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ARE PHOTON-PHOTON SCATTERING EXPERIMENTS FEASIBLE?

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A B S T R A C T

The significance of photon-photon scattering experiments and the experimental possibilities are discussed. The following techniques are mentioned: laser beams clashed with high energy γ ray beams, flash X-ray machines, nuclear explosions, synchrotron radiation, clashing of two γ ray beams.

1. INTRODUCTION

In this paper we discuss the significance and the experimental possibilities of seeing photons scattered on photons. Some more details are given in Ref. ¹⁾.

The essentially quantum-mechanical effect of light scattering on light in vacuum has never been observed ²⁾. This is mainly due to the extremely small cross-section, particularly in the visible range, where it is of the order of 10^{-65} cm^2 . Denoting by E_{cms} and θ the energy of one of the photons and the scattering angle in the cms, by m_e the electron mass, then, the elastic photon-photon differential cross-section can be written in good approximation as ³⁾

$$\begin{aligned} \frac{d\sigma}{d\Omega} &\approx 0,23 \cdot 10^{-31} \frac{(3 + \cos^2 \theta)^2}{4\pi} \left(\frac{E_{\text{cms}}}{m_e} \right)^6 \frac{\text{cm}^2}{\text{sterad}} ; \text{ if } E_{\text{cms}} \leq \frac{1}{2} \text{ MeV} \\ \frac{d\sigma}{d\Omega} &\approx 4,2 \cdot 10^{-31} \left(\frac{m_e}{E_{\text{cms}}} \right)^2 \begin{cases} [\ln(\frac{E_{\text{cms}}}{m_e})]^4 & \text{at } \theta = 0 \\ 1 & \text{at } \theta = \frac{\pi}{2} \end{cases} ; \text{ if } E_{\text{cms}} \gg \frac{1}{2} \text{ MeV} \end{aligned} \quad (1)$$

The $d\sigma/d\Omega$ goes through a maximum at $E_{\text{cms}} \approx 1.75 \text{ MeV}$ for $\theta = 0$, and $E_{\text{cms}} \approx 0.7 \text{ MeV}$ for $\theta = \frac{\pi}{2}$. At these points its value is respectively $4.1 \cdot 10^{-31} \frac{\text{cm}^2}{\text{sterad}}$ and $2.8 \cdot 10^{-31} \frac{\text{cm}^2}{\text{sterad}}$. Equation (1) is not to be believed when E_{cms} is high because, when deriving it, the existence of all particles, except photons and electrons, was neglected.

The results of photon-photon (hereafter written as $\gamma + \gamma$) scattering experiments when compared to available calculations at low energies ($E_{\text{cms}} \lesssim 10$ MeV), could be used to test quantum electrodynamics involving four photon divergent graphs. Any disagreement would be a great surprise ⁴⁾. For example, evidence for direct four photon interaction (not mediated by known virtual particles) would make the search for the W meson much less meaningful. At higher energies $\gamma + \gamma$ scattering experiments could yield information, without the overwhelming interference of unwanted strong interactions, about the two photon form factors of hadrons. [Only exceptionally is this possible with lepton storage rings ⁵⁾.] These could be compared with group theory predictions. The controversial $\pi, \eta \rightarrow 2\gamma$ form factors could be studied. Charge conjugation could be tested, searching for the appropriate final states, e.g., (in principle at least) $2\gamma \rightarrow 3\gamma$. All charged particles are expected to be produced at comparable rates, including the W , and the possible heavy electrons $\bar{e}$. A systematic search for resonances may be feasible if the experiments are good enough. One can study the propagator (whenever meaningful) of all charged particles, including (in contrast with electron storage rings) $\mu, W, \bar{e}$. The polarizations of the colliding γ can be manipulated directly ⁶⁾, the γ are real ¹⁾.

