(f) The flux and energy of a collimated beam of α-particles from a Po^{210} source, using standard scintillation counting techniques.

(g) The absolute light emission from an anthracene crystal excited by this α-particle flux, using the calibrated photomultiplier.

It was found that the fluorescence transmission spectrum and scintillation efficiency were independent of crystal thickness d, for $d>1.5$ mm, and the final results were obtained from the mean of measurements on 4 clear, polished anthracene crystals, exceeding this thickness. The absolute scintillation efficiency C_{IF} (total energy of fluorescence emission/total energy of incident radiation) was measured for several α-particle energies, from 0.042 percent at 1.18 Mev to 0.223 percent at 3.85 Mev, corresponding to 0.324 percent at 5.30 Mev. The mean wavelength of the fluorescence emission was 469 mμ, corresponding to a mean photon energy $E_F=2.65$ ev.

Hopkins[1] has observed that the scintillation efficiency of anthracene for excitation by 5.3-Mev electrons is 11.6 (± 0.2) times that for excitation by α-particles of the same energy. Hence we obtain $C_{IF}=3.76$ (± 0.07) percent for thick anthracene crystals at room temperature, excited by fast electrons. This corresponds to an energy expenditure $E_{IF}=70.5$ (± 3.8) ev/fluorescence photon.

This value may be compared with that derived from the "photon cascade" theory.[2] On this theory, the scintillation process consists of m molecular fluorescence emissions, of decay time $(t_f)_0$, and quantum efficiency q_0. The mean value of m is given by

$$m=(t_I)_T/(t_f)_0, \tag{1}$$

where $(t_I)_T$ is the technical scintillation decay time of a thick crystal. The scintillation quantum efficiency is

$$q_I=(q_0)^m, \tag{2}$$

the scintillation energy efficiency is

$$C_{IF}=E_Fq_I/E_Z, \tag{3}$$

and the energy expenditure/emitted photon is

$$E_{IF}=E_Z/q_I. \tag{4}$$

E_Z is the energy expenditure/primary photon, which on the theory is equated to the energy expenditure/ion-pair, i.e., $\sim$30 ev/primary photon.

For anthracene at room temperature, values of $(t_f)_0=3.5$ mμsec, $(t_I)_T=27$ mμ sec, and $q_0=0.9$ have been observed experimentally,[3] giving $m=7.73$ and $q_I=0.443$ from (1) and (2). Hence we obtain $E_{IF}=68$ ev/photon, in agreement with the direct experimental value.

A detailed account of this work will be published later. We wish to acknowledge the support received from the South African Council for Scientific and Industrial Research.

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Three-Body Scattering Problems

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In a recent paper, Borowitz and Friedman[1] obtain an expression for the exchange scattered amplitude in the Born approximation which differs from that given by Mott and Massey.[2] They question the procedure of expanding the entire solution in terms of a complete set of eigenfunctions of a Hamiltonian apparently because the coefficients of such an expansion must contain δ-functions, and they give a detailed proof of this latter assertion. They state further that in the case of, for example, the ionization of atoms by electron impact, Mott and Massey's result diverges.

Firstly we point out that if we make the same assumptions as Borowitz and Friedman, it is obvious that such an expansion will contain δ-functions. Using their notation, it is consistent with their assumptions to choose $V(r)=0$, and since

$$\sin k_0 r=\int dk\delta(k-k_0)\sin kr$$

the statement is immediately proved. However, their assumptions are not comparable to those of Mott and Massey who use essentially

$$r\phi_k(r)\sim\sin(kr+k^{-1}\log 2kr+\eta),$$

and not

$$r\phi_k(r)\sim\sin(kr'+\eta).$$

Since it is not clear in what way the presence of singularities such as δ-functions in the expansion coefficients constitutes an objection to the treatment, the point will not be pursued further.

