Spins and Parities of Excited States of Ce^{140} and Sr^{88}

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The angular correlations and the direction-polarization correlations of γ rays of Ce^{140} and Sr^{88} have been measured. Spins and parities have been assigned to the excited states of these nuclei as follows. Ce^{140}: 2.42 Mev, 3^-; 2.09 Mev, 4^+; 1.60 Mev, 2^+. Sr^{88}: 2.78 Mev, 3^-; 1.87 Mev, 2^+.

1. INTRODUCTION

THE measurement of the angular correlation and direction-polarization correlation of γ rays emitted in cascade leads to the assignment of angular momentum and parity.[1] We have made measurements of these types on the γ rays emitted from excited states of Sr^{88} and Ce^{140} using a γ-ray polarimeter similar to the instruments already described.[1] Gamma rays are scattered preferentially in a direction perpendicular to the electric vector in the incident beam. It is thus possible to distinguish between electric and magnetic radiations.

2. PRINCIPLES OF METHOD FOR DETERMINING DIRECTION-POLARIZATION CORRELATIONS

The degree of polarization to be expected for direction-polarization measurements on cascade γ rays has been calculated by several authors.[2]

The calculated correlations are expressed as functions of θ and ϕ, where θ is the angle between the directions of emission of the cascade γ rays, and ϕ the angle between the direction of the electric vector and the normal to the plane of the γ rays. The expected experimental direction-polarization correlation for a cascade is given by

$$W(\theta,\phi)=\eta_1(\phi)W_1(\theta,\phi)+\eta_2(\phi)W_2(\theta,\phi),$$

where $W_1(\theta,\phi)$ is the theoretical correlation when the polarization of one γ ray and the direction of the other are measured, and η_1 is the over-all efficiency of this measurement. $W_2(\theta,\phi)$ and η_2 are the corresponding quantities for the reverse measurement.

The γ-ray incident on the polarimeter is scattered preferentially in the plane perpendicular to its polarization. From the theoretical direction-polarization correlations, we calculate the ratio $N_\perp/N_\parallel$, where $N_\parallel$ is the number of γ rays scattered in the plane containing the γ rays of the cascade, and $N_\perp$ the number of γ rays scattered in the perpendicular plane.

The simplest case is presented by a cascade of only two γ rays. If, then, one γ ray is registered by the direction detector and the other enters the polarimeter, all the necessary information about the polarization of the other γ ray may be expressed by stating the intensities $W(\pi/2,\pi/2)$ and $W(\pi/2,0)$ in the linear polarizations parallel and perpendicular respectively to the plane containing the cascade γ rays.

$$N_\parallel=W(\pi/2,\pi/2)\times d\sigma_{\psi=0}+W(\pi/2,0)\times d\sigma_{\psi=\pi/2},$$
$$N_\perp=W(\pi/2,\pi/2)\times d\sigma_{\psi=\pi/2}+W(\pi/2,0)\times d\sigma_{\psi=0},$$

where $d\sigma_\psi$ is the differential cross section given by the Klein-Nishina formula for scattering of an incident quantum of energy k_0 through an angle δ, with an angle ψ between the direction of polarization of the incident γ ray and the plane of scattering.

$$d\sigma=\frac{e^4}{2m^2c^4}d\Omega\frac{k^2}{k_0^2}\left[\frac{k}{k_0}+\frac{k_0}{k}-2\sin^2\delta\cos^2\psi\right],$$

where k is the energy of the secondary quantum:

$$k=\frac{k_0}{1+(k_0/mc^2)(1-\cos\delta)}.$$

The ratio $R=d\sigma_{\psi=\pi/2}/d\sigma_{\psi=0}$ is a measure of the analyzing efficiency. Then, combining these expressions,

$$\frac{N_\parallel}{N_\perp}=\frac{p+R}{1+pR},\quad p=\frac{W(\pi/2,\pi/2)}{W(\pi/2,0)}.$$

Thus p is determined by the theoretical direction-polarization correlation for the decay-scheme investigated and R is determined by the geometry of the polarimeter and the energy of the γ ray. Measurements with polarized γ rays from oriented Mn^{54} nuclei[3] have given one experimental value of $R=1.9$ for γ rays of 0.85 Mev.

An average scattering angle of $\delta=80°$ has been chosen which gives R its maximum value, when the incident γ-ray energy is about 1 Mev.

