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

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Direct production of electron-positron pairs in two-photon collisions, the Breit-Wheeler process, is one of the basic processes in the universe. However, it has never been directly observed in the laboratory because of the absence of the intense γ-ray sources. Laser-induced synchrotron sources emission may open a way to observe this process. The feasibility of an experimental setup using a MeV photon source is studied in this paper. We compare several γ-ray sources and estimate the expected number of electron-positron pairs and competing processes by using numerical simulations including quantum electrodynamic effects.

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I. INTRODUCTION

According to the theory of quantum electrodynamics (QED) [1], an electromagnetic radiation with a sufficiently high energy density may create a matter in the form of particle-antiparticle pairs. The electron-positron production $\gamma + \gamma \rightarrow e^+ + e^-$ is the lowest threshold process in the photon-photon interaction, which is of crucial importance in nature, controlling the energy release in γ-ray bursts, active galactic nuclei, black holes, and other explosive phenomena [2,3]. It is also responsible for the TeV cutoff in the photon energy spectrum of extragalactic sources [4].

The e^+e^- pair creation in a collision of two photons was first theoretically predicted by Breit and Wheeler [5] following the discovery of the positron by Anderson [6]. The effective cross section of such a process is of the same order as the Thomson cross section, i.e., $=8\pi r_e^2/3 = 6.65 \times 10^{-25}$ cm^2 where $r_e = e^2/4\pi\epsilon_0 m_e c^2 = 2.8 \times 10^{-13}$ cm the electron classical radius, ϵ_0 is the vacuum dielectric permittivity and e is the elementary charge. While the pair creation in photon collisions takes place on astrophysical scales [3], its experimental observation is difficult because of available photon fluxes of very low intensity [7,8]. The linear Breit-Wheeler (BW) process, $\gamma' + \gamma \rightarrow e^+ + e^-$ is the first-order perturbative QED process, which is followed by the multiphoton processes $\gamma' + n\gamma \rightarrow e^+ + e^-$ [9,10]. This multiphoton electron-positron pair production has been observed experimentally at the Stanford Linear Accelerator Center (SLAC) [7,11] in collisions of a high-energy electron beam with a terawatt laser pulse. However, the electron beam energy was not sufficient for the first-order BW process.

The SLAC experiment consisted of injecting a beam of $\sim 10^9$ electrons with an energy of 46.6 GeV into an intense laser beam with a relativistic amplitude $a_0 = eE_0/m_e\omega_0 c \sim 0.5$, where m_e is the electron mass and c is the light velocity, E_0 and ω_0 are the laser electric field amplitude and frequency. It was a two-step process. At the first step, the laser photons at 527 nm, i.e., with an energy $\hbar\omega_0 \simeq 2.35$ eV, where $\hbar$ is the Planck constant, were converted in ~ 30 GeV γ rays in the linear and nonlinear Compton backscattering processes $n\omega + e^- \rightarrow e^- + \gamma$ with $n = 1$–4 [12]. Approximately 10^6 high-energy photons per shot have been produced. At the second step, these high-energy photons were collided with the laser photons producing pairs $\gamma + n\omega \rightarrow e^+ + e^-$. Although the probability of this process was very low, the authors observed about 100 positrons in 20 000 laser shots. According to the energy conservation, at least four optical photons, $n = 4$, were needed for this nonlinear BW process. In this configuration, colliding with an optical laser beam the first-order BW process would require 200 GeV photons.

