Pair creation in collision of γ-ray beams produced with high intensity lasers

X. Ribeyre,* E. D’Humières, S. Jequier, and V. T. Tikhonchuk

Univ. Bordeaux-CNRS-CEA, Centre Lasers Intenses et Applications,
UMR 5107, 33405 Talence, France

M. Lobet

Univ. Bordeaux-CNRS-CEA, Centre Lasers Intenses et Applications,
UMR 5107, 33405 Talence, France and
CEA, DAM, DIF, F-91297, Arpajon, France

(Dated: April 30, 2015)

Abstract

Direct production of electron-positron pairs in photon collisions is one of the basic processes in the Universe. The laser induced synchrotron source of γ-rays may open for the first time a possibility to observe this process in laboratory. Based on numerical simulations including the quantum electrodynamic effects we propose an experimental set-up using a MeV photon source aiming to produce more than $10^4$ Breit-Wheeler pairs per shot.
According to the theory of quantum electrodynamics (QED) [1], a sufficiently high energy density electromagnetic radiation may create matter in the form of particle-anti-particle pairs. The electron-positron production $\gamma' + \gamma \rightarrow e^+ + e^-$ is the lowest threshold process in photon-photon interaction, which is of crucial importance in Nature, controlling the energy release in Gamma Ray Bursts, Active Galactic Nuclei, black holes and other explosive phenomena [2, 3].

The $e^- e^+$ pair creation in a collision of two photons was first theoretically predicted by Breit and Wheeler (BW) [4] following the discovery of the positron by Anderson [5]. The effective cross section of such a process ($\sim r_e^2 \approx 10^{-25} \text{cm}^2$) is of the same order as the Thomson cross section ($r_e$ is the electron classical radius). However, up to now nobody has succeeded to observe it in laboratory because of a relatively low photon fluxes available. The linear BW process, $\gamma' + \gamma \rightarrow e^+ + e^-$ is the first order perturbative QED process, which is followed by the multiphoton processes $\gamma' + n\gamma \rightarrow e^+ + e^-$ [6–8]. The multiphoton $e^- e^+$ pair production processes have been observed experimentally at the Stanford Linear Accelerator Center (SLAC) [9, 10] in collisions of an electron beam with a terawatt laser pulse. However, the electron beam energy was not sufficient for the first order BW process.

Observation of the BW process is difficult because of other pair-production reactions, essentially in charged particle collisions. The major competing processes are the electron collision with a nuclei, $e^- + Z \rightarrow Z + e^+ + 2e^-$, the trident process, with the effective cross section $\sim Z^2 \alpha^2 r_e^2$ and the Bethe–Heitler (BH) process [11] $\gamma + Z \rightarrow Z + e^+ + e^-$, which has a higher cross section $\sim Z^2 \alpha r_e^2$. Here, $\alpha = 1/137$ is the fine structure constant. Both processes are efficient for the positron production with intense laser pulses and high-Z targets [12, 13]. However, they introduce quite strong limitations on the noise level for detecting the BW process. Experiments [14, 15] showed production of $\sim 10^{10}$ positrons per shot from a thick gold target. This illustrates the difficulty in detecting the BW process, which requires a clean interaction environment therefore excluding any heavy material and preferring a collision of intense and energetic photon beams in vacuum.

A possible experimental scheme for studies of the BW process was suggested in Ref. [16]. The authors proposed to collide a GeV photon beam with a bath of thermal photons at a temperature of $\sim 300 \text{eV}$. The laser intensities above $10^{21} \text{W/cm}^2$ are then required to accelerate electrons to GeV energies, which then generate the photons. Such an experimental configuration could be realized on the NIF or LMJ laser facilities [17, 18] coupled to the
petawatt systems PETAL and ARC, respectively. The authors expect a production of $\sim 10^5$ BW pairs in a single laser shot. However, the proposed scheme cannot be operated with multiple laser shots, and it is prone to a high noise level due to the presence of a significant mass of a heavy material.

In this letter, we propose another experimental approach for the observation of the BW process. This scheme offers a possibility of conducting a multi-shot experiment with a reliable statistics on laser systems with pulse energies on the level of a few joules and in a low noise environment without heavy elements. This scheme relies on a collision of relatively low energy (few MeV), intense photon beams. Such beams can be created in interaction of intense laser pulses with thin plastic targets. By colliding two of them in vacuum, one would be able to produce a significant number of $e^-e^+$ pairs in a controllable way. This paper provides details of the experimental setup, estimates of the expected yield of reactions and possible ways of creation of a photon source with requested parameters.

