Simultaneity in the Compton Effect† ††

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The Bothe-Geiger experiment has been repeated under improved conditions of time resolution, obtained by using stilbene scintillation counters. The recoil electron and scattered photon are emitted together within a time interval of less than 1.5×10^{-8} second. The electron and photon are also projected without a delay larger than 1.5×10^{-8} second after arrival of a quantum. The familiar concepts used in discussions of the Compton effect are shown to be valid.

I. INTRODUCTION

A CELEBRATED experiment by Bothe and Geiger[1] (1925) demonstrated that in a single Compton encounter the recoil electron and scattered photon appear simultaneously. Simultaneous, in this experiment, meant "occurring together within a time interval of 10^{-3} second." This experiment was important at its time since it differentiated sharply between the theory of the Compton process as we now know it[2] and an alternative theory[3] in which the recoil electron and photon are not simultaneous and in which the conservation laws of energy and momentum hold only in a statistical manner.

Later events[4] have confirmed the original picture of Compton. Although in 1936 some doubt was expressed concerning simultaneity in the Compton process[5] the work of many investigators showed that the original experiment of Bothe and Geiger was correctly interpreted. The later investigators[6–11] however, did not reduce the measured interval of simultaneity to less than 10^{-4} second. The results of the quoted experiments rest on statistical interpretations of the data in which half (or more) of the coincidence observations were assigned to chance or background effects. Thus, the number of coincidences constituted a small fraction of the total number of observed coincidences. There is little doubt that the interpretations were correct. However, it has generally been stated by the authors of the papers, that a clear-cut and unequivocal proof of the individual Compton process was still lacking.

The purpose of this paper is to show that such a direct proof can be given and that the Compton process is indeed simultaneous within a period of 1.5×10^{-8} second or less. These results are made possible by the advances in fast counting techniques in the last two years.

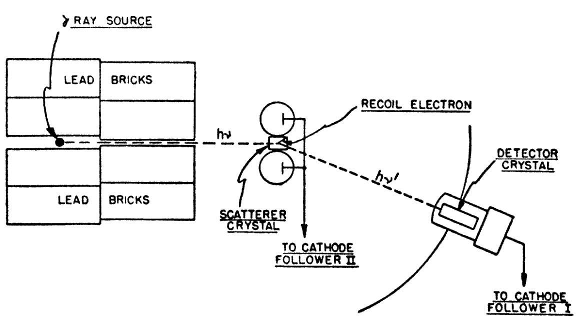

Fig. 1. Sketch of Compton scattering apparatus.

II. EXPERIMENTAL

A. Apparatus

Figure 1 shows a schematic view of the experimental arrangement.[12] The source of radiation is a cobalt rod of dimensions, $\frac{1}{8}$ in. diam.$\times\frac{3}{8}$ in. long, which emits the radiation Co^{60} (1.17, 1.33 Mev). The source strength is approximately 20 millicuries. A fine pencil of gamma-rays is formed by collimation of the radiation by a channel ($\frac{1}{8}$ in.$\times\frac{1}{8}$ in.) in two adjoining lead blocks of total path length 27.5 cm.

The pencil of gamma-rays passes through a "scatterer" crystal cube of stilbene ($\frac{1}{2}$ in. on a side). Figure 2 shows the trace left by this gamma-ray beam in a photographic plate (Eastman 103-0) placed at the position of the crystal. The outline of the stilbene scatterer is also shown in its relative position as used in the experiment. It may be seen that the beam is small, well collimated and passes through the middle of the crystal cube. Two matched (1P21) photo-multiplier tubes view the scatterer crystal. The electrical outputs of these photo-multiplier tubes are connected in parallel. The scatterer crystal, as implied by its name, is used as a scatterer but actually has a double function since it also provides the recoil electron light pulse or scintillation which the photo-multiplier tubes detect.

The scattered photon, in general leaves the scatterer

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[1] W. Bothe and H. Geiger, Zeits. f. Physik **32**, 639 (1925).
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[3] Bohr, Kramers, and Slater, Phil. Mag. **47**, 785 (1924).
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and moves out into the surrounding air. A second longer stilbene crystal, which we have called the "detector," is placed in a position on a circle around the scatterer, as shown in Fig. 1. Some of the scattered photons will have Compton encounters with the electrons of this crystal thus again producing electron recoil pulses. The detector crystal is a rectangular parallelopiped of dimensions $\frac{1}{2}$ in$\times\frac{1}{2}$ in.$\times 1$ in., and is viewed by a pair of matched photomultipliers connected in parallel. Thus if the Compton process is simultaneous, some coincidences in time should be observed between the pulses in the scatterer and detector. In most of the experiments the center of the detector was placed at a distance of 7.3 cm from the center of the scatterer. The detector crystal therefore subtends a plane angle of approximately 10° at the center of the scatterer.