In the case of several γ rays of the same or of different cascades entering the polarimeter, one has to work out completely the values of $N_\parallel$ and $N_\perp$ from the known values of the differential Compton cross sections for each energy and from the values of $W(\theta,\phi)$ for each correlation involved.

* This work was performed during the tenure of an I.C.I. Research Fellowship. Now at the Ecole Normale Supérieure, Paris, France.

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

[2] D. L. Falkoff, Phys. Rev. 73, 518 (1948); D. R. Hamilton, Phys. Rev. 74, 782 (1948); S. P. Lloyd, Phys. Rev. 88, 906 (1952). L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. 25, 729 (1953).

[3] Bishop, Daniels, Durand, Johnson, and Perez, Phil. Mag. 45, 1197 (1954).

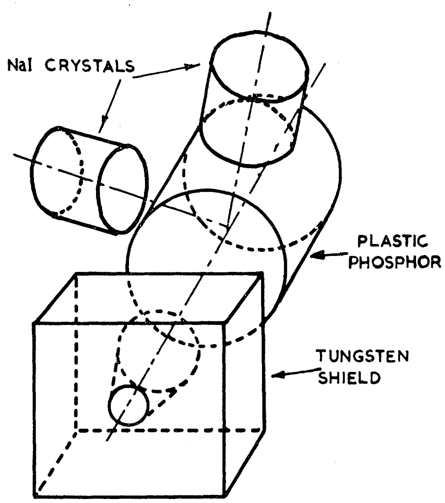

FIG. 1. Schematic diagram of the polarimeter.

APPARATUS

The instrument consists of a direction detector and a polarimeter. The polarimeter is composed of three scintillating phosphors and photomultiplier tubes situated behind a 5-cm thick tungsten collimator (Fig. 1). The center phosphor (channel 3) into which the γ-ray beam is collimated is a cylinder of polystyrene activated with diphenyl tetrabutadiene. The dimensions are varied according to γ-ray energy since double scattering within this phosphor must be minimized. For γ rays of 100-kev energy or less, the diameter was $1\frac{1}{4}$ inches and the height $1\frac{1}{2}$ inches. For higher energies, a diameter of 2 inches and height of 2 inches were adopted. With these dimensions, not more than 15 percent of the scattered γ rays will undergo secondary scattering before escaping to the side counters (channels 1 and 2). The side phosphors are 1-inch cubes of NaI (Tl activated). One is situated in the plane containing the γ rays of the cascade, the other is situated in the perpendicular plane.

All phosphors are surrounded with a diffusely reflecting shield of TiO_2 paint. The direction counter (channel 4) consisted of a cylinder of NaI (Tl activated) $1\frac{1}{2}$ inches in diameter and $1\frac{1}{2}$ inches in length. The direction of one γ ray in a cascade was determined with this detector and the polarization of the other in the polarimeter.

The over-all efficiency of direction-polarization measurements is small and if reasonable counting rates are to be maintained, strong sources of γ rays must be used. In this case, the average counting rates of channels 3 and 4 are large, and a short resolving time must be introduced to reduce the number of random coincidences. Figure 2 is a block diagram of the apparatus.

Channels 3 and 4 were made of E.M.I. (6262) 14 stage photomultipliers with a fast saturated signal taken from each collector and mixed in a short resolving time coincidence circuit. Proportional signals were taken from the ninth dynodes of the photomultipliers in channel 3 and channel 4. They were amplified linearly and fed through gates opened by the output of the coincidence circuit. Once through the gate, these pulses are fed into single-channel kicksorters. The two pulses thus obtained are coincident within the resolving time and each corresponds to a chosen γ ray.

For the annihilation quanta emitted by a source of Na^{22}, a resolving time of 5×10^{-9} sec was obtained with NaI crystals on both channels. A resolution of 7 percent was found given by the width of the photoelectric peak at half the maximum counting rate on the peak.

The output pulses corresponding to the desired events in channels 3 and 4 were then fed to a modified Harwell 1036 *B* type coincidence unit, where the number of coincidences of channels 3 and 4 with either channel 1 or channel 2 was measured simultaneously (3×10^{-7} sec resolving time).

