Search for the Splitting of Gamma-Ray Photons in the Electric Field of the Nucleus*

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A search has been made for an effect predicted by quantum electrodynamics closely connected with vacuum polarization, namely, the splitting of gamma-ray photons in the electric field of the nucleus. The scattering of 1.1-MeV gamma rays from a 2-Ci source of Zn^{65} in various target elements has been investigated. The spectrum of the sum of the two photon pulses appearing simultaneously in two NaI(Tl) scintillating crystals, situated at backward angles with respect to the target, was recorded over long periods of time. Evidence for the production of photon pairs, whose energy sum is equal to that of the original incident photon, has been obtained for copper and cobalt nuclei. For photon pairs produced in these nuclei, at average angles of 105° with respect to the incident photon direction, and of 130° with respect to each other, we estimate the differential cross section to be $(3\pm1)Z^2(\Delta w/mc^2)10^{-35}$ $cm^2/(sr)^2$, where Δw is the energy interval corresponding to one component of the pair. This is about six times larger than the value predicted theoretically by Shima. However, double Rayleigh scattering from bound electrons may also contribute to the splitting process, and no exact quantitative calculations of this have yet been made.

1. INTRODUCTION

WE report here the results of a search for the existence of a nonlinear effect predicted by quantum electrodynamics, namely, the splitting of an incident photon, in its interaction with the nuclear charge, into two emerging photons. This process arises basically through the interaction involving virtual positron-electron pairs and is closely related to Delbrück scattering of light by light. All three, being vacuum polarization phenomena, are described by closed-loop Feynman diagrams [Figs. 1(a), 1(b), 1(c)].

The predicted cross section for the scattering of light by light[1] is extremely small and the process has so far not been observed. While the predicted cross section for Delbrück scattering is appreciable at energies around 1 MeV, and many experiments have been carried out, the interpretation at these energies is hindered by lack of sufficiently detailed theoretical knowledge of scattering amplitudes and relative phases of the Delbrück and Rayleigh contributions.[2,3] At higher energies, however, experiments seem to confirm theoretical predictions.[4,5]

The magnitude of the expected photon splitting has been discussed in the theoretical works of Williams,[6] Bolsterli,[7] Shima,[8,9] Sannikov,[10] Bukhvostov *et al.*,[11] and Talman.[12] Experimentally, the effect is characterized by the simultaneous appearance of two photons whose energy sum is equal to that of the original incident photon. Competing processes which must be considered as possibly producing similar events are double Rayleigh scattering from bound electrons[12,13] with the production of two photons, and double nuclear Compton scattering [Fig. 1(d)].

In this work the scattering of 1.1-MeV photons in various target elements has been investigated. Despite the extremely low cross section expected, which is about 10^{-32} $cm^2/(sr)^2$ for Z around 30, strong indications of the production of photon pairs in the expected spectral range have been obtained for copper and cobalt.

2. EXPERIMENTAL DETAILS

The experimental setup used is shown in Fig. 2. This includes a 2-Ci source of 1.1-MeV gamma rays

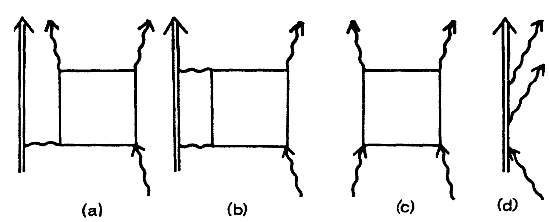

FIG. 1. Feynman diagrams: (a) vacuum polarization contribution to photon splitting; (b) Delbrück scattering; (c) scattering of light by light; (d) double Compton scattering by nuclear charge (double Thompson scattering).

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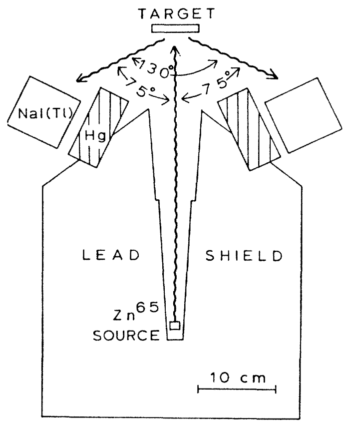

FIG. 2. Experimental setup. Solid angle extended by scattering target at source, $3\times10^{-3}\times4\pi$ sr, and by each detector at target, 0.12 sr.

(Zn^{65}) in a lead collimator, the scattering target, two photon detectors [3-in×3-in NaI(Tl) crystals mounted on 58 AVP photomultipliers] situated at backward angles, and mercury shields between the detectors to minimize the scattering of radiation from one detector to the other. The spectrum of the sum of the photon pulses appearing simultaneously in the two detectors was recorded electronically. Since the rate of events expected to satisfy the energy condition for splitting did not exceed about one every few hours while single scattered photons (mostly through Compton scattering) appeared at each detector at the rate of about 3×10^4/sec, it was found essential to develop electronic circuitry which is both fast and stable over long periods of time.

Two fast-coincidence circuits (resolving time 20 nsec), one set to respond to prompt events and the other to delayed events, with suitable gates, were employed to enable pulses from the detectors to be added and recorded concurrently in two sets of channels of a multichannel pulse-height analyzer, according to whether the events were prompt or delayed. The recorded spectra were limited to events in which the energy of each single component was greater than 420 keV. Pileup rejection circuits[14–16] for each detector were used in order to minimize spectrum distortion at the high single counting rate. To ensure that prompt and delayed events are recorded with the same efficiency, the prompt and delayed modes of operation were automatically interchanged between the two fast-coincidence circuits at the end of every minute.