2. EXPERIMENTAL TECHNIQUES ^{1), 4)}

- a. Laser beam clashing with high energy γ -ray beam ⁷⁾, combines the advantages of one high intensity (but low energy) source with those of a high energy (low intensity) source ($E_{\text{cms}} \lesssim 1$ MeV). In this section, laser beam quanta will be referred to as "photons", and those in the γ ray beam as " γ ". Their laboratory energies will be denoted by ω and Ω respectively, and α is the laboratory angle formed by the two incoming quanta. Then $E_{\text{cms}} = \sqrt{2\omega\Omega(1-\cos\alpha)}$.

A Q switched ruby laser can produce 10^3 MWatt intensities in 30 nanosecond pulses ⁸⁾, with $\omega = 1.78$ eV. Such a beam can be considered a "stationary (i.e., low energy) photon target" containing about 10^{20} photons, 9 metre long, and whose shape can be manipulated optically.

To estimate the possibilities consider two, hopefully realistic, examples:

The SLAC machine, in stage I of its development ⁹⁾, could be used to produce bremsstrahlung γ rays, which could collide with the photon target. Let us choose $\alpha = \pi$ and a laser beam radius of 1 mm. Even if one considers only γ rays with Ω between 15 and 16.5 GeV, one expects the number of elastically scattered γ pairs per laser pulse to be $N \approx 2 \cdot 10^{-4}$. In stage II, if one considers only γ with $30 \text{ GeV} \leq \Omega \leq 33 \text{ GeV}$, one expects $N \approx 1/3 \cdot 10^{-2}$.

A 200 GeV machine capable of producing 10^{12} primary particles in nanosecond bunches, could be used to produce π^0 , decaying into γ , which in turn collide with the photon target. With the same parameters as above, and considering only $150 \text{ GeV} \leq \Omega \leq 165 \text{ GeV}$, one expects ¹⁰⁾ $N \approx 2.5 \cdot 10^{-2}$.

The counting rates can be improved by using higher intensity primaries, more than one laser, and mirrors ¹⁾. At SLAC, short 1 A pulses were planned and we assume that they will become available there or at some other machine; that at least ten lasers can be temporarily used for the present purpose; that the laser beam can be rescattered at least 100 times. Then, the number of $\gamma + \gamma$ elastic scattering events between two successive firings of the same laser will be at least 4, and 60 at SLAC for stage I and II respectively. An analogous increase in counting rate for the 200 GeV machine is expected. A further increase can be gained by considering a larger $\Delta\Omega$ range.

Most γ rays will be scattered close to the forward direction. Therefore, good collimation of the incoming γ is imperative. This question is discussed in more detail in Ref. ¹⁾ where the expected angular distributions are also given. In the above estimate, losses due to collimators and shields are not taken into account.

- b. Flash X-ray machines ¹¹⁾ could be used to clash to X-ray beams, ($E_{\text{cms}} \lesssim 10$ MeV). For purposes of an estimate, consider a machine with parameters similar to those now built commercially ¹²⁾. Machines specifically built for the present purpose may well perform better. Consider a Marx generator running into a Blumlein generator, the pulse of which is applied to an X-ray tube with 10 MV voltage and capable of producing 1000 r at one metre distance in 60 ns pulses.

$\gamma + \gamma$ elastic scattering. Available intensities permit the measurement of the integral over E_{cms} of the cross-section. The dominant contribution will come from the maximum region [See Eq. (1)]. Place n machines on a circle with radius L and shields to absorb all γ leaving the source at an angle $> 45^\circ$ with the plane of the circle. Detect those pairs of photons which are scattered close to perpendicularly to this plane. If all machines are scattered simultaneously, then the number of elastic scattering events per flash is of the order of

$$N(\gamma + \gamma \rightarrow \gamma + \gamma; n) \approx \frac{1}{5} n(n-1) ; \text{ if } 1 \text{ cm} < L \lesssim 10^2 \text{ cm} \quad (2)$$