It is of more importance to note that the result of Mott and Massey, correctly interpreted, does *not* diverge and is in fact on the same basis as that of Borowitz and Friedman, the difference between the two being, of course, the familiar post-prior discrepancy. This discrepancy may be shown to equal

$$\int e^{-i\mathbf{k}_n\cdot\mathbf{r}_2}\phi_0(\mathbf{r}_2)d\mathbf{r}_2\bigg[\lim_{r_1\to\infty}\int_{-1}^{+1}\int_0^{2\pi}\{e^{i\mathbf{k}_0\cdot\mathbf{r}_1}\operatorname{grad}(\phi_n^*(\mathbf{r}_1)) -\phi_n^*(\mathbf{r}_1)\operatorname{grad}(e^{i\mathbf{k}_0\cdot\mathbf{r}_1})\}r_1^2d\mu d\Phi\bigg], \tag{1}$$

and if n is discrete it thus vanishes as has been pointed out by Bates, Fundaminsky, and Massey.[3] To prove that this result is, as would be expected, generally true it need only be noted that if n is in the continuum, (1) must be replaced by

$$\frac{1}{\Delta k_n}\int_{k_n}^{k_n+\Delta k_n}dk_n\{\text{expression (1)}\},$$

where Δk_n is arbitrarily small but not identically zero (see Gordon[4]); and clearly this expression vanishes as

$$\sin(r\Delta k_n)/r\Delta k_n.$$

Finally it may be worth while to point out that the formula obtained by Borowitz and Friedman is the same as would be found by following the Mott and Massey procedure for direct scattering and using a properly symmetrized wave function throughout.

I wish to thank Professor D. R. Bates for many helpful comments.

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Polarization of the Three-Photon Annihilation Radiation*

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We have used a triple coincidence counter method to investigate the polarization of the gamma-rays resulting from the three-photon annihilation of positrons and electrons.[1] Of the many polarization effects that one might expect, we have chosen to investigate the simplest from the experimental point of view, i.e., the polarization of any one of the gamma-rays relative to the plane of emission of the three photons. The measurement was conducted for the symmetrical case (equal angles beangles between the photons).

A thin sample of Na^{22} (1.4×10^6 dis/sec) was located in the center of a bell-shaped Al container (2.5 cm in diameter, 0.44 g/cm² thick) filled with a dense atmosphere of SF_6. Positrons from this source formed positronium[2] and provided a sufficiently intense source of three-quantum annihilation events. Three NaI(Tl) scintillation counters were used to detect the gamma-rays, and were placed as indicated in Fig. 1. Counters A and B detected

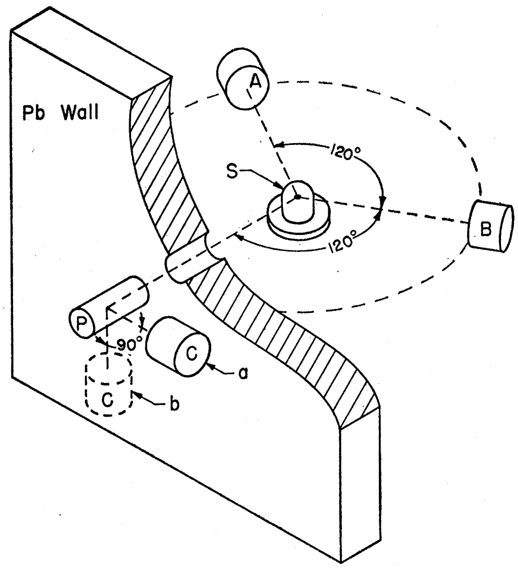

FIG. 1. Apparatus.

two of the three annihilation rays directly, while counter C detected the third ray only after it had been scattered by the polystyrene cylinder P. Triple coincidences were counted with counter C alternatively in positions a and b (Fig. 1). In such positions counter C detected rays scattered respectively parallel or perpendicular to the plane ABP. The background of triple coincidences was measured by lifting counter A at 45° away from the plane BPS, as described in the account of our previous work.[1] The geometric equivalence of positions a and b was checked by counting single scattered rays; the counting rates never differed by more than 10 percent in the two positions.

The experimental results, after subtraction of background are shown in Table I.

TABLE I. Experimental results.