3. RESULTS AND DISCUSSION

Survey experiments were carried out using targets of different Z, and it turned out that intermediate-Z targets proved to be favorable from the point of view of separation of true splitting events in the sum spectra around 1.1 MeV from background coincidence events producing a tail in the sum spectra almost up to 1.1 MeV by various processes (e.g., successive bremsstrahlung from photoelectrons, and annihilation of positrons formed in pair production accompanied by Compton scattering of one or both photons). We show, therefore, in Figs. 3(a) and 3(b) results obtained from copper and cobalt targets when the direction of the detected scattered photons form a backward angle of 75° with the incident photon beam, and 130° among themselves. Since copper and cobalt are very close in atomic number and the separate results were very similar, they were combined in the figure. Figure 3(a) shows the prompt and delayed sum spectra; the true coincidence spectrum (prompt minus delay) is shown in Fig. 3(b). Figure 3(c) shows the corresponding prompt, delayed, and true spectra in the absence of any scattering target. This background spectrum above 1.1-MeV coincides, in fact, with the tail of the spectrum of Fig. 3(b) obtained in the presence of the target, and is

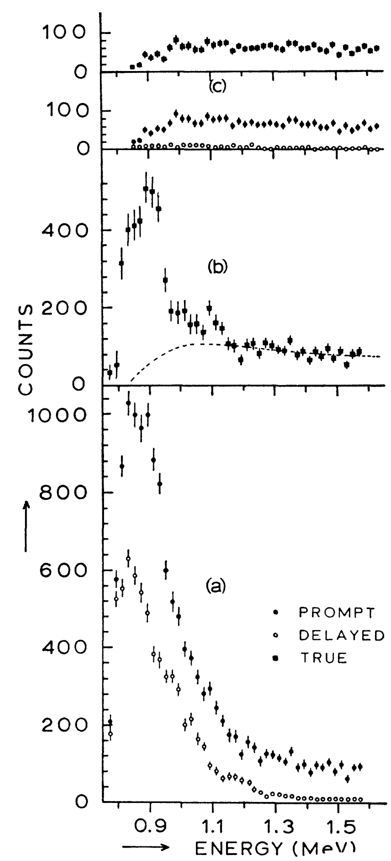

FIG. 3. Spectra of the sum of the energies of photons absorbed simultaneously in the two detectors. (a) Prompt and delayed sum spectra combined from a copper target (362 h, source strength 2.5×10^{10}/sec) and a cobalt target (510 h, source strength 1.9 $\times10^{10}$/sec). Both targets 0.35 cm thick. (b) "True" events (prompt minus delayed) derived from (a). Broken curve corresponds to "true" background from (c) suitably normalized. (c) Prompt, delayed, and "true" sum spectra recorded in the absence of any scattering target.

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almost certainly due to cosmic rays. Altogether, the measurements leading to Fig. 3 lasted a total of 1350 hours during which daily calibrations of the measuring system were performed.

Most of the true events at the lower energy end of the spectrum in Fig. 3(b) can be accounted for by successive scattering events in the target, such as successive bremsstrahlung of photoelectrons or annihilation photons from positrons created in pair production. Although the detectors were not in line with the target, an annihilation photon pair can still be recorded if one of the components undergoes scattering in the target. These contributions tail towards 1.1 MeV, the energy of the primary photons, and thereby make it difficult to discern distinctive features of a monoenergetic sum at that energy. Nevertheless, there is undoubtedly an excess of events above background at 1.1 MeV and moreover there is rather convincing evidence for a peak in the sum distribution at this energy. We think that most of excess events above background around 1.1 MeV are very probably produced by splitting events. (Experiments carried out with aluminum, tin, and bismuth targets all showed an accumulation of true sum events around 1.1 MeV. The corresponding derived cross sections fit quite well a Z^2 dependence; this provides further confirmation that the sum events recorded around 1.1 MeV do not result predominantly from the tail of the spectrum produced by coincidence photons in successive scattering for which a much higher Z dependence is expected.)

We estimate the probable number of splitting events recorded in 872 h with copper and cobalt targets to be about 120. From this number we estimate the differential cross section for $Z\sim 28$ to be

$$(3\pm 1)Z^2(\Delta w/mc^2)\ 10^{-35}\ \mathrm{cm}^2/(\mathrm{sr})^2,$$

where Δw is the energy interval corresponding to one component of the pair.

Shima,[8,9] using Feynman's relativistic formulation of quantum electrodynamics, has calculated cross sections for splitting arising through nuclear electric fields, regarding the nucleus as a point charge of infinite mass, and has obtained a general formula for the cross section giving the energy and angular distribution of the splitting components. He has also worked out numerical values for many cases of interest. For the geometry employed in this experiment he predicts[17]

$$5.2\times 10^{-36}Z^2(\Delta w/mc^2)\ \mathrm{cm}^2/(\mathrm{sr})^2.$$

This is six times smaller than the value observed by us. There is as yet however, no exact quantitative theory of the contribution of double Rayleigh scattering from bound electrons to the splitting process, although Talman's[12] rough estimates for medium Z suggest that the relative contribution should be quite small.

In conclusion, we repeat that the results for $Z\sim 28$ strongly indicate the existence of photon splitting. However, in the absence of accurate quantitative predictions on double Rayleigh scattering and in view of the possible oversimplification in treating the nucleus as a point charge of infinite mass in Shima's calculations of the vacuum polarization contribution, it is difficult at this state to separate with certainty the various contributions. Neither of the expected theoretical cross sections for nuclear Raman excitation[18] or for double Compton scattering from nuclear charge[7] is comparable to that observed.

There seems to be no doubt that modern experimental techniques are now adequate to measure processes of the type discussed here despite the small cross section. We may, therefore, expect that further experimental and theoretical work will lead to an elucidation of these basic interactions. Of great importance, for example, would be a measurement of the energy spectrum and angular distribution of the photon pairs.

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