BREIT-WHEELER SCATTERING EVENTS PRODUCED BY TWO INTERACTING COMPTON SOURCES

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Abstract

We present the dimensioning of a photon-photon collider based on conventional Compton gamma sources for the observation of Breit-Wheeler pair production and QED gamma-gamma generation. Two symmetric electron beams, generated by photocathodes and accelerated in linacs, produce two primary gamma rays through Compton back-scattering with two high-energy lasers. Tuning the system energy above the Breit-Wheeler cross section threshold, a flux of secondary electrons and positrons is generated. The process is analyzed by start-to-end simulations. The Monte Carlo code 'Rate Of Scattering Events' (ROSE) has been developed ad-hoc for the counting of the QED events. Realistic numbers of the secondary particles yield, referring to existing or approved set-ups, a discussion of the feasibility of the experiment and the evaluation of the background are presented.

INTRODUCTION

The development of high-energy, high-brilliance photon pulses and high-brightness electron beams opens the way to the study processes so far unobserved like the Breit-Wheeler pair production (BWPP, $\gamma\gamma \to e^- e^+$) [1] or to the $\gamma\gamma \to \gamma\gamma$ elastic scattering. Several different experimental schemes for the detection of the BWPP have been proposal [2–8] but no one so far implemented. Advanced Compton sources generating hard X and gamma radiation [9], presently in construction, will permit to explore the center of mass energy region around 1-2 MeV and more, close to the peak of the elastic $\gamma\gamma$ scattering and just beyond the threshold of BWPP. Other QED collisions such as secondary Compton ($e^-\gamma \to e^-\gamma$), Møller scattering ($e^-e^- \to e^-e^-$), triplet pair (TPP, $\gamma e^- \to e^-e^+e^-$) and muon pair photo-production (MPP, $\gamma e^- \to e^-\mu^+\mu^-$) produce background. In ref. [10] we presented the dimensioning of a $\gamma\gamma$ collider based on Compton gamma sources. To this aim, a code named ROSE (Rate Of Scattering Events) was developed [11] and benchmarked with respect to the code CAIN [12] for Compton emission [13].

In this paper, we analyze the Breit-Wheeler pair production from the collision of two gamma-ray beams generated by state-of-the-art Compton sources. The scheme of the source is shown in Fig. 1.

We study and optimize the rate of events and we will show that the background from TPP, Møller and Compton

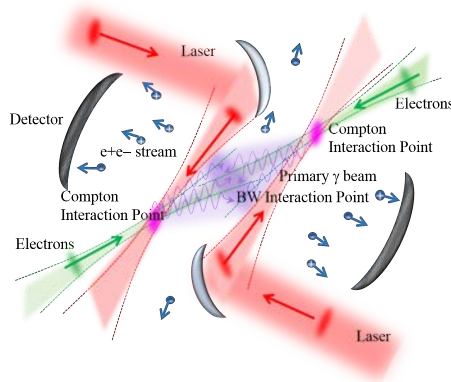

Figure 1: Scheme of the BW interaction.

scattering, that we quantify and discuss, is not a limiting factor in measurements of BWPP.

KINEMATICS AND CROSS SECTION OF THE BREIT-WHEELER SCATTERING

The binary reaction ($\gamma\,\gamma \to e^-\,e^-$) is usually analyzed in the center of mass reference frame (CM) where, giving the invariant mass $\sqrt{s} = \sqrt{2(E_1 E_2 - \underline{p}_1 \cdot \underline{p}_2)}$ (E_1, E_2 being the energies of two primary photons with momenta, in natural units, respectively $\underline{p}_1$ and $\underline{p}_2$ in the laboratory and c=1), the final state particles 3 and 4 acquire the energies $E_{3,4}^{CM} = \sqrt{s}/2$, with momenta $\underline{p}_3^{CM} = -\underline{p}_4^{CM}$, equal in modulus, directed at angles $\theta_3^{CM} = \pi - \theta_4^{CM}$ and $\varphi_3^{CM} = \pi + \varphi_4^{CM}$ [14].