**Direct observation of the BW process in laboratory** The energy threshold of the BW process is defined by the energy and momentum conservation. Assuming that both, electron and positron are produced at rest in the center of mass reference system, the threshold condition writes

$$E_{\gamma_1}E_{\gamma_2} = 2m_e^2c^4/(1 - \cos \theta),$$

where $\theta$ is the angle between the colliding photons with energies $E_{\gamma_1,2}$ respectively. For the optimal geometry of a head-on collision, $\theta = \pi$, the product of energies of colliding photons should be larger than 0.25 MeV$^2$. The appropriate choice of photons depends on the available sources. For example, with high intensity optical sources, lasers, providing an enormous amount, $> 10^{20}$ of $\sim 2$ eV photons, in a very short pulse of 20 – 30 fs, one would need to seek a counterpart source of a few hundred GeV photons. This was the choice in the SLAC experiment [9]. However, the only known source of such energetic photons would be the Compton backscattering, which requires a few hundred GeV electron beam. It is produced in km-scale linear accelerators, which are major facilities requiring rather expensive preparation campaigns. Moreover, with expected number of Compton photons $\sim 10^5$, the probability of BW process remains very small.

Another known source of intense photons is a hohlraum heated by a high energy laser pulse [16]. While delivering a laser energy of a few hundred kJ inside a mm-size gold cavity, one can create a black body-like radiation with the effective temperature of 200 – 300 eV [20].
The counterpart photon source is then in the GeV range. However, this scheme, apart of making the photon interaction in a harsh hohlraum environment, faces another challenge of producing an efficient GeV photon source. Although several approaches could be considered [21], none of them is demonstrated today, and it would be difficult to make a valid prediction of how efficient such a source could be. It is much easier to produce lower energy photons in a few MeV range. According to Eq. (1), a collision of two such photon beams at a large angle could produce the $e^-e^+$ pairs. This is the idea of our proposal of BW demonstration with MeV photon beams. Before discussing the possible compact sources of intense photons, we estimate the necessary conditions for such an experiment.

The use of MeV photons allows to reduce significantly the requirements on the photon source for a BW experiment. Assuming two cylindrical $\gamma$ beams with a diameter $D$ intersecting at an angle $\phi$, the interaction volume will be $V \sim D^2/\sin \phi$ if the pulse duration $c\tau > D/\sin \phi$. Correspondingly, for the optimum pulse duration $c\tau \simeq D/\sin \phi$ the number of pairs will be $N_p \sim N_\gamma^2 r_e^2/D^2$, where $N_\gamma$ is the total number of photons in the bunch. In practical units and for 1 MeV beams one has:

$$N_p \sim 100 E^2/D^2, \quad (2)$$

where $E$ is the photon beam energy in joules and $D$ is the beam diameter in mm. Therefore, two beams having an energy of 1 J each and a diameter of 0.1 mm will produce in average $10^4$ pairs per shot. Such a photon source is already available [19], producing in average 2 J photon bunches with an effective temperature of 6 MeV. Moreover, MeV photon bunches could be created routinely in the new generation of 10 PW laser facilities under construction in the framework of the ELI [22] and Apollon projects [23].

**Intense compact sources of MeV photons** As demonstrated previously to produce more than $10^4$ pairs per shot, we need a source of MeV photons with the energy of 1 J and a beam collision in an interaction zone 100 $\mu$m wide. Several $\gamma$-ray sources may correspond to these conditions. A large number of MeV photons can be produced with intense lasers by using the Bremsstrahlung conversion [19], betatron [24] and synchrotron emission [25].

The regime of emission, the collimation and the conversion efficiency depend on the laser intensity and target density. The source should produce a collimated emission in order to separate the emission and interaction zones and to ensure that pairs will be generated in a given direction determined by the experimental setup (see Fig. 1). The brightness of the
FIG. 1. Experimental setup for the BW pair production with MeV colliding photon beams. The magnetic field (B) allows to avoid parasite pairs during the γ–beams collision.

The photon source is also crucial to produce a sufficient number of pairs far from the source.