Series	Position a (parallel) counts/hr	Position b (perpendicular) counts/hr	Ratio par./perp.
I	7.0 ± 1.2	3.6 ± 1.0	1.92 ± 0.55
II	9.4 ± 1.3	5.4 ± 1.2	1.73 ± 0.37
III	10.3 ± 1.3	5.2 ± 1.0	2.00 ± 0.43
IV	8.3 ± 1.3	4.7 ± 1.1	1.78 ± 0.44
Average			1.87 ± 0.23

The theory[3] predicts a polarization ratio 3/1 in favor of rays plane-polarized with the electric vector perpendicular to the plane of the three photons. A rough Monte-Carlo computation,[3] taking into account the geometry of the experiment and the anisotropy of Compton scattering for polarized photons, leads to the prediction of a ratio (parallel/perpendicular) 1.80 ± 0.15 for the result of the experiment, performed as described above. This is in agreement with the experimental value.

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Effect of the Electric Quadrupole Interaction on the $\gamma-\gamma$ Directional Correlation in Cd^{111}. II

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IN a previous letter[1] we described experiments with metallic indium single crystals containing In^{111}, which indicate that the interaction which influences the angular correlation in this type of source is electric in origin. Furthermore, the magnetic decoupling experiments showed that the magnetic interaction cannot be responsible for the observed attenuations in polycrystalline sources, which were previously measured.[2] It is therefore reasonable to assume that these attenuations are also due to the coupling between the electric quadrupole moment of the nucleus and the inhomogeneous electric crystalline field.

In this letter we describe some new measurements confirming this hypothesis and we discuss the hypothesis in connection with older experiments.

Angular correlation measurements in sources in which no inhomogeneous electric fields exist at the radioactive nucleus should show the undisturbed correlation according to our quadrupole hypothesis. Experiments on three types of such sources have been carried out:

Type a: Cubic crystals. (The active atoms must be in lattice positions and the crystals must be sufficiently large and perfect. Nevertheless, cubic crystals do not exclude interaction with higher electric moments and therefore offer the possibility to be measured.)

Type b: Solutions. (Care must be taken to avoid hydrolysis and/or precipitation.)

Type c: Melts.

Experiments with sources of the first type were performed in the earlier work of the Zürich group.[2] The active atoms were embedded in different metals by the double stream evaporation method. Cubic crystallizing metals (Ag, Cu) showed close to the maximum anisotropy, $A=[W(180°)-W(90°)]/W(90°)=-0.20$, under certain conditions (sufficiently large and pure crystallites and sufficient thickness of the source), whereas crystals with lower symmetry than cubic (In, Te, Cd, Se) always gave considerably less than the maximum value of the anisotropy.

Experiments with sources of the second type have been reported.[3,4] Aqueous solutions of $InCl_3$, InI_3, $In_2(SO_4)_3$, $In(NO_3)_3$, and others gave $A=-0.20$, whereas crystalline sources of the same compounds showed nearly isotropic correlations. The disappearance of the attenuation of the angular correlation when a crystalline source is dissolved in water gives the most striking evidence for the quadrupole hypothesis.

We have recently measured sources of the third type. Indium metal containing In^{111} was carefully reduced with hydrogen and sealed into an evacuated thin-walled Pyrex glass capsule. As no special crystallization methods were used, the sources were poly-

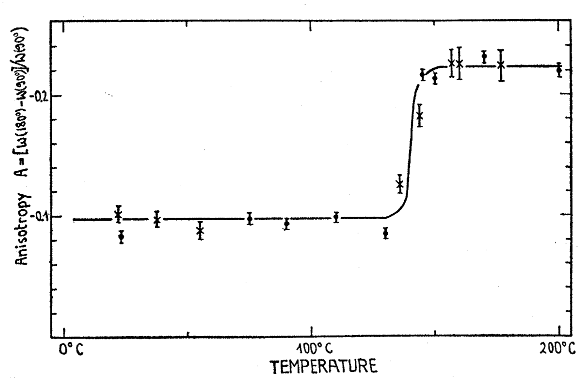

FIG. 1. Elimination of the quadrupole interaction by melting a polycrystalline metallic indium source. Anisotropy *vs* temperature. ● run 1, ✕ run 2-