$$2 \leq n \leq 6$$

Electron pair production. Available intensities permit measurement of differential cross-section. Place two flash X-ray sources $3L$ cm from each other. Suppose $2L$ cm of this are used up by shields, and L cm is the interaction region. Collimate the two X-ray beams to K radians and collide them head on. To decrease background, detect those electrons emitted at large angles to the X-ray beams. The number of pairs produced ³⁾ per flash is of the order of

$$N(\gamma + \gamma \rightarrow e + e') \approx \frac{1}{2} 10^4 K^2 \{\text{radian}\} / L \{\text{cm}\} ; \text{ if } L \leq \tau \cdot c \quad (3)$$

where c is the velocity of light.

- c. Nuclear explosions ^{*)}. The total energy yield of a 100 kiloton explosion is about ¹³⁾ $5 \cdot 10^{27}$ MeV. About 3.5% of this is taken up by "instantaneous" γ radiation lasting about 70 ns ¹³⁾. Assume that of this, only 3% is not absorbed by the material ¹⁴⁾. Since most γ rays have energies ¹⁾ of the order of 1 MeV, we expect about $5 \cdot 10^{24}$ γ rays produced in a pulse train about 21 metre long.

As an example, suppose that two synchronized underground explosions, 100 kilotons each, take place at a distance ℓ from each other. Let the interaction region be $2.5 \cdot 10^3$ cm long, and its distance from either explosion at least 10^4 cm. Then, even instantaneous neutrons with 20 MeV energy will arrive at the interaction region at least 1 μ sec after the $\gamma + \gamma$ scattering has taken place, and this should give ample time to make observations and transmit the data. The shock wave arrives even later ¹³⁾. Assume that the tunnels transmit a γ beam with angular divergence K . Then, the number of $\gamma + \gamma$ elastic scattering events, following one pair of explosions, is about

$$N(\gamma + \gamma \rightarrow \gamma + \gamma) \approx 1.5 \cdot 10^8 \left[\frac{K \{\text{radian}\}}{\ell \{\text{cm}\}} \right]^2 \quad (4)$$

*) The practice of performing this experiment, in conventional laboratories, should be discouraged because of the detrimental effect it may have on the personnel, equipment and general appearance of the neighbourhood.

When $K=10^{-2}$ radians, $\ell = 10^4$ cm, one expects about $7.5 \cdot 10^5$ scattered photon pairs. In addition to the central tunnel which can lead the γ beams to head-on collision, one can build additional tunnels¹⁾. These may intersect, for example, at right angles. They can be used for control purposes (e.g., rearrange collimators), to insert γ ray polarizers (analysers), or to study electron pair creation with or without polarizers. All tunnels may have to be evacuated completely and background from the walls can be controlled with collimators.

How exactly the two explosions can sufficiently well be synchronized, depends on the mechanical details of the exploding device.

- d. Synchrotron radiation. The total radiated energy, P (integrated over all photon emission angles and wavelengths), per electron, per second, around the whole circumference of a circular machine is¹⁵⁾

$$P = \frac{2}{3} \frac{e^2 c}{R^2} \gamma^4 \quad (5)$$

where e , R , γ , v are the electron charge, machine radius ($1/\sqrt{1-v^2/c^2}$), and the velocity of the circulating electrons respectively. For purposes of an order of magnitude estimate we assume¹⁶⁾ that all photons have a wavelength $\lambda \approx \frac{4\pi}{3} R \gamma^{-3}$. At energies of interest the angular distribution is sharply peaked near parallel to the velocity vector of the emitting electron¹⁵⁾.

Radiation from a storage ring now planned at SLAC would be much too low to give observable counting rates when colliding with itself. When colliding it with bremsstrahlung γ rays produced by an electron machine, the counting rates are still somewhat low ¹⁾. Next, we mention the principle of a possible design ¹⁾ whose aim is to use machines (mainly storage rings) as intense photon sources, while still fulfilling their primary purpose. Instead of letting the electrons circulate along a circle with radius R , let them leave that circle along a tangent at point A, then make a sharp turn with radius of curvature R' between B and C, and finally return to the main circle at point D along a tangent. In other words, the electrons travel on a "hump" between A and D. Let us define $r \equiv R/R'$.