The experimental selection of the γ ray which is measured in the polarimeter can be achieved by making use of the fact that the polarimeter is a crude Compton spectrometer. As an example, we show in Fig. 3 that the differential pulse height spectrum in channel 3 due to recoil Compton electrons in the plastic phosphor for the γ rays of Sr^{88} shows two Compton edges. Each recoil Compton electron is accompanied by a scattered γ ray. Those recoil Compton electrons which are accompanied by a scattered γ ray detected in channel 1 or 2 have a reasonably well-defined energy. This is shown (Fig. 4) by the differential pulse height spectrum of those pulses in channel 3 which are in coincidence with pulses in channel 1 or 2.

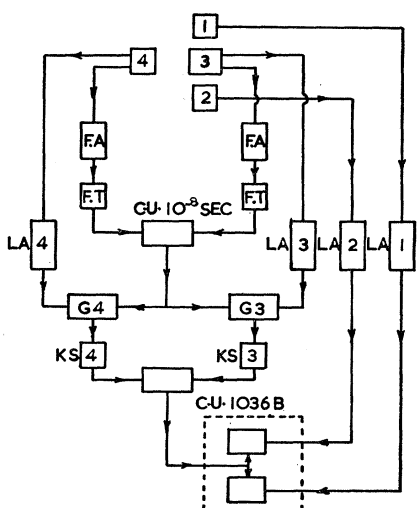

FIG. 2. Block diagram of the electronic apparatus. *F.A.*—fast amplifier. *F.T.*—fast sensitive trigger. *C.U.*—coincidence unit. *L.A.*—linear amplifier Harwell type 201. *G.*—gate. *K.S.*—kicksorter. For simplicity the scalers and E.H.T. supplies are not shown.

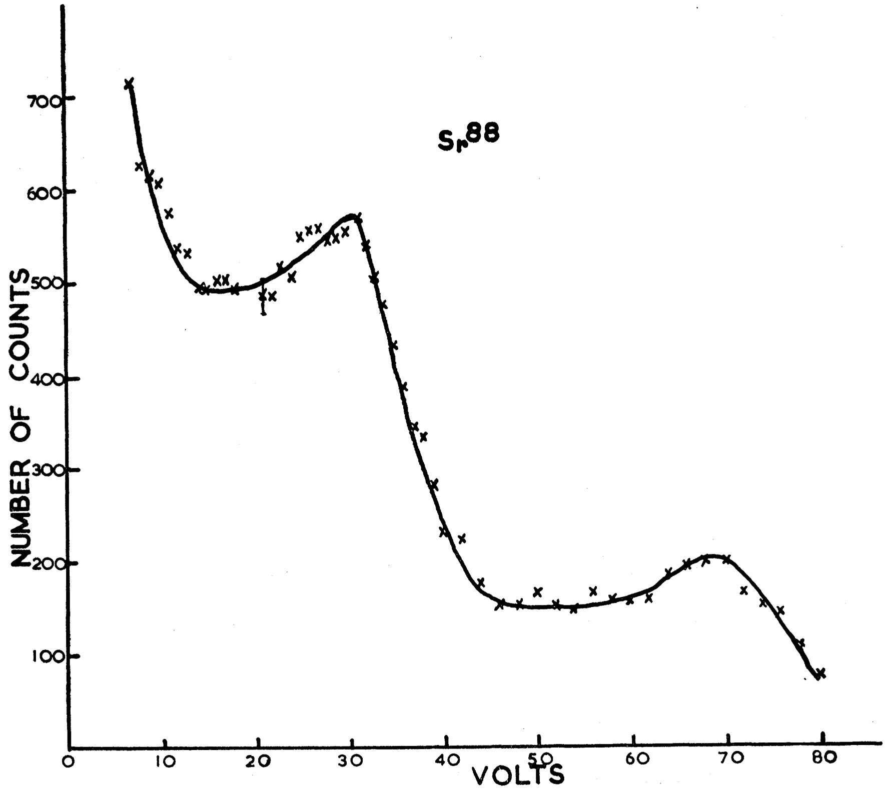

FIG. 3. The differential pulse height spectrum due to recoil electrons in the plastic phosphor from the γ rays of Sr^{88}.

EXPERIMENTAL RESULTS

Ce^{140}

One of the nuclei studied was Ce^{140}. La^{140} decays by complex β^- spectrum to various excited states of Ce^{140}. The γ-ray energies as determined by several authors[4–6] are in good agreement. They do not allow however a final conclusion as to the decay scheme. We have made measurements of noncoincident and coincident spectra and also of the angular correlations of those γ rays to which we could hope to assign parities by direction-polarization correlation measurements. They are the γ rays of 0.328, 0.485, 0.815, 1.60 Mev energy traced in heavy lines on Fig. 5. We found they fitted well into the scheme proposed by Peacock *et al.*[4] (Fig. 5).