Customary Monte Carlo strategies for analyzing the problem rely on the random sampling of the angles φ_4^{CM} and θ_4^{CM} followed by the acceptance-rejection method weighted by the differential cross section $d\sigma/d\Omega$ (Fig. 2).

The last step is the Lorentz transformation back to the laboratory system with the determination of $\underline{p}_{3,4}$ and $E_{3,4}$.

The total cross sections of all the involved processes are reported in Fig. 3 as functions of the relevant center of mass energy $\sqrt{s}$.

For electron beams with energies close to $E_e = 260$ MeV ($\gamma \approx 520$), that, in collision with a laser with $E_{ph,L} = 1.2$ eV, produce Compton radiation with energy up to $E_{ph,r} = 4\gamma^2 E_{ph,L} \approx 1.2$ MeV (the energy in the center of mass of the two Compton photons being $\sqrt{s_{\gamma\gamma}} \lesssim 2.4$ MeV), the total Breit-Wheeler cross section presents a broad peak at about 10^{-1}b just beyond the threshold at 1 MeV and not far from

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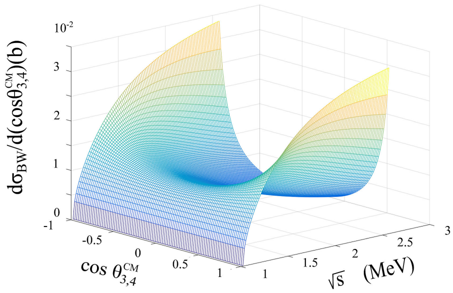

Figure 2: Differential-cross-section $d\sigma_{BW}/d(\cos\theta^{CM}_{3,4})$ averaged on the angle $\phi^{CM}_{3,4}$ for Breit-Wheeler scattering in the plane $(\sqrt{s}, \theta^{CM}_{3,4})$.

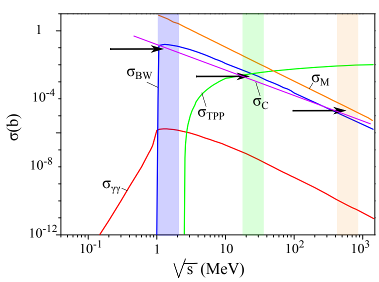

Figure 3: Total cross-section in b for gamma gamma ($\sigma_{\gamma\gamma}$, red line), Breit-Wheeler (σ_{BW}, blue line), TPP (σ_{TPP}, green line), Møller (σ_M, orange line) and Compton (violet line) scatterings versus the energy in the center of mass $\sqrt{s}$ (in MeV) of each process. In blue, green and orange the center of mass energy regions involved in the various processes for electron energy of about 260 MeV. The arrows mark the values of the cross sections. The Møller cross section has been evaluated with a cut at $|\cos\theta| < 0.999$.

the $\gamma\gamma$ peak, but five order of magnitude larger. In correspondence to this electron energy value, (where the electron-gamma energy in the center of mass is $\sqrt{s_{e\gamma}} \lesssim 36$ MeV) the TPP cross section is more than one order of magnitudes smaller than the Breit-Wheeler one. First of all, we evaluate the emitted Compton radiation whose energy spectrum ranges between $E_{ph,L}$ and $E_{ph,r}$ [15]. Two counterpropagating twin Compton sources, whose interaction points have been placed at a distance $2L$ of few millimetres, are considered. The parameters of both beams are reported in Table 1, and reflect the ELI-NP-GBS [9] performances in single-bunch mode. The electron beam lines are similar to those shown in Ref. [10], with the difference that the electron energy is slightly larger (260 MeV, instead than 240) and, since the BW cross section is five order of magnitude larger than $\gamma\gamma$, and the focusing much less critical.