The most known photon source is based on the Bremsstrahlung process [19, 26]. Such a source is realized by focusing of an intense laser radiation on a mm-thick target of a high-Z material, gold or tungsten, for example. Broadband sources with energies of a few MeV are available. The Bremsstrahlung emission of high energy photons from the energy conversion of MeV electrons in high-Z material have been considered in many configurations. The electrons can be first produced by wakefield laser acceleration to the GeV level before being sent to the target. Such a source can be also realized by directly focusing an intense laser pulse on a mm-thick target. In this case, a larger number of hot electrons is produced in the MeV range [19, 26] for a laser intensity around $10^{21}$ Wcm$^{-2}$. Photon beams with the energy of 1-2 J and a duration of 150 fs have been produced in the broad energy range of 3-50 MeV. Their divergence is about 30°or larger. The efficiency of the laser energy conversion into γ-rays is around 2%. However, the use of a high-Z converter results in production of a large amount of $e^-e^+$ pairs, greater than $10^{10}$ [14].

The betatron sources is generated via the accelerated electrons undulating in the bubble structure of the wakefield. By focusing a femtosecond laser beam of $10^{18}$ W/cm$^2$ inside a plasma waveguide capillary, $10^8$ photons in range of 20–150 keV are generated with a divergence less than 1°[24]. But the total γ-ray beam yield is around 1 $\mu$J in the 100 keV range, which is far from the requirements for the BW experiment.

The Thomson and Compton sources are more suited for very high photon energies, above a hundred MeV, where their efficiency is higher [10, 21]. In the experiment [27], one laser
pulse was focused in a gas cell to produce a relativistic electron beam, and another laser pulse was focused on that electron beam to produce $\gamma$-photons from the inverse Compton scattering. About $10^7$ photons at the energy of 6 MeV are generated with a low divergence of less than 1°.

**TABLE I. Comparison of the different $\gamma$ sources.**

| Sources     | Bremss. | Betatron | Compton | Synch. |
|-------------|---------|----------|---------|--------|
| $\gamma$ energy | 3–50 MeV | 20–150 keV | 1–10 MeV | 1–10 MeV |
| Beam energy | 1–2 J | 1 $\mu$J | 10 $\mu$J | 1–10 J |
| Efficiency | $2 \times 10^{-2}$ | $10^{-6}$ | $10^{-5}$ | $10^{-2}$ |
| Divergence | 30° | 1° | 1° | 30° |
| Reference | [19] | [24] | [27] | [25] |
| $N_p$, Eq.(2) | 300–1200 | under BW | $2.5 \times 10^{-5}$ | 300–3$x \times 10^4$ |
| at 500 $\mu$m | threshold | |

In the MeV range the most suitable source could be based on the synchrotron emission of energetic electrons in the intense laser field. This process takes place in interaction of very high intensity laser pulses $\sim 10^{22–23}$ W/cm$^2$ with light targets having density less than 1 g/cm$^3$. The numerical studies published so far predict a significant non-collimated emission of high-energy photons in both thin-foil and gas jet laser interaction, with energies up to tens of MeV for a laser conversion of several tens percents [25, 28–30].

Table I presents a comparison between the $\gamma$-ray sources considered in this paper. The Bremsstrahlung and synchrotron sources are the most suitable for the pair production due to their better conversion efficiency.

The performance of the synchrotron source was studied in numerical simulations with the two-dimensional particle-in-cell code CALDER [31]. A typical angular-energy spectrum for the case of laser interaction with a 8 $\mu$m thick aluminium foil is shown in Fig. 2. The target with the electron density 600 times the critical density was irradiated by a laser pulse at normal incidence with an intensity of $10^{23}$ W/cm$^2$ at 1 $\mu$m wavelength. The synchrotron radiation is produced in a wide range of angles $\langle \theta \rangle \sim 60^\circ$ with the maximum emission angle at 34° corresponding to a photon energy of 200 keV. This is of the same order as has been reported in Bremsstrahlung experiments. The peak position of the radiated energy peak
can be estimated as $0.3 \hbar \omega_0 a_0^3$ where $\omega_0$ is the laser frequency and $a_0$ is the dimensionless relativistic laser amplitude [25]. A significant production of photons in the range below 10 MeV was observed. It represents around 18% of the total radiated energy.

![Spectral and angular distribution of the emitted photon energy in the interaction of a laser pulse at $10^{23}$ W/cm$^2$ with a 8 µm aluminium target.](image)

These simulation results can be extrapolated to the next generation of high power laser facilities by taking as an example the Apollon system [23] delivering the energy $E_{\text{las}} = 150$ J in a 15 fs pulse. The photon pulse duration is equal to the laser pulse duration and corresponds to the full length at half maximum of $l_\gamma \sim 4.5 \mu$m. Similarly, the photon beam radius near the source can be approximated by the laser focal spot radius $R_\gamma \sim 2 \mu$m. The conversion efficiency of 15%, which corresponds to a photon pulse energy of 22 J. According to the emission diagram shown in Fig. 2, the total number of photons emitted in the range 1-3 MeV in the forward direction is $\sim 10^{12}$. The photon source brightness in this spectral domain is $\sim 0.14$ J/MeV/sr and the brilliance $2 \times 10^{15}$ photons/sr/mm$^2$/s in a 0.1% bandwidth.