Different spin and parity assignments have been given for the first excited states. Robinson and Madansky[7] gave a spin 2 for the 1.60-Mev level, a spin 4 for the 2.41 Mev level. Roggenkamp *et al.*, as quoted in Hollander, Perlman, and Seaborg,[8] gave a 1^+ assignment to the 1.60 Mev level, a 3^+ assignment to the 2.41-Mev level.

(a) *Angular Correlations*

The angular correlations were first measured. In order to measure the correlation between the 0.815-Mev and 1.60-Mev γ rays, the γ rays of lower energy were biased off. One inch cube NaI crystals were used at a distance of 15 cm from the source. Corrections were applied for the finite solid angles of the detectors and the data were reduced by a least squares analysis. This

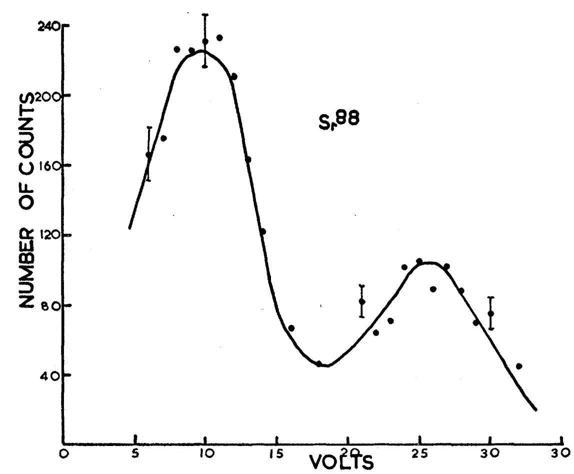

FIG. 4. The differential pulse height spectrum due to recoil electrons which are in coincidence with scattered γ rays detected in the side channels of the polarimeter.

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[4] Peacock, Quinn, and Oser, Phys. Rev. **94**, 372 (1954).
[5] Cork, Stoddard, LeBlanc, Branyan, Martin, and Childs, Phys. Rev. **83**, 856 (1951).
[6] Beach, Peacock, and Wilkinson, Phys. Rev. **76**, 1624 (1949).
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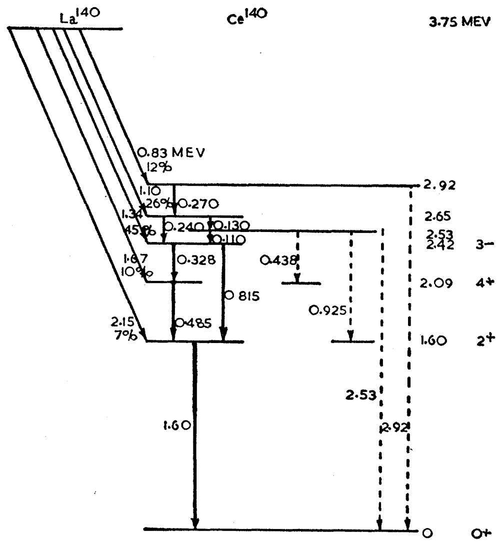

FIG. 5. The decay scheme of La[140]. The γ rays studied in the present experiments are indicated by heavy lines.

measurement, corrected for geometry, gave:

$$W(\theta)=1-(0.0745\pm0.019)P_2+(0.013\pm0.024)P_4.$$

The result is consistent with either a 3, 1, 0 or a 3, 2, 0 scheme for which the correlation is:

$$W(\theta)=1-0.0714P_2.$$

Next, the angular correlation between the 0.485-Mev and 1.6-Mev γ rays was measured. The 0.485-Mev γ ray was selected by placing the kicksorter channel on the corresponding photoelectric peak in the coincidence spectrum. The observed correlation was than corrected for the fraction of the 0.815 Mev–1.6 Mev cascade also accepted, since the channel includes part of the Compton spectrum of the 0.815-Mev γ ray.

The uncorrected correlation was found to be

$$W(\theta)=1+(0.050\pm0.012)P_2+(0.016\pm0.015)P_4.$$

This becomes, after correction for the 0.815-Mev Compton distribution and for geometry,

$$W(\theta)=1+(0.083\pm0.015)P_2+(0.021\pm0.019)P_4.$$

This result is consistent with a 4, 2, 0 scheme for which

$$W(\theta)=1+0.102P_2+0.009P_4.$$

Combining the results for the two measured angular correlations, we have a spin scheme 3, 4, 2, 0. The angular correlation between the 0.328-Mev and 1.60-Mev γ rays (without observing the intermediate radiation of 0.485 Mev) could be used to confirm the result but this was not measured separately.