The detector is placed on a "spectrometer" arm and may be placed at various distances, up to 30 cm from the center of the scatterer crystal. Thin metal housings for both sets of photo-multipliers are used to shield the tubes from undesired light signals.

The coincidences have been detected by photographing the scatterer and detector pulses on an oscilloscope screen. Figure 3 illustrates the method used. In the figure each pair of photo-multipliers is connected with a cathode follower through a pulse shaping circuit. The cathode followers are connected to fast amplifiers with half-power point, on the high frequency side, at 19 megacycles/second. The amplifier and pulse shaping circuit designs are due to W. C. Elmore.[13] The connections to the amplifiers are made through coaxial lines which are used for delay purposes.

The pulse from the detector cathode follower is taken also to the sweep circuit of a cathode-ray oscillograph[14] through a Model 501* amplifier. The delay line I in the detector circuit is long enough (200 feet) to allow the rise of the detector pulse to be seen. The delay thus allowed for is the time necessary for the trigger circuit to start a sweep. The amplifier pulse in the detector circuit is applied to the upper plate of the pair of vertical plates of the oscillograph, as shown in Fig. 3. Typical stilbene detector traces are shown in Fig. 4 labeled "a."

The scatterer circuit resembles the detector circuit

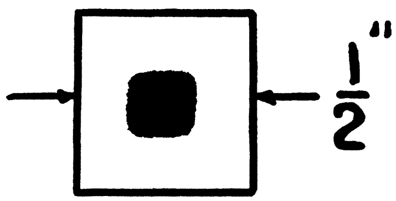

FIG. 2. Photograph of gamma-ray beam at position of scatterer crystal. The outline is that of the stilbene scatterer.

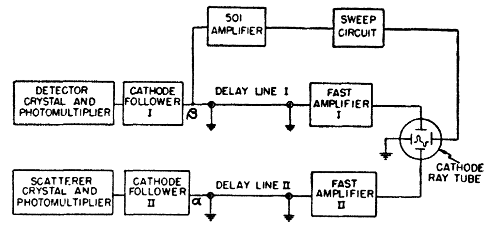

FIG. 3. Block diagram of scheme for detecting small time differences.

except that a longer delay line II is used (290 feet) and the 501 amplifier is dispensed with since the useful trigger is already supplied by the detector circuit. The amplifier output of the scatterer circuit is brought to the lower vertical plate of the CRO. Whereas the detector crystal provides an "up" pulse as seen in Fig. 4 marked "a," the scatterer supplies a down pulse, delayed with respect to the detector pulse, as shown in "b" of Fig. 4. If the detector and scatterer pulses are truly simultaneous then the corresponding time interval between the two pulses should be the same as the time interval when known simultaneous pulses are applied to the detector and scatterer circuits. If simultaneous, the delay between the two pulses in the typical Compton traces should be due merely to the difference in length of the delay lines I and II.**

Not all traces initiated by the detector correspond to Compton encounters originating from the collimated Co^{60} beam. Room contamination, natural background gammas and cosmic rays may actuate the detector crystal without a corresponding down pulse such as is observed in the Compton encounters. The traces marked "a" in Fig. 4 represent such background pulses. Those marked "b" are the true Compton double pulses. In this experiment, the discriminator bias of the triggered sweep circuit was set at such a value that only those traces appeared whose detector pulses were larger than about four or five times the average height of noise pulses. If noise pulses were permitted to trigger the sweep many more traces would have been observed but photography of the pulses would have been made difficult by the superposition of a large number of pulses. In the experiment at 90°, Fig. 7, the bias was lowered somewhat to permit smaller detector pulses to be observed.

Recoil electrons which are produced by Compton encounters in the scatterer may be projected or scattered in directions to enter the detector and cause spurious simultaneous pulses. In this experiment, such "electron coincidences" have been avoided by placing a $\frac{1}{16}$-in. absorber sample of aluminum in front of the detector.

