) placed directly in front of the radioactive source. Because of the dependence of the photoelectric cross section on energy and the effects of anisotropy and scattering of the photoelectrons, it is advisable to use sources such that the energies of the gamma-rays being compared are as nearly alike as possible in order that the errors due to the above effects may be small. It is often difficult to obtain such sources, however.

The gamma-rays used for comparison measurements were the 880-kev gamma-ray from Sc^{46} and the 1.117- and 1.332-Mev gamma-rays from Co^{60}. These sources could be calibrated by coincidence counting techniques and the external conversion lines obtained quite accurately with the spectrometer. The empirical formula of Gray[12] was used to obtain the dependence of the photoelectric cross section on energy. The probable errors given for the values of α obtained by this method do not include possible errors caused by uncertainty in the dependence of the photoelectric cross section on energy or the effects of anisotropy or scattering of the photoelectrons.

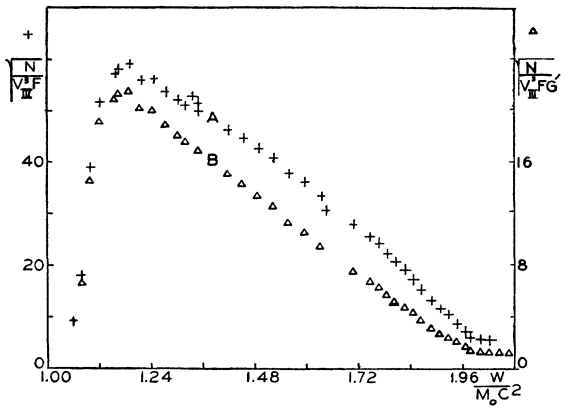

FIG. 2. A: The uncorrected Fermi plot of the 518-kev beta-ray spectrum from Cs^{137} (left scale). B: The Fermi plot of the 518-kev beta-ray spectrum from Cs^{137} when corrected with the correction factor G' (right scale).

A typical example of the data obtained for the determination of r_α, i.e., the internal conversion line of Cs^{137}, is shown in Fig. 3.

The values of α obtained by this method ($\alpha=r_\alpha/N_\gamma t$, N_γ obtained by external conversion comparison measurements) are given in Table I. The average of the values obtained by this method is $\alpha=0.097\pm0.003$.

It should be noted that this method of determining the internal conversion coefficient of the gamma-ray is entirely independent of all of the other decay processes of Cs^{137} and in particular does not make any use of the Fermi theory of beta-ray decay.

C. Internal Conversion Coefficient of the Cs^{137} Gamma-Ray Second Method

The second method of determining the internal conversion coefficient of the Cs^{137} gamma-ray which we used is the method B discussed in the paper of Waggoner, Moon, and Roberts,[9] i.e.,

$$\alpha=[(A/r_\alpha w)-1]^{-1}=[(A/A_\alpha)-1]^{-1}, \tag{2}$$

where A is the area under the beta-ray spectrum for the beta-ray which leads to the excited state, which then decays by the emission of the gamma-ray whose internal conversion coefficient is to be measured, A_α is

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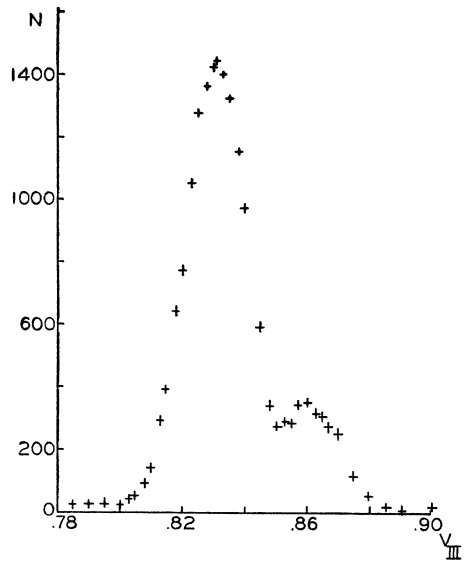

FIG. 3. The K and $L+M+N$ internal conversion lines for the gamma-ray involved in the decay of Cs^{137}.

the area under the internal conversion line, and w is the line width for the particular source and spectrometer adjustment, $w=A_\alpha/r_\alpha$. Equation (2) assumes that the same source is used to obtain both A and A_α and that the spectrometer has the same adjustment for both measurements.

In order to obtain A for the Cs^{137} sources the momentum plot of the beta-ray spectrum was reconstructed from the corrected 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 corrected Fermi plot (correction factor G') observed at higher energies.

The values for the internal conversion coefficient of the Cs^{137} gamma-ray obtained by this method are given in Table I. The average of the values of α obtained by this method is $\alpha=0.097\pm0.005$. The probable error given includes possible error due to the high energy beta-ray spectrum which was not of sufficient abundance[3] to be accurately corrected for otherwise.

TABLE I. Experimental values of the internal conversion coefficient of the gamma-ray involved in the decay of Cs^{137}. Value obtained for ratio of number of K conversion electrons to number of $L+M+N$ conversion electrons=4.7.

Method of measurement	Cs^{137} source number		$\alpha_K\times10^2$
External conversion comparison against Sc^{46}	7		9.20
	19		10.15
		Average	9.7±0.3
Co^{60}	7		9.69
	19		9.72
		Average	9.7±0.3
Comparison of areas A_α/A	7		9.86
	19		9.52
		Average	9.7±0.5

IV. CONCLUSIONS

A. The 518-kev beta-ray spectrum has an energy dependence which can be associated with the correction factor[11] G'. This is the shape predicted by the Fermi theory of beta-ray decay and the Gamow-Teller selection rules for a beta-ray transition for which the spin changes by two units ($\Delta I=\pm2$) and there is a change in parity.