Observation of the BW process is difficult because of other pair-production reactions in charged particle collisions. The major competing processes are: the electrons collision with a nucleus, $e^- + Z \rightarrow Z + e^+ + 2e^-$, the so-called trident process, with the effective cross section $\sim Z^2\alpha^2 r_e^2$, and the Bethe-Heitler process [13] $\gamma + Z \rightarrow Z + e^+ + e^-$, which has a larger cross section $\sim Z^2\alpha r_e^2$. Here, $\alpha = e^2/4\pi\epsilon_0\hbar c = 1/137$ is the fine structure constant. Both processes are efficient for the positron production with intense laser pulses and high-Z targets [14,15]. However, they introduce strong limitations on the noise level for detecting the BW process. Experiments carried out at the Jupiter and OMEGA EP laser facilities [16,17] showed production of $\sim 10^{10}$ positrons per shot from a thick gold target irradiated with a laser pulse having intensity $\sim 10^{20}$ W/cm^2. Recently, at the ASTRA-GEMINI laser facility, a high-density (10^{16} cm^{-3}) and small divergence (10–20 mrad) positron beam has been created by a high-intensity laser beam irradiating a gas target and using a secondary high-Z target [18–20]. These examples illustrate the difficulty in detecting the BW process, which requires a clean interaction environment excluding heavy materials and prefers a collision of intense and energetic photon beams in vacuum.

A possible experimental scheme for studies of the BW process was suggested recently by Pike *et al.* [8]. The authors proposed to collide a GeV photon beam with a bath of thermal photons at a temperature of ~ 300 eV. The GeV photons are supposed to be created in the bremsstrahlung process of laser accelerated electrons in a mm-thick gold target.

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Laser intensities above 10^{19} W/cm^2 are required to accelerate electrons to GeV energies with gas jets using laser-wakefield acceleration, and intensities above 10^{21} W/cm^2 are required for solid targets. These electrons then generate the high-energy photons. The thermal x rays can be produced inside a high-Z *Hohlraum* with a separate laser pulse having energy of a few hundred kJ. Such an experimental configuration could be realized on the LMJ or NIF laser facilities [21,22] 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 can be operated only in a single-shot regime on an existing high-energy laser system, and it is prone to a high noise level due to the presence of a significant mass of heavy material. Moreover, the authors of a recent study of the bremsstrahlung process on a petawatt laser facility with the intensity close to 10^{21} W/cm^2 [23] reported a photon spectrum with a relatively low effective temperature of less than 10 MeV and a cut-off energy below 100 MeV. The softening of the photon spectrum is explained by an efficient creation of secondary electrons in the gold target. These observations demonstrate the difficulty to create an efficient GeV photon source based on the bremsstrahlung process. However, a source based on laser-wakefield electron acceleration can be suitable to produce a GeV electrons beam [24].

In this paper, we propose another experimental approach for the observation of the BW process. The scheme relies on the collision of two relatively low-energy (few MeV), intense photon beams. Such beams can be created by interacting intense laser pulses with thin aluminium targets or short and dense gas jets. By colliding two of them in vacuum, one would be able to produce a significant number of electron-positron pairs in a controllable way. It offers the possibility to conduct a multishot experiment with a reliable statistics on laser systems with pulse energies of the level of a few joules and in a low-noise environment without heavy elements. We provide details of the experimental setup, analytical estimates and numerical simulations of the expected yield of reactions and possible ways to create a photon source with requested parameters.

II. BREIT-WEELER PAIRS PRODUCTION IN LABORATORY

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

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

where ϕ is the angle between the colliding photons with energies $E_{\gamma_{1,2}}$, respectively. For the optimal geometry of a head-on collision, $\phi = \pi$, the product of energies of the colliding photons should be larger than 0.25 MeV^2. The appropriate choice of photons depends on the available sources. In the SLAC experiment with a laser delivering ~ 2 eV photons in a very short pulse of 20–30 fs, one would need a counterpart source of a few hundred GeV photons. 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 the expected number of Compton photons $\sim 10^5$, the probability of the BW process remains very small, which does not allow the direct BW process observation.

Another known source of intense photons is a *Hohlraum* heated by a high-energy laser pulse [8]. 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 [25]. This corresponds to a very significant number of photons $\sim 10^{20}$ confined in a millimeter-size volume on a nanosecond time scale. The counterpart photon source is then in the GeV range, which can be created today in the laboratory-scale laser installations [26]. However, this scheme [8], apart of making the photon interaction in a harsh *Hohlraum* environment, faces another challenge in producing an efficient GeV photon source. Although several approaches could be considered [27], 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 electron-positron pairs. This is the basis of our scheme to demonstrate the BW process: a collision of two identical MeV-photon beams. Pairs production is analytically estimated in two different cases: (i) GeV photon with thermal photons bath [8] and (ii) MeV-MeV photon collision.