[13] W. C. Elmore, to be published.
[14] V. Fitch and E. W. Titterton, Rev. Sci. Inst. **18**, 821 (1947).
* Rise time 1.0×10^{-7} second, gain $3\times10^{+5}$.

** The transit time of electrons in the photomultiplier tubes ($\sim 2\times10^{-8}$ second) cancels out when the difference in time between two pulses is measured. The spread in transit times is too small to measure with this apparatus (R. D. Sard, J. App. Phys. **17**, 768 (1946)).

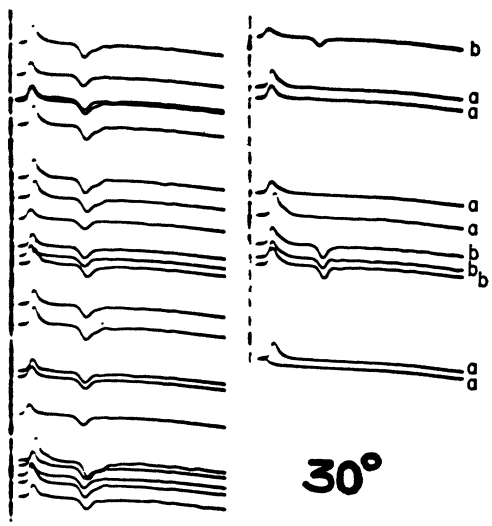

FIG. 4. Synthetic and Compton pulses at 30°. Time interval between peaks is 0.16 microsecond.

B. Calibration

Figures 4–7 show samplings of results obtained at photon scattering angles of 30°, 50°, 70°, and 90°. At 30° and 50° whole sections of the film are reproduced as originally taken. At 70° and 90° the Compton pulses occur at a low rate so that individual "b" type traces were taken from the film and collected together for the composite pictures used in the figures. Each of the "b" type traces is clear evidence for the individual Compton process.

At the left in Figs. 4 and 5 synthetic simultaneous pulses are shown. These pulses were obtained by opening the scatterer circuit at point α in Fig. 3 and supplying delay line II and scatterer amplifier with the detector pulse from β. The detector circuit was undisturbed otherwise. The detector pulse therefore appears in both the up and down positions, the up pulse corresponding to amplifier I and the down pulse to amplifier II. This method of obtaining simultaneous pulses will be called "method A."

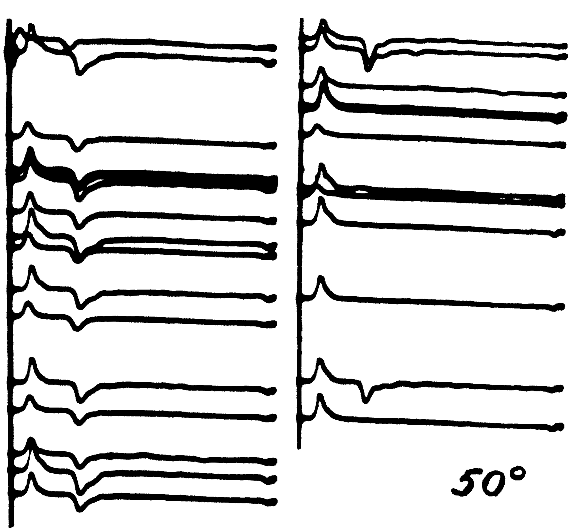

FIG. 5. Pulses at 50°.

Figure 8 shows synthetic simultaneous pulses produced by method A and a calibration signal from a 10-megacycle standard oscillator. It can be seen that the time interval between the pulse peaks is approximately 0.16 microsecond. It may also be observed that the sweep is not exactly uniform and thus the time scale not exactly linear with distance.

Method A does not really provide "true simultaneous" pulses in our comparison for the reason that the scatterer photo-multipliers and the cathode follower of the scattering circuit have not been used in exactly the same manner as in investigating Compton traces. To test this point we have placed one each of the detector and the scatterer photo-multipliers (the former without detector crystal present) adjacent to the scatterer crystal. Thus both photo-multipliers view the same pulses in the same crystal—the scatterer. Both pulses are now amplified and treated in the same manner as in studying Compton pulses. This method of obtaining precise simultaneous pulses gave results exactly equivalent to those of method A within the experimental error. We have preferred method A for most of our work since only small changes in the electrical connections are required in going from Compton traces to such simultaneous traces. More elaborate changes in the equipment are required in going from Compton traces to the traces of method B.

