Simultaneity in the Compton Effect*

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The simultaneity in the Compton effect has been investigated by using scintillation counters and fast coincidence techniques. By the use of a gamma-ray source of a known, very short, lifetime (Ni^{60}) it was possible to apply a first moment investigation to the time delays involved.

It is shown that the order of magnitude of all possible time delays involved in the Compton effect does not exceed 10^{-11} second. Upper limits previously given were $\sim 10^{-8}$ second.

IN 1950, Hofstadter and McIntyre, and Cross and Ramsey[1] repeated the Bothe-Geiger experiment[2] (1925) under improved conditions of time resolution (1.5×10^{-8} second). Experiments reported in this paper lower the limit of such time measurements by three orders of magnitude.

The ability to obtain this shorter time limit is due to two facts: (1) the time resolution of our technique is about one order of magnitude better; (2) the use of a gamma-ray source of a *known*, very short, mean life (Ni^{60}) permits one to apply a first moment investigation which is much more accurate in coincidence technique. This gives an additional improvement of two orders of magnitude.

It has been shown previously[3] that, in the cascade of $Co^{60}-Ni^{60}$ the β particle and the Compton recoil electron released by the gamma radiations (γ) of Ni^{60} appear within a time interval of less than 10^{-11} second. This result was used to provide an upper limit for the decay times involved. More precisely, it demonstrates that $\theta+\langle t_e\rangle \leqslant 10^{-11}$ second, where θ is the mean life of the excited state of Ni^{60} (the fact that Ni^{60} has two excited states and therefore emits two gammas is not important here), and $\langle t_e\rangle$ is the average of the possible random time delays t_e in the release of a Compton electron, e, by γ. Thus $\langle t_e\rangle$ must be less than 10^{-11} second, i.e., the emission of a Compton electron is "simultaneous with the incident gamma" within 10^{-11} second. Since t_e is always positive (the recoil cannot appear earlier than the β), the probability of obtaining a t_e greater than $n\langle t_e\rangle$ is certainly not greater than $1/n$.

The upper limit given here for $\langle t_e\rangle$ is also valid for a constant time delay of the same amount in every Compton process, as discussed by Hoffman, Shenstone, and Turner.[4] They point out that such a constant time delay could not be detected in a coincidence experiment involving *only* Compton electrons released by a primary and its scattered gamma and that, from previous experiments of Piccard and Stahel,[5] one can deduce an upper limit of 10^{-7} second for this constant time delay.

In a separate experiment, to be described below, we measured coincidences between two Compton electrons, e and e', released by the primary and the scattered gamma, γ and γ'.

If there is a random time delay t in the release of the γ' wave train and $\langle\tau\rangle$ is the mean time length of this wave train, then the average time of appearance of e', *related to the time of appearance of the* β, after subtraction of times of flight, is $\theta+\langle t\rangle+\langle\tau\rangle+\langle t_e\rangle$. Here we make the reasonable assumption that the average of the possible random time delay in the release of e' by γ' is also $\langle t_e\rangle$.

Coincidence measurements between e and e' gave for the average of the time delays, t', between the appearance of these two electrons $\langle t'\rangle=\langle t\rangle+\langle\tau\rangle\leq 1.5\times10^{-11}$ second. Thus both $\langle t\rangle$ and $\langle\tau\rangle$ are less than 1.5×10^{-11} second. Since both t and τ are positive, the probability of getting a value for either of them greater than n times the average is less than $1/n$.

The experimental arrangement is shown in Fig. 1. Two small diphenyl acetylene crystals A and B (8×8

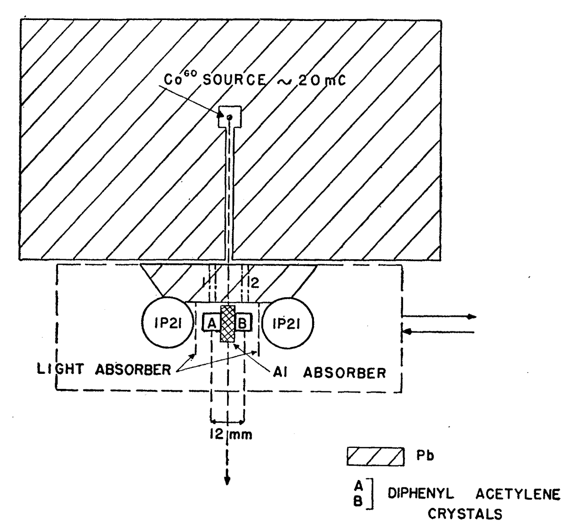

FIG. 1. Experimental arrangement.

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[2] W. Bothe and H. Geiger, Z. Physik 32, 639 (1925).
[3] Bay, Henri, and McLernon, Phys. Rev. 97, 561 (1955).
[4] Hoffman, Shenstone, and Turner, Phys. Rev. 50, 1092 (1936).
[5] A. Piccard and E. Stahel, J. phys. et radium 7, 326 (1936).