The cross section of the BW process is given by the expression [1]:

$$\sigma_{\gamma\gamma}(s) = \frac{\pi}{2} r_e^2 (1 - \beta^2) \left[-2\beta(2 - \beta^2) + (3 - \beta^4) \ln \frac{1+\beta}{1-\beta} \right], \tag{2}$$

where $\beta = \sqrt{1 - 1/s}$ and $s = E_{\gamma_1} E_{\gamma_2} (1 - \cos\phi)/2 m_e^2 c^4$ is the relativistic invariant. This cross section is shown in Fig. 1. It achieves its maximum at $s \simeq 2$ and then decreases asymptotically as $1/s$.

In case (i), the thermal photons are described by the Planck distribution with the temperature T: $n(E_{\gamma_2}) = (E_{\gamma_2}^2 / \pi^2 c^3 \hbar^3)(e^{E_{\gamma_2}/T} - 1)^{-1}$. By integrating the cross section (2) over the energy of the second photon and the collision angle, one finds a probability per unit length for a photon of the energy E_γ to be converted into a pair in a collision with a thermal bath:

$$\begin{aligned} \tau_{\gamma\gamma} &= \frac{1}{4\pi} \int_0^\infty dE_{\gamma_2}\, n(E_{\gamma_2}) \int \sigma_{\gamma\gamma}(s)(1 - \cos\phi)\, d\Omega \\ &= \frac{\alpha^2}{\pi \lambda_C} \left(\frac{T}{m_e c^2} \right)^3 F(\nu), \end{aligned} \tag{3}$$

where $\lambda_C = \hbar/\mathrm{m_e c}$ is the Compton length and

$$F(\nu) = \frac{2}{\pi r_e^2 \nu^2} \int_{1/\nu}^\infty dx\, (e^x - 1)^{-1} \int_0^{x\nu} s\, \sigma_{\gamma\gamma}(s)\, ds$$

is a function of the variable $\nu = E_\gamma T / m_e^2 c^4$, which achieves a maximum close to unity for $\nu \simeq 2$.

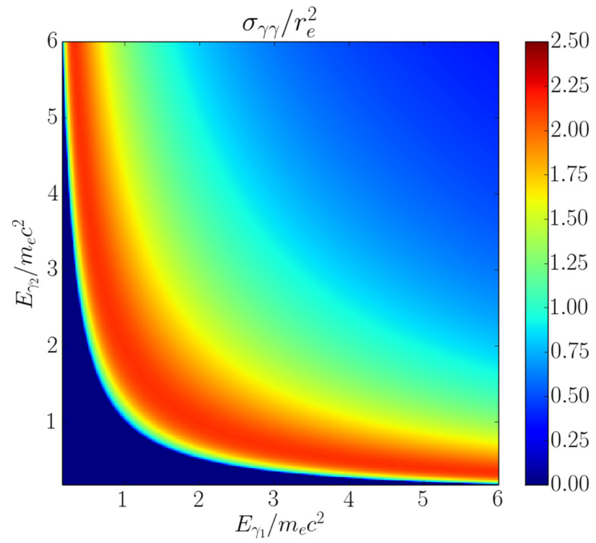

FIG. 1. Cross section $\sigma_{\gamma\gamma}$ versus E_{γ_1} and E_{γ_1} near the threshold for $\phi = \pi$.

As one can see in Fig. 2, a probability of creating a pair with 1 GeV photon increases from 10^{-6} cm^{-1} to 2×10^{-4} cm^{-1}, when the *Hohlraum* temperature increases from $T = 100$–400 eV. The total number of generated pairs, $N_p = N_\gamma \tau_{\gamma\gamma} L$ is proportional to the number of photons N_γ and the propagation length L. Then for $L = 1$ cm and $N_\gamma = 10^9$, one expects between 10^3 and 5×10^5 pairs per shot in that temperature range. The lowest pair number could be small compared to the expected noise level. Moreover, in the analysis of pairs production in a 1 GeV photon interaction with thermal photon in a high-Z *Hohlraum* one has to take into account that all pairs are generated inside the *Hohlraum* and their detection could be difficult. The authors [8] estimate $T = 250$ eV ($N_p = 5 \times 10^4$) as a figure of merit for such an experiment. Another important parameter is the intensity of the GeV photon source: one needs a reliable source of 10^9 photons per shot, or approximately 0.1 J in a bunch, the authors proposed to achieve this number with laser-wakefield accelerated electrons [24].