(*b*) *Direction-Polarization Correlations*

The direction-polarization correlations were then measured. Biases were set to accept the 0.328-Mev, 0.485-Mev, 0.815-Mev γ rays in the polarimeter and only the 1.60-Mev γ ray in the directional counter. The reason for this choice is the following.

Since Ce^{140} is an even-even nucleus, it is probable that the parities of the levels with spin 4 and spin 2 are both even. The parity of the level with spin 3 is less certain. If the parity were odd, both the 0.328-Mev and 0.815-Mev γ rays would be $E1$.

The expected direction-polarization correlations in this case, are

$$(0.815\text{–}1.60)\text{Mev}: W(\theta,\phi)=1-0.0714(P_2+\tfrac{1}{2}\cos2\phi P_2^2),$$

$$(0.485\text{–}1.60)\text{Mev}: W(\theta,\phi)=1+0.102(P_2-\tfrac{1}{2}\cos2\phi P_2^2)+0.009[P_4+\tfrac{1}{12}\cos2\phi P_4^2],$$

$$(0.328\text{–}1.60)\text{Mev}: W(\theta,\phi)=1-0.1403(P_2+\tfrac{1}{2}P_2^2\cos2\phi).$$

With the odd parity for the third excited level, the polarization-dependence for each of these cascades is of the same sign. If, however, the parity of the third excited state is even, then the coefficients of P_2^2 for the first and third cascades change sign, and thus the polarization dependence of these cascades is opposite in sign to that of the second cascade.

In the latter case, the direction-polarization correlation would be smaller than in the first case.

In order to calculate the expected ratios $N_\perp/N_\parallel$, it was necessary to know the relative intensities of the γ rays. They were investigated by several authors[4,9–11] with quite different results, as shown in Table I.

The relative intensities obtained from the pulse height spectra and the coincidence experiments which we made agreed well with the results of Bannerman *et al.*[9]

The various possibilities are given in Table II. If the other values quoted for the relative intensities of the γ rays are used, the calculated values for the last six schemes are less than unity. The calculated value for the first two schemes is not altered very much.

The experimental result found was

$$N_\perp/N_\parallel=1.077\pm0.022.$$

This is consistent with either 3^-, 4^+, 2^+, 0^+ or 3^+, 4^-, 2^-, 0^+. From the Goldhaber-Sunyar rule which would give 2^+ for the first excited state, and 4^+ for the second

TABLE I.

	0.328 Mev	0.485 Mev	0.815 Mev	1.60 Mev
Bannerman *et al.*[a]	5	39	29	100
Rall *et al.*[b]	3	6	13	100
Miller *et al.*[c]	1	10	20	100
Peacock *et al.*[d]	10	10	10	100

[a] See reference 9.
[b] See reference 10.
[c] See reference 11.
[d] See reference 4.

[9] Bannerman, Lewis, and Curran, Phil. Mag. **42**, 1097 (1951).
[10] W. Rall and R. G. Wilkinson, Phys. Rev. **71**, 321 (1947).
[11] L. C. Miller and L. F. Curtiss, Phys. Rev. **70**, 983 (1946).

excited state, we can expect that the first possibility is the correct one.

Support for this scheme is found by calculating the *ft* values for the β^- transitions from the ground state of La^{140} using the relative intensity measurements (Fig. 5). The parity of the ground state of La^{140} is likely to be odd according to the shell model. Thus a change of parity is necessary for those transitions leading to the 4^+ and 2^+ levels and no change for that leading to the 3^- level. The *ft* values from Moszkowski's tables are 9.7(2.15 Mev), 8.6(1.67 Mev), and 7.5(1.34 Mev). Thus the transition to the 3^- level seems to be more favored.

Sr^{88}

The second nucleus studied was Sr^{88}. The decay scheme[12,13] (Fig. 6) shows that two γ rays are emitted in cascade following *K*-capture and β^+ emission of Y^{88}. A cross-over γ ray occurs in 2 percent of the transitions. The source of Y^{88} was prepared by the reaction $Sr^{88}(d,2n)Y^{88}$ on the cyclotron of Birmingham University.