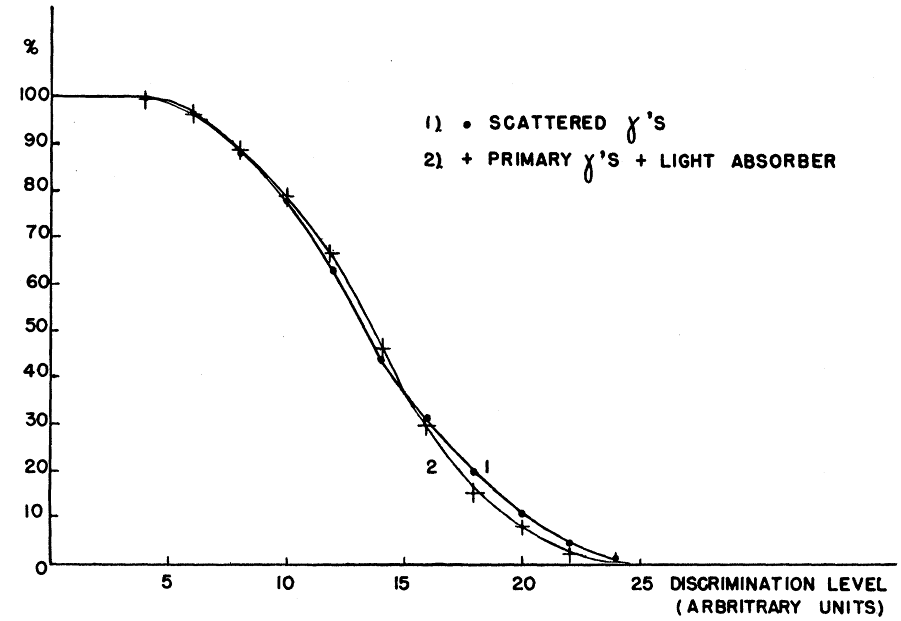

FIG. 2. Integral pulse-height distributions (taken in coincidence with the outputs of the C circuit) in detector A.

$\times 20$ mm^3) are separated by an Al absorber (800 mg/cm^2) each facing a 1P21 photomultiplier. The whole system is mounted as a movable assembly. Gamma rays from a Co^{60} source ($\sim$20 millicuries) are collimated by a Pb channel (6-mm diameter, 22-cm length). The position of the detector assembly can be changed in such a way that the γ beam impinges on either crystal A or B. The Compton-scattered gammas ($\sim$90°), resulting from primary scintillation events in one crystal are detected in the other crystal. Preliminary experiments showed that the coincidences detected are overwhelmingly true Compton coincidences and that <1 percent of them are due to chance coincidences and to the $[\gamma\gamma]$ coincidences of Ni^{60}. The coincidence counting rate obtained ($N_0 \sim 3$ per second) was in agreement with the value calculated for the experimental arrangement. This corroborates once more the result of the original Bothe-Geiger experiment showing that the electron and the scattered photon are emitted in the same elementary process. With independent probabilities for the emission of e and γ', N_0 would have been smaller by more than two orders of magnitude.

Delayed coincidence curves have been obtained (1) when crystal A was in the primary beam and B was excited by scattered gammas, and (2) in the reversed position. The time differences, (including times of flight of γ' and the possible time delays t'), change sign when passing from (1) to (2).

In order to obtain the highest possible number of

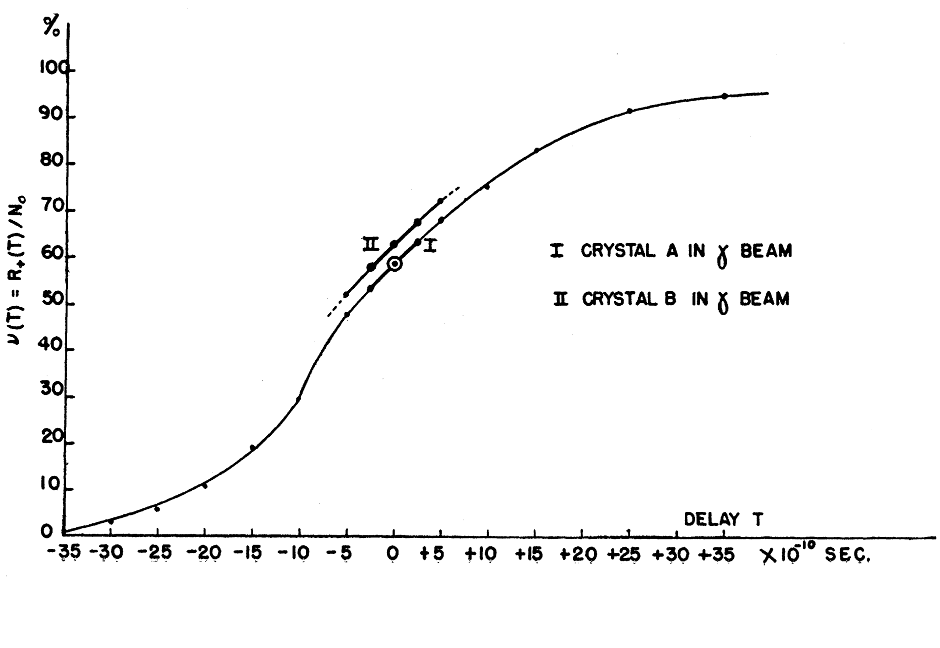

FIG. 3. Differential de-delay coincidence curves.