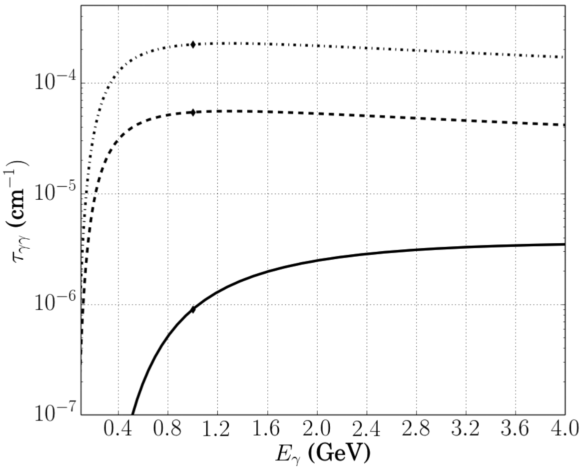

FIG. 2. Probability of BW pair creation per unit of length versus the incident photon energy E_γ for the thermal bath temperature, 100 (solid), 250 (dashed), and 400 eV (dash-dotted).

In case (ii), the use of MeV photons allows to reduce significantly the requirements on the photon source for a BW experiment. Assuming two conical γ beams with a divergence angle θ (half angle of the full divergence) intersecting at an angle ϕ, the interaction volume will be $V \sim 2\pi R^2 l_\gamma (1 - \cos\theta)$, where $l_\gamma = c\tau$ is the pulse length, τ is the pulse duration and R is the distance between the target and the collision zone. We suppose that R is much greater than the focal spot radius. The number of pairs can be estimated as $N_p \sim N_\gamma^2 \sigma_{\gamma\gamma}(\phi)/[2\pi R^2(1 - \cos\theta)]$, where N_γ is the total number of photons in the bunch. Taking for the estimate the maximum value for the cross section (2) the number of pairs, for 1 MeV beams and for $\phi = 180°$, reads

$$N_p \sim 10^8\, W^2/[R^2(1 - \cos\theta)], \tag{4}$$

where W is the photon beam energy in joules and R is the interaction distance in μm. Therefore, two beams having an energy of 1–10 J each, with a beam divergence angle $\theta = 30°$ and an interaction distance of $R = 500$ μm will produce in average 3×10^3–3×10^5 pairs per shot. A variation of the angle ϕ between the two photons beams may have a significant effect on the angular distribution of the pairs, which are emitted mainly in the bisector direction with respect to the incident photon beams. In the case of two counterpropagating photon beams the pair distribution is isotropic. By reducing the angle between the photon beams one may achieve a better collimation and an increase the pair number received by a detector. This conclusion follows from the relativistic kinematics considerations.

A source producing on average 2 J photon bunches with an effective temperature of 6 MeV is already available [23]. 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 [28] and Apollon [29] projects. The schematic experimental setup is shown in Fig. 3. Two photon beams are created from thin foils irradiated with laser pulses at a high intensity of 10^{22-23} W/cm^2. A separation of the interaction zone by a distance of 1–2 mm should be sufficient to distinguish between the pairs created in the BW process and the background as it is shown in the next section.

