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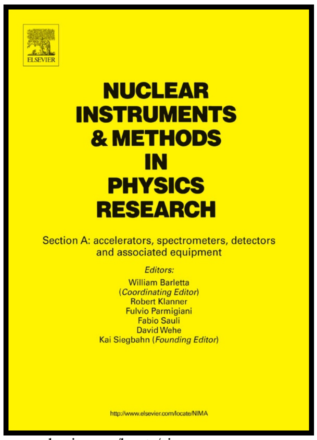

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Study of photon-photon scattering events

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We present the design of a photon-photon collider based on conventional Compton gamma sources for the observation of secondary $\gamma\gamma$ production. 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 to the energy of the photon-photon cross section maximum, a flux of secondary gamma photons is generated. The process is analyzed by start-to-end simulations from the photocathodes to the propagation of the QED photons towards the detector. The new 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 gamma yield, referring to existing or approved set-ups and a discussion of the feasibility of the experiment are presented.

I. INTRODUCTION

The recent development of high-energy, large-brilliance photon and electron beams opens the way to the study of QED collisions or decays that are so far unobserved or detected only in an indirect way.

One of the most elusive processes foreseen by QED is the light to light scattering ($\gamma\gamma \to \gamma\gamma$) [1] that, implied by the Dirac's theory of the electrons and studied since the early thirties, has never been observed so far, except as radiative correction to other processes. In particular, all the experimental attempts performed with photons with energies from fraction of eV to few keV, that, due to the exceedingly low values of the interaction cross section at these energies, constituted really demanding experimental challenges, have not shown excess of events above background in this range of parameters [2–9]. The development of radiation sources in the range of hard X and gamma wavelengths gives the perspective to reach and explore the cross section peak at about 1-2 MeV [10–13]. A promising method for generating QED secondary γ beams is based on two symmetric electron beams, generated by photocathodes and accelerated in linacs, that produce two primary gamma rays through the Compton back-scattering with two high energy lasers [14]. The two primary gamma pulses encounter and scatter. Tuning the gamma energies to the energy of the maximum of the photon-photon cross section, an amount of secondary gamma photons can be generated.

In this paper, we first present the development of a new Monte Carlo numerical code, named ROSE (Rate Of Scattering Events), for the dimensioning of a $\gamma\gamma$ collider based on conventional Compton gamma sources. The design of the source and the evaluation of the rate of QED events are then presented.

II. ARCHITECTURE OF THE CODE ROSE

The kinematics of the $\gamma\gamma$ collision is usually analyzed in the center of mass reference frame (CM) where, assigning the invariant mass $\sqrt{s} = \sqrt{2(E_1E_2 - \underline{p}_1 \cdot \underline{p}_2)}$ (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), the product particles acquire the energies:

$$E_{3,4}^{CM} = \frac{\sqrt{s}}{2} \qquad (1)$$

whereas the momenta $\underline{p}_3^{CM} = -\underline{p}_4^{CM}$, equal in modulus, have angles $\theta_3^{CM} = \pi - \theta_4^{CM}$ and $\varphi_3^{CM} = \pi + \varphi_4^{CM}$.

Customary Monte Carlo strategies for solving the problem rely on the random sampling of the angles φ_4^{CM} and θ_4^{CM}, followed by the rejection test weighted by the differential cross section $d\sigma/d\Omega$.

The last step is the return to the laboratory system by inverse Lorentz transformation:

$$E_{3,4} = \gamma_{CM}(E_{3,4}^{CM} + \underline{\beta}_{CM} \cdot \underline{p}_{3,4}^{CM}) \qquad (2)$$

$$\underline{p}_{3,4} = \underline{p}_{3,4}^{CM} + \frac{\gamma_{CM} - 1}{\beta_{CM}^2}(\underline{\beta}_{CM} \cdot \underline{p}_{3,4})\underline{\beta}_{CM} + \gamma_{CM} E_{3,4}^{CM} \underline{\beta}_{CM} \qquad (3)$$

where $\gamma_{CM} = (E_1 + E_2)/\sqrt{s}$ and $\underline{\beta}_{CM} = (\underline{p}_1 + \underline{p}_2)/(E_1 + E_2)$. Our project is aimed at the analysis of the scattering involving two realistic relativistic beams of gamma photons.