The radiation spectrum and energy distribution are presented in Fig. 4.

Due to the threshold at $\sqrt{s} = 2m_e$, only those photon couples with invariant mass $\sqrt{s} > 1.022$ MeV take part to

Table 1: Table of Electron Beam and Laser Parameters

Electron parameters		Laser parameters	
Electron energy (MeV)	260	Laser wavelength μm	1
Electron charge (pC)	250	Laser energy (J)	2
Transverse dim. (μm)	5	Waist (μm)	10
Long. dim. (μm)	400	Lon. dim. (mm)	1
Emittance (mm mrad)	0.5	Repetition rate(Hz)	100
Energy spread	$5\ 10^{-3}$		

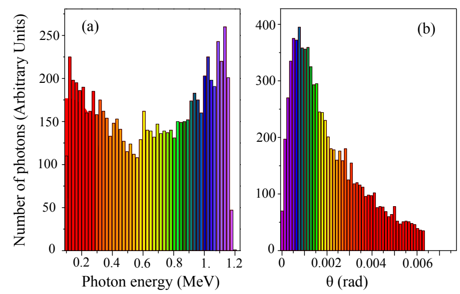

Figure 4: Spectrum of the radiation (a) and angular distribution (b). Similar colors code similar groups of photons.

BWPP. The Compton edge is at about $E_{ph,r} \approx 1.2$ MeV, therefore only photons with energies larger than 0.21 MeV can participate to the process. Due to the broad spectrum of the gamma rays, the collisions are not exactly symmetric, and a dispersion of the energy takes place, but the number of asymmetric collisions is small.

EVALUATION OF THE RATE OF EVENTS

We evaluate and optimize the Breit-Wheeler pair production, the angular and energy distributions and the total number of pairs.

The particles produced during the interaction as a function of energy E and zenithal angle θ in the laboratory frame are presented in Fig. 5, while their energy and angle distributions are in Fig. 6 for $2L = 8$ mm.

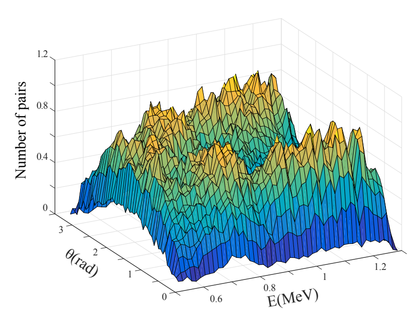

Figure 5: Energy-angle BW pair distribution in the laboratory frame.

The number of particles emitted orthogonally with respect to the axis of the system is quite large, the distribution decreasing only by 20% with respect to the peak.

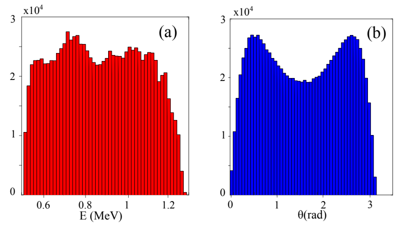

Figure 6: Energy (a) and angular (b) BW pair distribution.

Fig. 7 shows the total number of event for single shot as function of the distance between the two interaction points a with repetition rate of 100 Hz. With $L = 4$ mm, this number is about $N = 60\ event/h$, allowing a good statistics.

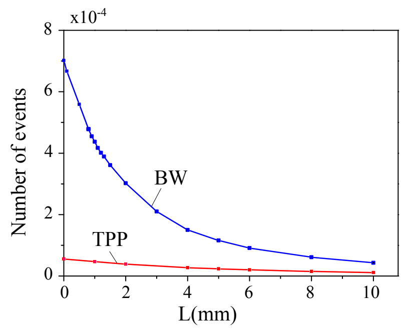

Figure 7: Total number of BW (blue curve) and TPP events (red curve).