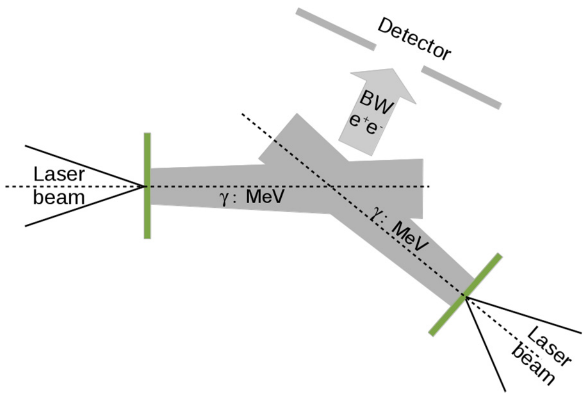

FIG. 3. Experimental setup for the Breit-Wheeler pairs production with MeV colliding photon beams.

TABLE I. Comparison of the different γ sources.

Source	Bremsstrahlung	Betatron	Compton	Synchrotron
Laser energy	100 J	5 J	20 J	100 J
γ energy	3–50 MeV	1–7 MeV	6–18 MeV	1–10 MeV
Beam energy	1–24 J	1 μJ	1 μJ	1–10 J
Efficiency	10^{-2}	10^{-6}	10^{-7}	10^{-1}
Divergence (θ)	$\sim$15°	$\sim$ 0.1°	$\sim$0.1°	$\sim$30°
Reference	[23]	[30]	[35]	[31]
N_p[a]	$\sim 10^4$	$\sim 10^{-3}$	$\sim 10^{-3}$	$\sim 10^4$

[a] Number of pairs according to Eq. (4) at a distance of 500 μm.

III. INTENSE COMPACT SOURCES OF MEV PHOTONS

According to the estimate (4) one may produce 10^3–10^4 pairs per shot, while using beams of 1–10 J of MeV photons. Various γ-ray sources can be considered: MeV photons can be produced via bremsstrahlung [23], betatron [30], Compton scattering [35], and synchrotron emission [31].

The regime of emission, collimation, and conversion efficiency depend on the laser intensity, duration, and the target properties. In order to make generation and detection of pairs experimentally feasible, the source should produce a collimated emission. This will allow us to define the direction of the pair emission and a create sufficient intensity of the photon beam in the collision area (see Fig. 3). The source brightness is also a crucial parameter allowing to produce a sufficient number of pairs far from the source. Table I provides a comparison between different γ-ray sources for BW pairs production.

The photon source based on the bremsstrahlung process can be realized by focusing an intense laser radiation on a mm-thick target of a high-Z material, gold or tungsten, for example. A large number of hot electrons is produced in the MeV energy range [34] for laser intensities 10^{20}–10^{21} Wcm^{-2}. In this case, 1–2 J beam of 3–50 MeV photons with a duration of 150 fs and an average angle θ of 15° has been reported [23]. The laser to γ-ray energy conversion around 2%. However, the use of high-Z material (gold) for the target leads to production of a large number of background e^+e^- pairs, greater than 10^{10} [16] due to the Bethe-Heitler process. This is much larger than the expected number of $\sim 10^4$ of BW pairs (see Table I).

The betatron sources of coherent radiation are produced with x-ray free electron lasers. By focusing a laser beam of 10^{18} W/cm^2 of a femtosecond duration inside a wave-guide plasma capillary, 10^8 photons in range of 20–150 keV are generated with a divergence $<1°$ [30]. However, the efficiency of such sources decreases with the photon energy. It should be possible to produce about 10^7 photons in the range of 1–7 MeV. Then the total beam energy is ~ 1 μJ, which is too low to produce a significant number of pairs per shot (see Table I).

The Thomson and Compton sources are more suited for higher photon and electron energies, above a hundred MeV, where their efficiency is higher [11,27,35]. In Ref. [35], one laser beam was used to produce a relativistic electron beam from a gas target, another laser beam was collided with the electron beam to produce photons from the inverse Compton scattering. In this experimental setup, 10^7 photons at 6 MeV can be generated with a low divergence $<1°$. But the pair number per shot is estimated to be $\sim 10^{-5}$, which is comparable to the betatron source (see Table I).

In the MeV range, the most suitable source is based on the synchrotron emission of energetic electrons in an intense laser field with an intensity $\sim 10^{22-23}$ W/cm^2. The numerical studies predict emission of photons with energies up to tens of MeV with the conversion efficiency of several tens percent [31,36–38].