(*a*) *Angular Correlations*

The angular correlation of the γ rays was first measured in order to confirm the spin assignments given to the levels by Steffen.[14] The results were consistent with either a 3, 2, 0 or 3, 1, 0 decay scheme. This leads to 8 possible schemes differing in assignments of spin or parity. From the results of the direction-polarization correlation experiment, which is discussed below, all but 2 could be eliminated.

(*b*) *Direction-Polarization Correlations*

Then, the direction-polarization correlations of the γ rays were measured.

The values of the coefficients η_1 and η_2 could be varied by altering the biases on both counters. Two measurements were made, firstly with $\eta_2=0$ by biasing channel 4 above the 0.91-Mev γ ray and secondly with both

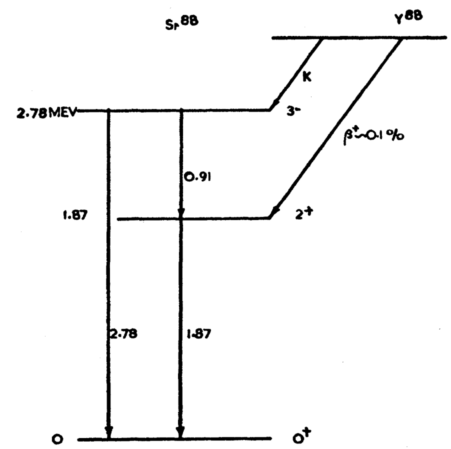

FIG. 6. The decay scheme of Y^{88}.

channels 3 and 4 at zero bias. However, for the latter conditions, η_1 and η_2 are still different since the over-all efficiency is a function of γ-ray energy.

W_1 and W_2 are given by:

$$W(\theta,\phi)=1-0.0714[P_2(\cos\theta)\pm\tfrac{1}{2}\cos 2\phi P_2^2(\cos\theta)],$$

with the plus sign for W_1, and the minus sign for W_2.

With no energy discrimination, the observed normalized ratio was

$$N_\perp/N_\parallel=1.033\pm0.016.$$

Various possibilities for the decay scheme would give the following values of $N_\perp/N_\parallel$ (0^+ is assumed for the ground state of the even-even nucleus Sr^{88}):

$$3^-\,1^+\,0^+,\ 3^-\,2^+\,0^+:\ 1.04$$
$$3^-\,1^-\,0^+,\ 3^-\,2^-\,0^+:\ 0.96$$
$$3^+\,1^+\,0^+,\ 3^+\,2^+\,0^+:\ 0.91$$
$$3^+\,1^-\,0^+,\ 3^+\,2^-\,0^+:\ 1.09.$$

The result is thus most consistent with the 3^-, 2^+, 0^+ or 3^-, 1^+, 0^+ scheme.

With $\eta_2=0$, the normalized value for the observed ratio was

$$N_\perp/N_\parallel=1.083\pm0.024.$$

The expected ratios would be:

0.91 Mev being an $E1$ or $M2$: 1.07

0.91 Mev being an $M1$ or $E2$: 0.94.

Thus the 0.91-Mev γ ray must be $E1$ or $M2$, the 1.87-Mev γ ray $E2$ or $M1$, and the decay scheme of Sr^{88} must be 3^-, 2^+, 0^+ or 3^-, 1^+, 0^+.

The internal conversion coefficient for the 0.91-Mev transition has been determined by Peacock and Jones[12] ($\alpha_K=27\times10^{-5}$) and Metzger and Amacher[15] [α_K

TABLE II.

Schemes	Calculated effects for a point geometry	Calculated effects for our geometry
$3^-, 4^+, 2^+$; $3^+, 4^-, 2^-$	$N_\perp/N_\parallel=1.21$	$N_\perp/N_\parallel=1.09$
$3^+, 4^+, 2^+$; $3^-, 4^-, 2^-$	$N_\perp/N_\parallel=1.05$	$N_\perp/N_\parallel=1.02$
$3^-, 4^-, 2^+$; $3^+, 4^+, 2^-$	$N_\perp/N_\parallel=0.90$	$N_\perp/N_\parallel=0.95$
$3^+, 4^-, 2^+$; $3^-, 4^+, 2^-$	$N_\perp/N_\parallel=0.88$	$N_\perp/N_\parallel=0.95$

[12] W. C. Peacock and J. W. Jones, U. S. Atomic Energy Commission Declassified Document AECD 1812, March 1948 (unpublished).
[13] R. T. Overman, U. S. Atomic Energy Commission Report AECD 354 (unpublished).
[14] R. M. Steffen, Phys. Rev. **90**, 321 (1953).
[15] F. R. Metzger and H. C. Amacher, Phys. Rev. **88**, 147 (1952).