If one would collide such two photon beams right at the source, about $10^8$ BW pairs will be produced. However, it is not a way to choose because of a large number of parasite $e^+e^-$ pairs produced in other reactions, which will be impossible to separate from the BW pairs. The pairs can be produced in the laser-target interface via the nonlinear BW process with the high energy photons generated due to the nonlinear Compton scattering or via the electron directly in the trident process. Moreover, deeper in the target the pairs can be generated by the high-energy photons generated in the Compton scattering or the Bremsstrahlung
interacting with the nuclei via the BH mechanism \cite{11} or directly by the energetic electrons via the trident process.

Our simulations show that at intensities $\sim 10^{22-23}$ W/cm$^2$, the pair production via the nonlinear BW process is extremely low, lower than $10^{-9}$ pairs produced per electrons per one laser period. The electromagnetic trident process is also rare with $10^{-6}$ pairs per electron per laser period \cite{32}. The BH is dominate process. The total number of electrons with the energies above 1 MeV (twice the rest mass of an electron) can be estimated as $N_e \sim \eta_{\text{abs}} E_{\text{las}} / \langle \varepsilon_e \rangle$ where $\eta_{\text{abs}}$ is the absorption coefficient and $\langle \varepsilon_e \rangle$ is the average electron energy. For the Apollon parameters about $10^{13}$ energetic electrons will be produced. Using the cross-section for the nonlinear Compton scattering \cite{6, 33}, about $N_\gamma \sim 10^{14}$ photons will be produced with an energy above 1 MeV. The number of pairs produced via the BH mechanism can be estimated as $N_p = \sigma_{\gamma Z} N_\gamma n_i L$, where $\sigma_{\gamma Z} \approx Z^2 \alpha r_e^2$ is the cross section, $n_i$ is the ion density and $L$ is the target thickness. The expected number of pairs produced in an aluminium target of a thickness of 8 $\mu$m is then about $10^9$. This estimate was confirmed using the calculated photon distribution and assuming a 15\% laser conversion efficiency. Thus there will be ten times more BH pairs than BW pairs if one will collide the photon beams right near the aluminium foil.

Reducing the target density could be a good option to suppress the parasite processes. The laser interaction with near-critical plasma is also an important source of high-energy photons. In a numerical simulation, we considered a hydrogen plasma of a density $4n_e$ and a thickness of 80 $\mu$m irradiated by an Apollon laser pulse. In this case, the average photon energy is equal to 2.7 MeV, the brightness is $\sim 0.4$ J/MeV/sr and the brilliance is $\sim 10^{16}$ photons/sr/mm$^2$/s in a 0.1\% bandwidth. The number of photons with the energy up to 1 MeV emitted in the forward direction is equal to $2 \times 10^{13}$. This is an order of magnitude larger than number of photons produced from a solid target, while the number of parasite BH pairs is reduced at least two orders of magnitude due to a lower ion charge. Thus a collision of two oppositely traveling photon beams in a near critical density target could be a valuable option for observation of the BW process. However, a separation of the BW and parasite pairs remains rather complicated.

A separation of the photon collision zone from the source offers a possibility of a more clear detection of BW pairs (see Fig. 1). Let us consider a distance of 500 $\mu$m which may reduce the noise coming from the BH parasite pairs. At such a distance more than hundred
times larger than the source size, the photon bunch can be assimilated with a homogeneous cloud of thickness defined by the laser pulse duration \( l_\gamma \) and radius \( R \sim x \tan \langle \theta \rangle \) linearly increasing with the propagation distance \( x \). The cloud volume can be written as \( V \sim \Omega l_\gamma x^2 \), where \( \Omega = 2\pi(1 - \cos(\theta)) \) is the average emission solid angle, and the average photon density decreases quadratically with the distance. Then, for a solid target \( \langle \theta \rangle \sim 30^\circ \) and at the distance \( x = 500 \mu m \) the size of the collision zone is \( 350 \mu m \), the photon density \( \langle n \rangle \sim 0.02 n_c \) and the expected number of BW pairs is \( 10^4 \). This value is consistent with the pair production given by the Eq. (2). The similar estimate stands also for a low density target. A collision of photon beams at a certain angle \( \phi \sim 90^\circ \) offers another important advantage for the BW pairs detection, as both, \( e^+e^- \) will be emitted in the preferential bisection direction. This may allow a better signal-to-noise ratio even in the case of a large number of parasite pairs.