coincidences, we used light absorbers for adjusting amplitude distributions as previously described.[3] Figure 2 shows the respective pulse-height distributions (taken in coincidence with the output of the C circuit) in detector A when excited by scattered gammas (average energy $\sim$360 kev), and when excited by primary gammas and a proper light absorber is placed between crystal and photomultiplier. The rms difference of the corresponding ordinates is 2.6 percent. A light absorber of the same transparency as used in detector A was necessary to equalize the pulse-height distributions for the two radiations in detector B. To utilize higher counting rates in the coincidence measurements we use the D_+ output[3] to gate the output of the C circuit (counting rate N_0), obtaining thereby $R_+(T)$, and then plot $\nu(T)=R_+(T)/N_0$ *versus* T. The linear portion of such a curve can be used to measure very short time delays.[6] When one changes from a "prompt" source to the source producing delayed events [probability density function $p(t')$ for the delay t'], the change $\Delta\nu$ of the ordinate at a chosen T is

$$\Delta\nu=\mu_1(p)d\nu/dT, \tag{1}$$

where $\mu_1(p)$ is the average time delay [first normalized moment of $p(t')$]. In our case (reversing the excitations in the channels) no prompt source is needed and $\Delta\nu$ is twice as large. Equation (1) thus gives $2\mu_1(p)$, or twice the average time delay. In Fig. 3 the entire delayed coincidence curve is shown for the case (1) when crystal A is in the beam, and only part of the delayed coincidence curve for the reversed case (2). We measured $\Delta\nu$ at $T=0$, recording $\sim$1300 coincidences for each case and repeating the measurements so that all together $\sim$13 000 coincidences were involved. The slope $d\nu/dT$ was measured separately between $T=-2.5\times10^{-10}$ second and $T=+2.5\times10^{-10}$ second. The average time delay was found to be $\mu_1(p)=(5\pm1.5)\times10^{-11}$ second, where the error is the standard deviation of the total set. The average time of flight calculated from the geometry was 4.5×10^{-11} second. After subtracting this from μ_1, the remaining part is within standard deviation. Thus the average time delay between the emission of the two Compton electrons e and e' is $\langle t'\rangle=\langle t\rangle+\langle\tau\rangle\leq1.5\times10^{-11}$ second.

As a summary, we may say that the emission of an electron and a scattered gamma in the Compton process is simultaneous with the incident gamma within a time of $\sim10^{-11}$ second. In addition, the mean time length of the outgoing γ' wave train is also less than 10^{-11} second. Quantum theoretical time uncertainties for the release of electrons from atomic bonds and the time length of the accompanying scattered-gamma wave train are smaller than 10^{-19} second and are thus far below the limits of present techniques.

[6] Bay, Meijer, and Papp, Phys. Rev. 82, 754 (1951).

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Connection Between Dirac's Electron and a Classical Spinning Particle

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A connection is established between the classical and wave mechanics of a spinning relativistic particle. In the case of a plane wave comprising both positive and negative energies, the 4-dimensional stream-lines of the current density 4-vector coincide with the world-lines of a classical particle. Moreover, the wave function represents the spinor (or quaternion) which determines the generalized intrinsic frame of reference attached to the world-line of the classical particle. This provides a geometrical interpretation for the unquantized Dirac field as well as for the total angular momentum.

ATTEMPTS have been made to establish a connection between Dirac's electron in wave mechanics and a classical relativistic spinning particle. Among others, Weyssenhoff[1] has sought properties of the spinning particle which were similar to the quantum-mechanical properties of the electron, without, however, explaining these similarities. Huang[2] has shown that a wave packet in Dirac's theory moves in the first approximation like a spinning particle in Weyssenhoff's classical theory. More recently, de Broglie[3] finds a relation between Dirac's electron and a Weyssenhoff particle by applying the W. K. B. approximation to the wave equation.

The purpose of this note is to report some results connected with this problem which were obtained from a general geometrical theory of world-lines. In the case of a plane-wave solution of Dirac's equation involving states of both positive and negative energy

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[2] K. Huang, Am. J. Phys. 20, 479 (1952).
[3] L. de Broglie, *La théorie des particules de spin* ½ (Gauthier-Villars, Paris, 1952).