B. The above results indicate that the selection rule obeyed in the 518-kev beta-ray transition is $\Delta I=\pm2$; change in parity and thus that the spin of the metastable excited state of Ba^{137} is 3/2 or 11/2, and the parity of this state is different from that of the ground state of Cs^{137}. Since the spin of the Ba^{137} ground state is known to be 3/2, in order to account for the low abundance of the 1.8-Mev beta-ray and the 158-second half-life of the metastable excited state of Ba^{137} we must, on the basis of beta-ray theory alone, assign the latter of these two values, 11/2, as the spin of the Ba^{137} metastable excited state.

TABLE II. Comparison of the experimental and theoretical (reference 13) values for the internal conversion coefficient for the Cs^{137} gamma-ray.

Experimental value of α_K	Theoretical values (reference 13) for α_K				
	$E(2^4)$	$E(2^5)$	$M(2^3)$	$M(2^4)$	$M(2^5)$
0.097±0.005	0.025	0.053	0.045	0.094	0.25

C. Since the results obtained for the value of the internal conversion coefficient as measured by the two different methods agree, it appears that the theory of beta-ray decay and the correction factor G' for the 518-kev beta-ray spectrum, in so far as they were used in one of these methods of determining the internal conversion coefficient and to the extent that the value of the internal conversion coefficient depends on this use, are in agreement with experiment.

D. The experimental value of the internal conversion coefficient of the Cs^{137} gamma-rays agrees unambiguously with the theoretical value[13] for magnetic 2^4-pole radiation, $M(2^4)$, as indicated in Table II. This agreement constitutes another experimental verification of the theory of internal conversion.[9,14]

E. Since the gamma-ray is $M(2^4)$-pole radiation, the selection rule obeyed in the gamma-ray transition must be

$$|I-I'|\leqslant4\leqslant|I+I'|\text{ ; change in parity;}$$

i.e., the parity of the Ba^{137} metastable excited state must

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

[14] Moon, Waggoner, and Roberts, Phys. Rev. **79**, 905 (1950).

be odd and the spin I satisfy the condition

$$|I-\tfrac{3}{2}| \leqslant 4 \leqslant |I+\tfrac{3}{2}|.$$

Thus, the spin I of the Ba^{137} metastable excited state must be 11/2. An assignment of a lower value, e.g., 9/2, would permit $E(2^3)$-pole radiation as a competing process of much higher probability (half-life[15] of less than 10^{-7} seconds) and internal conversion coefficient much different from the experimental value.

F. The value predicted for the spin of the Ba^{137} metastable state from the results on the 518-kev beta-ray transition (conclusion B) and the results on the internal conversion of the gamma-ray (conclusion E) agree, and thus, if we assume the theory of internal conversion is correct, as seems indicated, we may consider this agreement a verification of the Fermi theory of beta-ray decay and the Gamow-Teller selection rules. (It is of interest to recall here that the theory of internal conversion does not depend on any particular knowledge of nuclear structure nor is it based on any nuclear model.)

G. The assignment of spins and parities to the states involved in the decay of Cs^{137} would thus be as shown in Fig. 1. This assignment is in agreement with the shape and relative abundance of the 1.18-Mev beta-ray spectrum indicated by previous results[3,5] and with the 158-second half-life[3,15] of the metastable excited state of Ba^{137}.

H. The predicted spins and parities are also in agreement with the nuclear shell model,[2] which predicts that the parity of the ground state of Ba^{137} and Cs^{137} should be the same (even) and that there should be an 11/2, odd excited state near the ground state of Ba^{137}.

The radioactive isotopes used in this investigation were obtained from the Oak Ridge National Laboratory, Union Carbide and Carbon Corporation.

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Effect of Turbulence in Thermal Diffusion Columns*

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A certain amount of controlled turbulence improves markedly the separation factor and transport of thermal diffusion isotope separation columns. Measurements on this effect are reported for hot-wire columns 3 meters long, operating on argon gas, and with power input about 725 watts. At pressures three times that for onset of gene ral turbulence the separation factor q_e is still 1.5. Spacers made of pairs of cross-wires of 40-mil Ni wire attached to the hot wire every 10 cm along its length raise the separation factor q_e for optimum pressure from 9.1 to 27.2. If these spacers are attached every 5 cm, q_e rises further to 36. The optimum pressure increases from 0.17 atmos (no spacers) to 0.28 atmos. Identical operation of a similar column with a plain hot wire but with slight constrictions every 15 cm in the cold wall gives $q_e=26.6$. Introduction of these regularly spaced interruptions to the lamellar convective flow of the gas also increases the transport of the A^{36} isotope to the top of the column. Some analysis of these effects is given.

I. INTRODUCTION

IN the treatment of the thermal diffusion column by Furry, Jones, and Onsager,[1] and by others[2] it is specified that the vertical convective flow of the gas is lamellar, and that if any horizontal convective mixing does occur the separation of the isotopes is thereby reduced. There have been several reports,[3–7] however, that upon introduction of some turbulence, either by increasing the gas pressure sufficiently or by placing at regular intervals in the column partial obstructions to the gas flow, increases in the separation of the gas components result. Furthermore, recent thermal diffusion column work[8,9] with binary gas mixtures at high pressure, hence surely somewhat turbulent, has produced separations greater than the values predicted by the laminar-flow theory.

In their first long paper giving details of their simple

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