The code ROSE (Rate Of Scattering Events) has been first constructed and implemented for studying the photon-photon scattering and then applied also to other particle collisions and decays, as Breit-Wheeler, Triplet Pair Production (TPP), Compton scattering. Its main peculiarity is that it treats the scattering between two

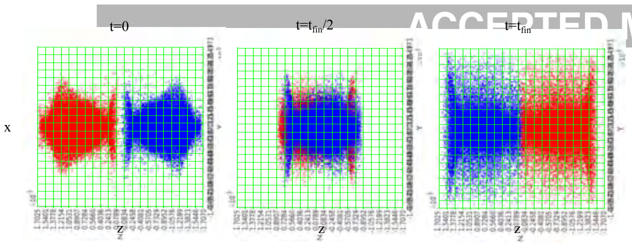

Figure 1: Snapshots of the dynamics (top view) in the case $N_{1,2} = 30000$, $I = 21^3$.

relativistic and realistic beams, following their time evolution in the laboratory frame. All the code entries have been set in a general way in order to treat particles with or without mass.

In the case of $\gamma\gamma$ scattering, starting from two colliding beams of photons (say beams 1 and 2) defined through the phase spaces of an appropriate number $N_{1,2}$ of macroparticles of weight respectively $q_{1,2}$, the procedure entails the definition of a fix common space grid where the kinematics takes place. The tracking of both beams during their overlapping up to the end of the scattering process permits to dimension the total space window that must contain both beams in all the interaction time. The initial time t_0 is the instant when the first collisions occur, the temporal evolution being discretized over a total of N_T steps. In Fig. 1, few snapshots of the dynamics are shown.

At a certain time t, each i-th ($i = 1, I$) cell contains $N_{1i}(t)$ and $N_{2i}(t)$ primary particles, forming $N_{c,i}(t) = N_{1i}N_{2i}$ couples. The local and instantaneous luminosity is given by:

$$\mathcal{L}_i(t) = \frac{q_1 N_{1i} q_2 N_{2i}}{\Delta x_i \Delta y_i} \tag{4}$$

where Δx_i and Δy_i are the transverse dimensions of the cell. 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 is given in terms of s and of the angle between $\underline{p}_1$ and $\underline{p}_4$ in the CM frame. In the code, furthermore, the cross section can be assigned either analytically or by points, depending on the calculation time consume. Typical values of the parameters of the calculation are $N_{1,2} = 30000$, $I = 100^3$, $N_T = 50$.

The successive return of the couple of particles generated in the collision to the laboratory system is ruled by the inverse Lorentz transformations (3) and (4). The phase space of the particles provides the angular and energy distributions of the offspring. The code, then, calculates the differential rate of events for cell and time interval:

$$\frac{dN_i(t)}{d\Omega} = \frac{d\sigma}{d\Omega}\mathcal{L}_i(t) \tag{5}$$

and, summing up on cells and time, the total angular distribution and, finally, the total number of events.

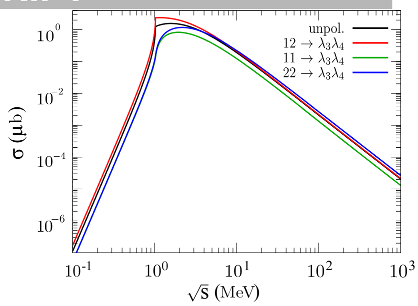

Figure 2: Semipolarized (linear polarization) and unpolarized total cross section of $\gamma\gamma$ scattering as a function of center of mass energy.