When the initiating detector pulse is small (bottom of Fig. 4) the sweep is observed to start at a position on the screen somewhat displaced to the left of the starting place for a large detector pulse. This, of course, is due to the time taken for the signal to reach the bias level of the sweep trigger circuit. In a large pulse the rise is steep and the time small. For a small pulse the time is roughly half the pulse base when converted to time units and therefore relatively long. As a consequence, traces appear in slightly different parts of the screen and are subject to the effects of non-linearity of the sweep. This fact has resulted in small variations in the distance between peaks in the pulses of methods A and B and in Compton coincidences. We have observed a maximum variation in the time-equivalence of the peak-to-peak measurements of about 1.5×10^{-8} second. This is considered to be the largest source of experimental error in the measurements here reported.

In Fig. 9 the upper trace shows a sample of an accidental occurrence of a scatterer pulse in the sweep interval of about 0.52 microsecond. The rate of occurrence of such accidentals can be estimated from the separate counting rates of scatterer and detector and is of the order of two per thousand traces. Our experimental data indicate two accidentals in 1137 traces.

III. RESULTS AND OBSERVATIONS

Figures 4–7 show at a glance that the Compton pulses are simultaneous to within 2×10^{-8} second. This value may be narrowed a little by more careful measurements, described below.

The pulses of Figs. 4, 5, 6, and 7 have been measured, along with many others, and compared with the traces of method A, such as those shown at the left in Figs. 4 and 5. Table I summarizes the results so obtained. In each of the 89 traces measured, the recoil electron and

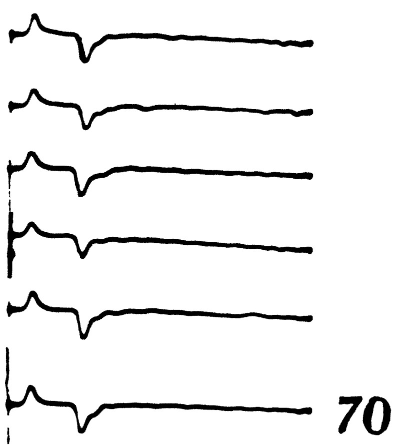

FIG. 6. Compton coincidences at 70°.

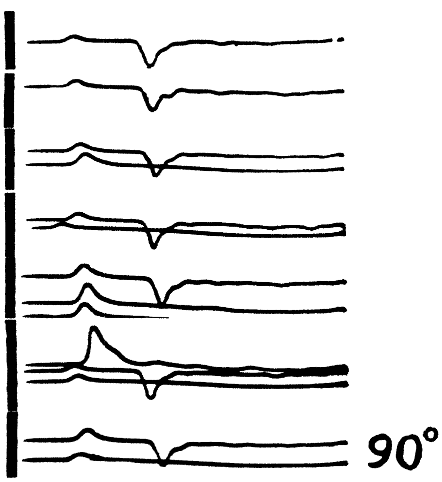

FIG. 7. Compton coincidences at 90°.

scattered photon pulses lie within $\pm1.5\times10^{-8}$ second of the standard 0.16 microsecond delay interval. We have excluded obvious accidental "near coincidences" of the type of Fig. 9 which occur in 0.2 percent of all traces. We consider this a proof that the Compton process is a simultaneous one wherein simultaneous means "occurring within an interval of 1.5×10^{-8} second." It would seem that there can be no doubt about simultaneity because of poor statistics of the data. Further since there is no difference outside the

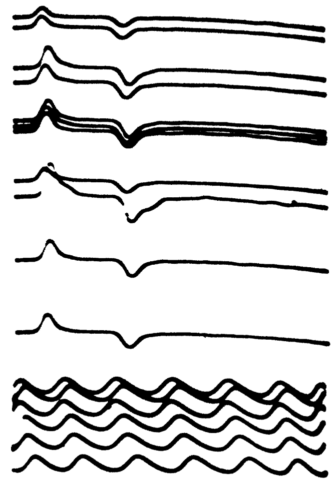

FIG. 8. Synthetic simultaneous pulses and calibrating 10 megacycle signal.

experimental error between the Compton pulses and the synthetic pulses obtained with delay lines, we may say that there is no constant or variable delay between arrival of the incident photon and the emission of recoil electron and scattered photon. This observation agrees with the experiment of Piccard and Stahel (1936).[15]