A promising configuration to obtain bright sources of MeV photons consists in the use of a few μm thin foil. At the laser-solid interface, the incident and reflected waves form a standing wave, producing electrons with energies up to several hundred of MeV, $\gamma_e \sim a_0$. These electrons interact with the laser field and radiate high-energy photons. The characteristic energy of emitted photons $E_\gamma \sim \hbar\omega_0 a_0^3$ corresponds to the MeV range for the dimensionless laser amplitudes $a_0 \sim 100$. Simulations performed in Refs. [31–33] show that tens of percent of the laser energy can be converted into a well-collimated beam of 1–10 MeV photons for the laser intensity $\sim 10^{22}$ W/cm^2. By colliding photons from two such sources one may produce 10^4 pairs per shot. This number is comparable to the bremsstrahlung source (see Table I), but with a much lower level of background pairs.

According to Table I, the bremsstrahlung and synchrotron sources are the most suitable for pair production in the proposed setup.

IV. FEASIBILITY OF A MEV PHOTON COLLIDER

With the next generation of intense laser facilities the expected laser conversion in high-energy photons is $\sim$15%, which corresponds to an energy of $\sim$20 J, for a laser energy of 150 J as for the Apollon facility [29]. It is demonstrated in numerical simulations with two-dimensional particle-in-cell code CALDER [39].

A. MeV photon source from solid target

An aluminum foil 8 μm thick is irradiated at normal incidence at an intensity 10^{23} W/cm^2. The target density is 2.7 g/cm^3, corresponding to the number density $n_{Al} \sim 60 n_c$. The simulation is made with periodic transverse boundary conditions damping longitudinal boundary conditions both for the fields and the particles. The grid spacing is $\Delta x = \Delta y = 0.03c/\omega_0$, the time step is equal to $\Delta t = 0.02\omega_0^{-1}$, with 30 macroparticles per cell. The simulation domain is $300c/\omega_0$ ($\sim$48 μm) long and $45c/\omega_0$ wide ($\sim$7 μm). The pulse has a Gaussian shape with the duration $T_l = 20\pi\omega_0^{-1} \sim 33$ fs. The focal spot radius is 2 μm.

A typical angular-energy spectrum of photons produced in the laser-thin foil interaction is shown in Fig. 4. The photon beam divergence is about $\sim$60° and the maximum emission angle is at $\theta = 34°$ for a photon energy of 200 keV.

The number of photons in the range of 1–3 MeV emitted in a forward direction is $\sim 10^{12}$. The photon brightness is $\sim$0.14 J/MeV/sr and the brilliance is 2×10^{15} photons/sr/mm^2/s/0.1 bandwidth.

The number of BW pairs produced in a collision of two cylindrical photon beams of densities $n_{\gamma,1}$ and $n_{\gamma,2}$ and distribution functions $f_{\gamma,1}(\gamma_1,\theta_1)$, $f_{\gamma,2}(\gamma_2,\theta_2)$ in the volume

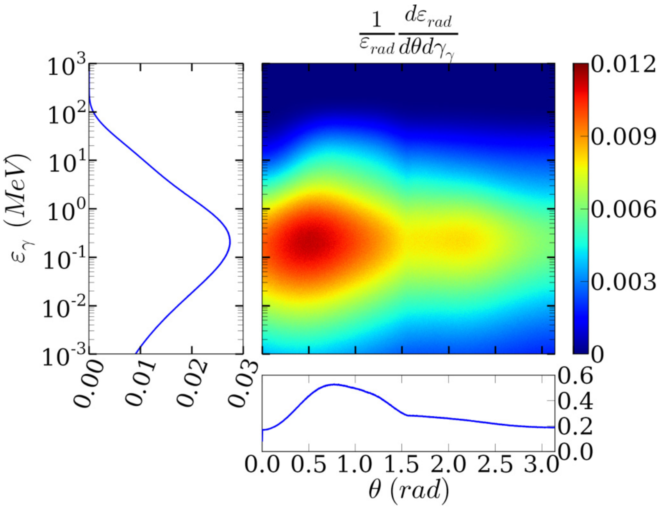

FIG. 4. Spectral and angular distribution of the emitted photon energy in the interaction of a laser pulse at 10^{23} W/cm^2 with an 8 μm aluminium target.