III. PHOTON-PHOTON SCATTERING EVALUATION

The study of the photon-photon scattering was the starting point of our project. The code ROSE, initiated for this specific purpose, was then generalized in order to apply it to a large class of phenomena in particle collisions and decays.

For the $\gamma\gamma$ scattering, the total cross section in the center of mass has been evaluated, for polarized or unpolarized photons, on the basis of the formulation of Ref. [15, 16] and few particular cases relevant to different combinations of the polarizations of the input photons are shown in Fig. 2.

The unpolarized differential cross sections $d\sigma/d\Omega$ for $\gamma\gamma$ collisions, evaluated as a function of $E_{CM} = \sqrt{s}$ and of the angle θ_{CM} between the photons 1 and 3, is instead presented in Fig. 3. Since the calculation of $d\sigma/d\Omega$ is time consuming, the $\gamma\gamma$ differential cross-section was given in the code by points on a grid in the plane $(E_{CM}, cos(\theta_{CM}))$ and, then, interpolated for the coordinates of each event.

The primary gamma rays has been produced via Compton back-scattering between an electron beam generated and accelerated in a photocathode [17] and a high energy laser [18, 19]. The tracking of the electron beam has been done with the code ASTRA [20], while the Compton interaction was performed with CAIN [21]. Fig. 4 shows the electron dynamics from the cathode to the interaction point. The focusing stage, that has been realized with three high gradient quadrupoles, is presented in the inner window. Typical values of the electron beam parameters at the interaction point are: charge 250 pC,

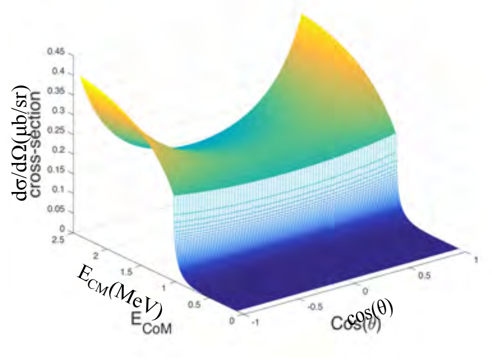

Figure 3: Differential cross section in the plane $(E_{CM}, \cos\theta_{CM})$

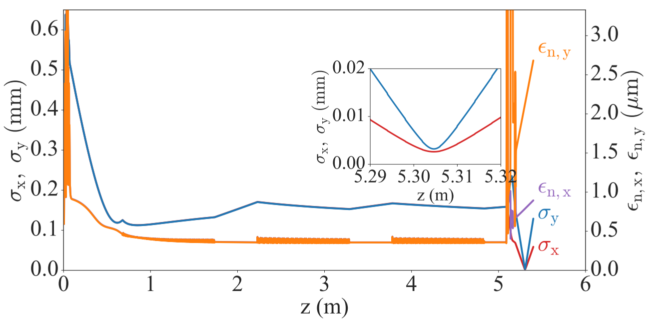

Figure 4: Electron beam line.

electron energy 250 MeV, transverse dimensions $\sigma_x \approx 2.6$ μm and $\sigma_y \approx 3.2\,\mu$m, normalized transverse emittances $\varepsilon_{n,x} \approx 0.79$ mm mrad and $\varepsilon_{n,y} \approx 2.12$ mm mrad and energy spread 0.7×10^{-4}. The colliding laser, with wavelength of 1 μm, has energy of 1 J and waist of about 10 μm. The spectrum of the $1.5\,10^9$ emitted photons, with energy less than 1 MeV, is shown in Fig. 5 before and after a slight collimation that reduces the totale flux by about one third of the total one, cutting the less energetic part of the radiation. The two symmetric Compton

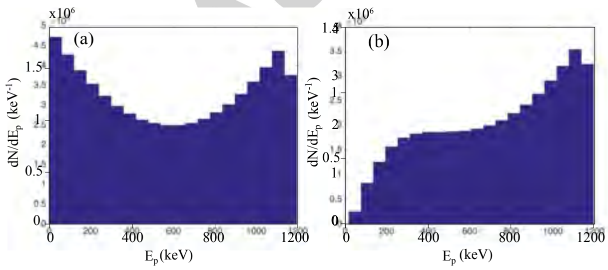

Figure 5: Photon spectra. (a) Total spectrum. (b) Spectrum after a collimation.