$=(34\pm 7)\times 10^{-5}$]. The theoretical values are:

	$E1$	$E2$	$M1$	$M2$
$\alpha_K\times 10^{+5}=$	28	68	66	165.

Both results are nearest to the coefficient of $E1$. The direction-polarization correlation measurements exclude $E2$ and $M1$. With these latter results, one is only left with a choice between $E1$ and $M2$ which puts the decision for $E1$ beyond any doubt. The decay scheme of Sr^{88} is then 3^-, 2^+, 0^+.

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Iridium-194†

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Electromagnetically enriched quantities of Ir^{193} were exposed for time intervals ranging from 0.5 to 2.0 hr on five successive occasions in the Brookhaven pile. The 19-hour Ir^{194} was found to emit gamma rays of energies 0.295, 0.325, 0.635, 0.640, 0.93, 1.14, 1.28, 1.45, 1.58, 1.77, and ~2.00 Mev. By coincidence studies, cascade relationships were established between ten pairs of gamma rays. The first and second excited states of the residual nucleus were located at 325 and 620 kev. The angular correlation function of the 0.295 Mev—0.325 Mev cascade was measured and found to correspond to a $2\rightarrow 2\rightarrow 0$ distribution, thus giving the spins of the first two excited states of Pt^{194}.

INTRODUCTION

THE 19-hour Ir^{194} has been shown on several previous occasions[1–10] to emit hard beta rays and gamma rays. It has been generally agreed that all but a few percent of the beta rays are contained in a very hard spectrum of maximum energy ~2.2 Mev. Beta-gamma coincidences have been detected,[6] showing the presence of at least one inner beta spectrum which is followed by gamma rays. Until recently,[10] only three gamma rays had been shown to be definitely related to the 19-hour period, a relatively hard one of energy ~1.4 Mev[6] and softer gamma rays at 0.3275 Mev[5–8] and 0.290 Mev.[9] Gamma rays at energies of 1.7 Mev and more have been suggested by the photodisintegration of beryllium and deuterium.[7] A far more complex gamma spectrum has been of late indicated in scintillation counter studies[10] wherein quantum energies of 0.32, 0.61, 1.18, 1.45, and ~1.8 Mev with relative intensities of 100, 22, 10, 5, and 1.2 were reported.

To investigate further the radiation characteristics and decay scheme of Ir^{194}, samples of metallic iridium of weight about 10 mg, isotopically concentrated[11] in Ir^{193}, were exposed on five successive occasions in the Brookhaven pile. The times of irradiation varied from 0.5 hour to 2 hours, and measurements were commenced at a time not exceeding twenty hours after removal of the exposed target material from the reactor and were continued in each case for a period of about three days. The gamma-ray spectrum of Ir^{194} was observed in sodium iodide scintillation spectrometers, and gamma-gamma coincidence data were obtained with two such spectrometers in coincidence. One sodium iodide detector was replaced by an anthracene counter to measure the beta spectra and observe beta-gamma coincidences.§

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* Research Fellow, Bartol; at present at the University of Glasgow, Scotland.
‡ Research Fellow, Bartol; at present at the Nobel Institute of Physics, Stockholm, Sweden.
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[6] C. E. Mandeville and M. V. Scherb, Phys. Rev. **73**, 1434 (1948).
[7] Richard Wilson, Phys. Rev. **79**, 1004 (1950).
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[9] Baker, Bleuler, and Steffen, Purdue University Progress Report. II, June, 1952, quoted by Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
[10] F. D. S. Butement and A. J. Poe, Phil. Mag. **45**, 31 (1954).

[11] On comparing the ratio of the activity of Ir^{194} to that of Ir^{192} in an isotopic target with the same ratio for a sample of normal elemental iridium, it was possible to conclude that the concentration of Ir^{193} was greater than 90 percent.

§ *Note added in proof.*—Since this article was submitted for publication, a paper by Johns and Nablo, Phys. Rev. **96**, 1599 (1954), has appeared. They report sixteen gamma rays from Ir^{194}, having resolved several additional quanta at high energies.