$V_\gamma = \pi R_\gamma^2 l_\gamma$ during the interaction time T_γ reads:

$$N_{\pm,BW} \sim n_{\gamma,1} n_{\gamma,2} V_\gamma c T_\gamma \int_{\gamma_{1\,\min}}^{\gamma_{1\,\max}} \int_0^\pi f_1(\gamma_1,\theta_1) \int_{\gamma_{2,\,\min}}^{\gamma_{2\,\max}} \int_0^\pi \times f_2(\gamma_2,\theta_2) \sigma_{\gamma\gamma}(1-\cos\phi) d\theta_1 d\theta_2 d\gamma_1 d\gamma_2. \tag{5}$$

This integral was calculated by using the photon distribution function f_γ shown in Fig. 4. The expected number of pairs is 10^8 produced right at the source.

However, this configuration is not the best choice to isolate pairs produced by the Breit-Wheeler process due to the fact that the Bethe-Heitler and trident mechanisms also contribute to the pair production. Knowing the number of photons produced $\sim 10^{12}$, the expected number of pairs from the trident process is 10^7 for the aluminium target $Z = 13$.

The number of pairs produced via the Bethe-Heitler (BH) mechanism can be estimated as $N_{pBH} = \sigma_{\gamma Z} N_\gamma n_{Al} L$, where $\sigma_{\gamma Z} \simeq Z^2 \alpha r_e^2$, the cross section σ_{γ_Z}, and the number of pairs produced in an aluminum target of thickness $L = 8\,\mu$m is 10^9.

Since the expected number of BH an BW pairs is compatible at the source, the photon collision zone needs to be separated from the source. A distance of 500 μm seems to be a reasonable compromise between a reduction of the background noise and a photon beam divergence. The expected number of Breit-Wheeler pairs can be estimated from the photon function distribution shown in Fig. 4 according the following expression:

$$N_{\pm,BW} \sim n_{\gamma,1} n_{\gamma,2} V_\gamma \int_{\gamma_{2\,\min}}^{\gamma_{1\,\max}} \int_{\gamma_{2\,\min}}^{\gamma_{2\,\max}} f_{\gamma,1} f_{\gamma,2} \sigma_{\gamma\gamma} l_\gamma d\gamma_1 d\gamma_2. \tag{6}$$

At a distance of 500 μm, considering a density of $n_\gamma \sim 3 \times 10^{19}$ cm^{-3} and a divergence angle of 35° we obtain a pair yield of 10^3, which is in agreement with Eq. (4) for the photon beam energy of 20 J.

B. MeV photon source from gas target

The laser interaction with a near-critical plasma could be also a bright source of high-energy photons. Moreover by choosing a low-Z gas the yield from BH process may be suppressed. We have performed numerical simulations considering a hydrogen plasma of a density $4n_c$ and a thickness $l_H = 80\,\mu$m. The laser pulse at an intensity of 10^{23} Wcm^{-2} ($a_0 = 270$) with a Gaussian temporal profile $T_l = 30$ fs was focused in a focal spot of a radius of 5 μm. The simulation box is 1400 c/ω_0 long and 500 c/ω_0 wide with a grid spacing $\Delta x = \Delta y = 0.2c/\omega_0$ and a time step $\Delta t = 0.2\omega_0^{-1}$ with 40 macroparticles per cell. The plasma has a $\cos^2$ density profile in the longitudinal direction and a constant in transverse direction with an initial temperature of 100 eV. Absorbing boundary conditions are applied in the longitudinal direction and thermalizing boundary conditions are used in the transverse direction.