The qualitative estimates and numerical simulations show that about \( 10^4 \) BW pairs can be produced with existent sources of MeV photons. Two \( \gamma \)-ray sources are well adapted, the Bremsstrahlung and synchrotron sources offering a good conversion efficiency. Although the expected number of BW pairs could be easily detected, the major challenge is to discriminate them from other pairs created essentially by the trident and BH processes in the photon source target. The spatial separation of the photon-photon interaction zone seems to be the best way for the detection of the BW pairs emitted in the preferential direction. This setup threfore offers the possibility to directly observe the BW process for the first time in the laboratory and could have important applications for astrophysics.

We acknowledge the financial support from the French National Research Agency (ANR) in the frame of "The Investments for the Future" Programme IdEx Bordeaux - LAPHIA (ANR-10-IDEX-03-02) - Project TULIMA. This work is partly supported by the Aquitaine Regional Council (project ARIEL).

* ribeyre@celia.u-bordeaux1.fr

[1] V. B. Beresteskii, E. M. Lifshitz and L. P. Pitaevskii, 1982, Quantum Electrodynamics (Elsevier Butterworth-Hienmann, Oxford).

[2] T. Piran, Rev. Mod Phys. 76, 1143 (2004).
[3] R. Ruffini et al., Physics Reports 487, 1-140 (2010).
[4] G. Breit and J. A. Wheeler, Physical Review 46, 1087-1091 (1934).
[5] C. D. Anderson, Physical Review 43, 491-494 (1933).
[6] A. I. Nikishov and V. I. Ritus, Sov. Phys. JETP 19, 529 (1964).
[7] N. B. Narozhnyi, A. I. Nikishov, V. I. Ritus, Sov. Phys. JETP 20, 622 (1965).
[8] Y. B. Wu and S. S. Xue, Phys. Rev. D 90, 013009 (2014).
[9] D. L. Burke et al., Phys. Rev. Lett. 79, 1626 (1997).
[10] C. Bamber et al., Phys. Rev. D 60, 092004 (1999).
[11] H. Bethe and W. Heitler, Proc. R. Soc. A 146, 83 (1934).
[12] E. P. Liang, S. C. Wilks, M. Tabak, Phys. Rev. Lett. 81, 4887 (1998).
[13] J. Myatt et al., Phys. Rev. E 79, 066409 (2009).
[14] H. Chen et al., Phys. Rev. Lett. 102, 105001 (2009).
[15] H. Chen et al., Phys. Plasmas 21, 040703 (2014).
[16] O. J. Pike et al. Nature Photonics 8, 434 (2014).
[17] G. H. Miller, E. I. Moses and C. R. Wuest, Nucl. Fusion 44, S228 (2004).
[18] Giorla J. et al. Plasma Phys. Control. Fusion 48, B75 (2006)
[19] A. Henderson et al., High Energy Density Phys. 12, 46 (2014).
[20] D. A. Callahan et al., Journal of Physics: Conference Series 12, 022021 (2008).
[21] K. Nakajima, High Power Laser Science and Engineering 2, e31 (2014).
[22] http://www.extreme-light-infrastructure.eu/
[23] http://cilexsaclay.fr/
[24] S. Cipiccia et al. Nature Physics 7, 867 (2011).
[25] R. Capdessus et al., Phys. Rev. Lett. 110, 215003 (2013); Phys. Rev. E 86, 036401 (2012);
Phys. Plasmas 21, 123120 (2014).
[26] A. Compant La Fontaine, J. Phys. D: Appl. Phys. 47, 325201 (2014).
[27] G. Sarri et al., Phys. Rev. Lett. 113, 224801 (2014).
[28] T. Nakamura et al., Phys. Rev. Lett. 108, 195001 (2012).
[29] C. P. Ridgers et al., Phys. Plasmas 20, 056701 (2013).
[30] L. L. Ji et al., Phys. Plasmas 21, 023109 (2014).
[31] M. Lobet et al., arXiv preprint arXiv:1311.1107 (2013).
[32] A. R. Bell and J. G. Kirk, Phys. Rev. Lett. 101, 200403 (2008).
[33] A. I. Nikishov and V. I. Ritus, Sov. Phys. JETP 25, 1135 (1967).