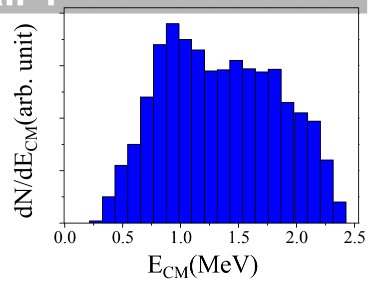

Figure 6: Center of mass energy dispersion.

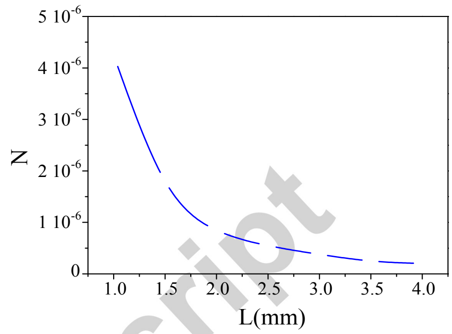

Figure 7: $\gamma\gamma$ event rate

gamma beams collide in an interaction point placed at a distance L from each Compton IP. The interaction region has transverse extension depending on the distance and on the divergence of the photons, that scales as the inverse of the electron Lorentz factor γ_e. The two primary gamma beams have been divided in cells whose dynamics has been followed in time. Due to the broad spectrum of the gamma rays, collisions are in general not symmetric, and a dispersion of the energy in the center of mass E_{cm} takes place, as shown in Fig. 6, where the distribution of E_{cm} for all the collisions is presented. The center of mass Lorentz factor γ_c, in principle, ranges therefore between 1 and γ_e.

However, due to the Compton energy-angle correlation, photons encounter preferably other photons with similar energy, the number of asymmetric collisions is therefore quite contained and the center of mass Lorentz factor γ_c varies between 1 and 1.5.

The propagation of the gamma beams across the $\gamma\gamma$ interaction point, the broadness of the spectrum and the asymmetry of the collisions have been taken into account in the evaluation of the number of events of secondary gamma production. The most energetic particles are ejected along the axis of the system, but a considerable amount of photon moves perpendicularly. Collecting all data, the total amount of QED events evaluated per single shot and as a function of the distance L between the Compton and $\gamma\gamma$ interaction points is shown in Fig. 7.

With a repetition rate of 100 Hz, one event per hour is achieved for L between 1 and 2 mm. Tripling the distance ($L = 4$ mm) would mean passing to a generation rate in defect of one event each ten hours. The optimum work interval is therefore quite below this value.

Conclusions

The gamma gamma production is not the only event taking place. Other concomitant processes occur: the Breit-Wheeler pair production ($\gamma\gamma \rightarrow e^+e^-$) [22], the triplet pair production (TPP) ($\gamma e^- \rightarrow e^+e^-e^-$) [23], this last occurring as a consequence of the collisions between the primary electrons and gammas, the Mϕller scattering ($e^-e^- \rightarrow e^-e^-$) [24]. As regards the Breit-Wheeler scattering, this process is one of the manifestations of the mass-energy equivalence and it has never been detected due to the difficulty in preparing colliding gamma ray beams, although the more complex multiphoton Breit-Wheeler has been first observed almost twenty years ago. Strategies for avoiding or containing the background flux on the detector could involve the use of electric or magnetic fields for deflecting the secondary charged particles beams or, in the case TPP and Mϕller scattering, the development of a geometry which foresees that the primary beams do not cross each other. This can be achieved by driving the electron beams along slightly curved paths, balancing the advantage of diminishing the background from TPP and Mϕller scattering, with the decrease of flux due to side Compton interaction.

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