The most interesting possibility is to clash to synchrotron radiation beams. For example, inserting a "hump" in both beams in intersecting storage rings, the two intense radiations can be directed towards a common interactions region, T , of volume V . Let us choose the distance of T from both sources to be $\ell \gtrsim 10$ cm, its dimensions small compared to ℓ , let it extend $5 \cdot 10^{-3} \ell$ cm, above and below the plane of the storage ring, let the section $(B,C) \lesssim 10$ cm. Choose $R = 33$ m, $\gamma = 6 \cdot 10^3$, beam emittance in the vertical direction $eV = 5 \cdot 10^{-4}$ cm $\times$ radian. Then the number of $\gamma + \gamma$ scattering events in T per second is approximately given by

$$N_{\gamma+\gamma}(H, I, V, \ell) \approx 1/5 \cdot 10^{-24} \frac{20}{\ell \{cm\}} \frac{R'^2}{\ell^2 R'^2} [I \{Amp\}]^2 V \{cm^3\} [H \{kgauss\}]^8$$

; valid if $E_{cms} \lesssim \frac{1}{2} \text{ Mev}$; $\alpha \approx \pi(6)$

Here H is the magnetic field producing the radius of curvature R' , and I is the circulating electron current. Let us choose $\ell = 20$ cm, and the projection of T on the plane of the storage ring, approximately a square with sides 5 cm long. If we choose $I = 1$ A, then the number of $\gamma + \gamma$ scattering events per hour in the interaction region will be $5 \cdot 10^{-6}$; 2.0; and 500 respectively, when H is 60; 300; and 600 kgauss. If we choose $I = 20$ A, then these numbers will be $2 \cdot 10^{-3}$; 800; and $2 \cdot 10^5$ (!) respectively.

In the above example, the dimensions of region (B, C) are:
length: ≤ 5 cm; height: ≤ 2 mm; width: width of electron beam.
Magnetic fields in such volumes can be constructed to reach 60 kgauss, and even 300 kgauss, when pulsed. Perhaps even 600 kgauss can be reached in small volumes. The total energy loss per centimeter in region (B, C) is $4.7 \cdot 10^{-3}$ MWatt; $1.2 \cdot 10^{-1}$ MWatt; and $4.7 \cdot 10^{-1}$ MWatt when $H=60$; 300; and 600 Kgauss.

The spectrum and polarization of synchrotron radiation is very well known ¹⁵⁾. It can be controlled by changing v and H . The beam is well collimated and the scattering will be close to isotropic in the laboratory. For all these reasons this may be one of the most elegant ways to study $\gamma + \gamma$ elastic scattering. In addition, the experiment can be done, while the storage rings are operated for other purposes.

- e. High energies. To do $\gamma + \gamma$ experiments at high energies by clashing two γ ray beams, one would like to have a luminosity, $\mathcal{L}$, at least 10^{28} and preferably $10^{30} \text{cm}^{-2} \text{sec}^{-1}$ when studying purely electromagnetic processes. For hadron production $\mathcal{L}$ should be at least about 10^{30} and preferably $10^{32} \text{cm}^{-2} \text{sec}^{-1}$.

One does not need, of course, two accelerators to produce two γ beams to be clashed ¹⁾. Moderate energy primaries can be turned around with magnets and even high energy ones with storage rings. In addition, linacs operated by sections can, in principle, be re-arranged to produce clashing primaries.

The luminosities which can be attained with presently available machines are still too low for our purposes. However, with machines which are now technically feasible, luminosities around 10^{31} and higher could be reached ¹⁾. It may not be too early to start thinking seriously about these possibilities.

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where N is sensitive to this shape, $F \approx 11$, and has been
included.