It may be observed that the scattered photon pulses are, on the average, larger than the recoil electron pulses at the angular position of 30°. In this position the photon has the average energy of 0.96 Mev while the recoil electron has the average energy of 0.29 Mev. At 90° the photon energy is 0.38 Mev and the recoil electron 0.87 Mev. At 55° scattering angle the energies are equal. It can be seen from Figs. 4–7 how these facts are reflected in the pulse heights. An exact correlation cannot be expected because of the varying energy given up by the scattered photon to the detector crystal and the relatively poorer optics of that system. The scatterer system has better optics since all light pulses originate in or near the center of the stilbene cubes (see Fig. 2). In fact, the observations made with method B show that the light flashes detected by two photo-

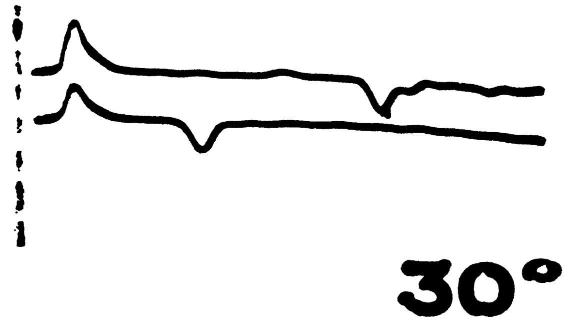

FIG. 9. An accidental "near coincidence."

[15] A. Piccard and S. Stahel, J. de phys. et rad. **8**, 326 (1936). See also Hoffman, Shenstone, and Turner, Phys. Rev. **50**, 1092 (1936).

TABLE I.

Total number of intervals measured	89
Standard deviation of set	5.5×10^{-9} second
Outside limits	$\pm10\times10^{-9}$ second
Difference between averages of Compton and true simultaneous intervals.	-5.0×10^{-9} second

multipliers, facing two opposing sides of the stilbene cube, are within 20 percent of each other. The recoil electron light pulses in the scatterer are also quite uniform at any given angle. Examples of this behavior can be seen in Figs. 4–7.

From a study of the various figures it can be seen that the stilbene pulses apparently have a decay time which lies within or possibly just outside the rise time of our amplifier. These pulses are therefore well matched to this problem. It can be seen in Fig. 10 that the decays are longer in materials such as naphthalene, anthracene, and naphthalene-anthracene. In these cases the scatterer has been made of the materials quoted. In all cases the detector has been a stilbene crystal. The results also show that the stilbene pulses have a rise time less than 1.5×10^{-8} second.

A final incidental observation may be made to the effect that the method outlined may be used to provide a source of gamma-rays varying from the value of the homogeneous incident pencil of gamma-rays down to a value of about 200 kilovolts at 180°.

IV. CONCLUSIONS

A finding of non-simultaneity would be of great physical significance[16–19] if the interval of time were larger than the expected quantum-theoretical interval. The quantum-theoretical expectation values of observing the recoil electron and the scattered quantum are high when the time interval is of the order λ/c where λ is the Compton wave-length and c the velocity of light. This time is of the order of 10^{-20} second and so lies much beyond the limit of present technical skills. Nevertheless, the experiment here reported represents the closest approach to the theoretical time limit which has so far been demonstrated. The experiment shows clearly the validity of the concepts used in the familiar derivations of the Compton formulas.

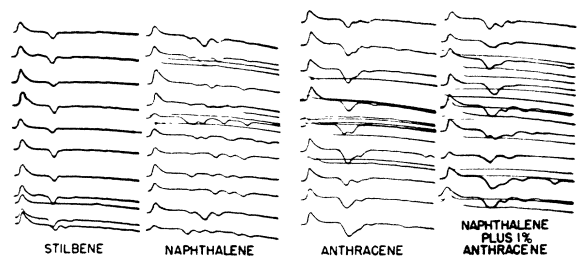

FIG. 10. Compton coincidences using stilbene, naphthalene anthracene and naphthalene+1 percent anthracene as scatterers.

V. ACKNOWLEDGMENT

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[16] P. A. M. Dirac, Nature **137**, 298 (1936).
[17] E. J. Williams, Nature **137**, 614 (1936).
[18] R. Peierls, Nature **137**, 904 (1936).
[19] N. Bohr, Nature **138**, 25 (1936).