At the end of simulation more than 90% of the laser energy has been absorbed and 45% has been transferred to high-energy photons. The time-integrated photon spectrum in energy ε_γ and emission angle θ is shown in Fig. 5. The maximum emission is located around 28° and the angular width corresponds to 15°. The forward emitted energy photon is 47 J (70% of the radiated energy) in a range 0.1–10 MeV. A brilliance is equal to 10^{16} photons/sr/mm^2/s/0.1 bandwidth and a brightness is 0.4 J/MeV/sr. The number of forward emitted photons of an energy up to 1 MeV is equal to 2×10^{13}. The average photon energy is equal to 2.7 MeV.

By colliding two such photon beams at the source according to Eq. (5) one may create 10^8–10^9 pairs. At a distance $R = 500\,\mu$m from the source, the beam average radius is $R_{\gamma R} \sim 200\,\mu$m and the photon density 6×10^{19} cm^{-3}. The expected yield of the BW pair according to Eq. (6) is 10^3–10^4, similar to the case of an aluminium target. The focal spot is larger in case of a gas target but the pulse duration is longer.

An estimate of the background pair yield due to the Bethe-Heitler mechanism, is of the order of 10^8 ($\sim 10^7$

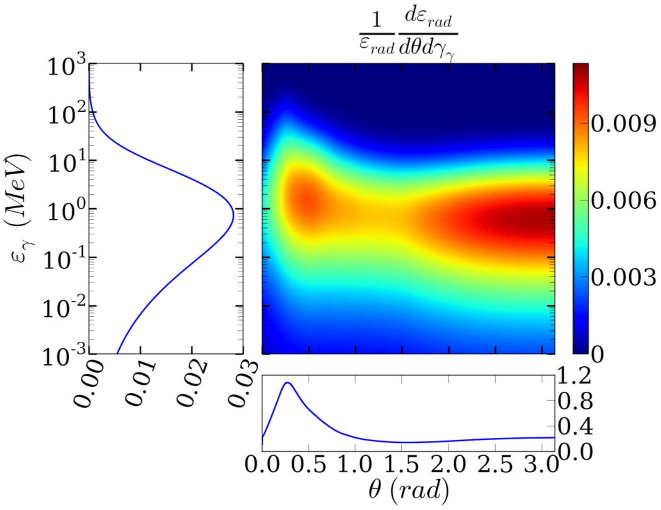

FIG. 5. Spectral and angular distribution of the emitted photon energy in the interaction of a laser pulse at 10^{23} W/cm^2, in the case of gas target, $n_e = 4n_c$, 80 μm.

forward emitted). This is similar for the aluminium target. A suppression of the pair production due to a smaller ion charge is compensated by the difference in the photon spectrum, the total radiated energy, and the fact that all photons (forward and backward emitted) contribute to the BH process. Therefore, for the detection of the BW process one needs to separate the photon-photon interaction zone from the source targets. The collision of photon beams at an angle $\theta \sim 90^\circ$ offers another important advantage for the BW pairs detection, as both electron and positron will be emitted in the preferential bisection direction. This may allow a better signal-to-noise ratio even for a large total number of background pairs.

V. CONCLUSION

Qualitative estimates and numerical simulations show that about 10^8 BW pairs can be produced with existing sources of MeV photons. This number is comparable with the expected number of BH pairs. A separation of the BW and BH processes can be achieved by placing the photon collision zone far from the source. About 10^4 pairs can be generated at the distance $R = 500\ \mu\text{m}$ from the source. This number is comparable to the pair number given in Ref. [8], however, with a much better control of background processes. The choice of the distance and a crossing angle give a possibility to optimize the signal-to-noise ratio. Two suitable γ-ray sources, the bremsstrahlung and synchrotron sources, are offering a good conversion efficiency. Although the expected number of BW pairs is sufficiently high, the major challenge is to discriminate them from other pairs created by the trident and Bethe-Heitler processes in the photon source target. A shield could be designed to eliminate high-energy photons and pairs production processes [19,20]. Moreover, to deflect the background pairs, a strong magnetic field (100 Tesla) could be used [40]. A spatial separation of the photon-photon interaction zone is a promising way for the detection of the BW pairs emitted in the preferential direction. Further work is needed for estimation of the pair number and energy spectrum in the chosen experimental configuration.

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