All the calculations have been performed by using ROSE, a dynamical Monte Carlo code, implemented for studying the photon-photon scattering and then extended to other collisions, as BWPP, TPP, Compton and Møller scattering. Its main peculiarity is that it treats the scattering between two relativistic and realistic beams, following their time evolution in the laboratory frame. This is necessary whenever there is a significant spread in the invariant mass of the beam-beam collisions. The tracking of both beams during their overlapping up to the end of the scattering process permits to dimension the total space window. The time evolution has been discretized over a total of N_T steps. At a certain time t, each i-th ($i = 1, I$) cell contains $N_{1i}(t)$ and $N_{2i}(t)$ primary particles, forming $N_{c,i}(t) = N_{1i}N_{2i}$ pairs. For each input couple, once that the output angles are randomly sampled in the center of mass reference frame, energies and momenta of the generated pair are evaluated, followed by a Monte Carlo procedure for accepting or rejecting the event on the basis of the value of the differential cross section $d\sigma/d\Omega$ of the process. This last function must be given as a function of s and of the angle between $\underline{p}_1^{CM}$ and $\underline{p}_4^{CM}$ in the CM frame. The code, then, calculates the double differential rate of events for cell and time interval and summing up on cells and integrating on time, the total angular distribution and, finally, the total number of events.

A Lorentz boost provides the angular and energy distributions of the pairs in the laboratory system. Typical values of the parameters of the calculation are $N_{1,2} = 30000$, $I = 100^3$, $N_T = 50$.

CONSIDERATIONS ABOUT BACKGROUND

The background has been then evaluated. Besides the photons scattered by $\gamma\gamma$ elastic collision ($\gamma\gamma \rightarrow \gamma\gamma$), the background is constituted by photons due to Compton ($e^-\gamma \rightarrow e^-\gamma$) and triplets ($e^-\gamma \rightarrow e^+e^-e^-$) generated by the primary electrons impinging the primary Compton gamma rays [16, 17] and by the electrons of the Møller scattering ($e^-e^- \rightarrow e^-e^-$). The QED gamma-gamma events are completely negligible due to the extremely low value of the total cross section. As regards the secondary Compton scattering, producing photons up to 260 MeV, the total cross section at $\sqrt{s} = 36$ MeV is about 5 mb, almost two orders of magnitude lower than the BWPP's. Their total number is about $8\,10^{-6}$ with the lower energy photons ($1 - 2$ MeV) spread all over the solid angle and the most energetic ones confined into a thin angle around the electron propagation axis. The total number of TPP particles is reported in Fig. 7, red curve. It is always smaller than the BW flux and, up to $L = 4$ mm, it maintains less than 15% of the BW.

The value of the Møller total cross section reported in Fig. 3 (orange curve) has been evaluated by setting the cut at $\theta \leq 0.04$ rad. With this selection, that disregards a very thin region, the number of Møller events is still two order of magnitude smaller than the BW one. Finally, the system is under the threshold of the muon photo-production. The number of events for all the processes is presented in Table 2.

Table 2: Number of Events for Single Shot, L=4 mm

BW	C	$\gamma\gamma$	TPP	M	MPP
$1.6\,10^{-4}$	$8\,10^{-6}$	$<10^{-8}$	$2.6\,10^{-5}$	$1.5\,10^{-6}$	0

CONCLUSION

We have demonstrated that with state-of-the-art devices and with not particularly demanding parameters this process neatly emerges from the background of competing processes and can be easily detected. Strategies for separating the charged particles from photons based on the detection by electric or magnetic fields, or the development of geometries avoiding the direct collision between the electron beams and primary gammas, thus decreasing the triplet pair rate production should be analysed. Also the detection system needs an *ad hoc* design, that can be based on the wide literature in the field. The photon-photon collider that we describe would also be controllable and flexible, permitting, in particular, the manipulation of photon polarization in a way that would allow extensive tests of the properties of the BW process. This collider would also be the first such facility, and it would open the way to further exciting developments.

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