Creation of Electron-Positron Pairs in Photon-Photon Collisions Driven by 10-PW Laser Pulses

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A novel approach is proposed to demonstrate the two-photon Breit-Wheeler process by using collimated and wide-bandwidth γ-ray pulses driven by 10-PW lasers. Theoretical calculations suggest that more than 3.2×10^8 electron-positron pairs with a divergence angle of 7° can be created per shot, and the signal-to-noise ratio is higher than 10^3. The positron signal, which is roughly 100 times higher than the detection limit, can be measured by using the existing spectrometers. This approach, which could demonstrate the e^-e^+ pair creation process from two photons, would provide important tests for two-photon physics and other fundamental physical theories.

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The interaction between two photons, which is theoretically well understood by quantum electrodynamics (QED) theories [1–3], has never been observed directly. Experimental study of photon-photon interaction could provide important tests for fundamental theories in physics [1]. The e^-e^+ pair creation from two-photon interaction, named the Breit-Wheeler (BW) process ($\gamma + \gamma' \to e^+ + e^-$) [4,5], is considered to be the first step toward two-photon physics [1–3], since the cross section of the BW process is several orders of magnitude larger than that of photon-photon scattering [6]. In the past few years, there has been increased interest [6–12] in investigating the two-photon BW process in the laboratory, even though the multiphoton BW process ($\gamma + n\gamma' \to e^+ + e^-$) was demonstrated in 1997 [13].

The conventional accelerator-based photon-photon collider [6,8,9] is considered to be controllable, reliable, and reproducible, but a large machine is needed [6]. A laser-based photon-photon collider [7,10–12] could produce 10^2–10^5 two-photon BW events in a single shot. Pike *et al.* [7] proposed the first scheme of a photon-photon collider in vacuum. In that scheme, a large number of background events are generated from the Bethe-Heitler process [14,15] since most of the γ-ray photons out of the focal spot interact with the hohlraum. Ribeyre and co-workers [10,11] proposed a photon-photon collider to produce e^-e^+ pairs in a preferential direction by using mega-electron-volt photon sources. However, efforts are needed to distinguish the signal from the much larger number of background positrons generated from the stage of γ-ray source production [16–18].

The production of the two-photon BW process is a function of photon number, collision area size, and photon-photon cross section [10]. Laser power density above 10^{23} W/cm^2 should be accessible in the upcoming laser facilities [19,20]. Under such power density, a large number ($>10^{13}$) of γ rays (>0.511 MeV) [16,18,21–27] can be generated with a large divergence angle of $\sim 30°$ [16,22,25,27,28]. The photon source of such a huge number could be a perfect choice for a photon-photon collider only if the photon divergence and the background positrons can be greatly reduced.

In this Letter, a photon-photon collider is proposed by using the wide-bandwidth γ-ray pulses generated from the interaction between 10-PW lasers and narrow tube targets [24]. In each γ-ray pulse, $\sim 10^{14}$ γ-ray photons are collimated into a divergence angle of 3°. Theoretical calculations suggest that more than 3.2×10^8 positrons with a divergence angle of 7° can be generated in a single shot. The signal of the collimated positrons is roughly 100 times higher than the detectable threshold of the existing spectrometer [29,30], and the noise level (positrons generated from other processes) is less than 0.1% of the signal. With this proposal, observation of the two-photon interaction predicted by the QED theories would become a reality in the laboratory.

In the photon-photon collisions, more events can be generated with higher flux photon beams. The rapid development of high power lasers [31] is paving the way to generate energetic and high flux γ-ray sources [3]. Recently, a high flux γ-ray pulse generated through the interaction between an ultraintense laser pulse and a narrow tube target was theoretically and numerically studied [24]. The narrow tube target was suggested to be produced by using commercial 3D printers [32]. In the interaction, electrons are pulled into the narrow space by the laser transverse electric field at the beginning, and slip into the acceleration phase of the longitudinal electric field which accelerates the electrons longitudinally and surpass transverse momenta [33], resulting in the collimation of energetic electrons. The dynamics of the collimated energetic electrons in the narrow tube target has also been demonstrated by other groups [33,34]. Because of the transverse modulation of the electron density, large charge separation fields are generated near the target surface. After an acceleration distance of $< 100\ \mu$m, the electrons slip into the deacceleration and are pulled back to the tube wall by the charge separation fields which significantly enhance the γ-ray radiations near the tube wall. The γ-ray photons can be well collimated since the spread angles of the photons are determined by the emitting electrons [35]. The physical model works well in both 2D and 3D simulations. The narrow tube target has also been proposed to generate collimated energetic electrons [33], ultrahigh brilliance x-ray source [34], and γ-ray source [32] with the readily available laser pulses.

Figure 1 shows the design of the photon-photon collider. The 10-PW lasers, whose power density is 3.2×10^{23} W/cm^2, irradiate edges of two narrow tube targets [24] for the generation of γ-ray pulses. The γ-ray pulses collide in the interaction area at an angle θ_c. The power density of the remaining laser pulse is much lower than 5.0×10^{20} W/cm^2 after propagating in vacuum for a distance $d_1 \geq 70\ \mu$m from the target end to the collision point. One can safely avoid the e^-e^+ pairs produced from the multiphoton BW process between the γ-ray photons and the remaining laser pulse from the other side [16,36]. The length of the targets d is fixed to 200 μm because most of the photons are generated at 70–200 μm. The effective distance from the γ-ray source's original location to the collision point approximates $d_1 + 130\ \mu$m. The spectrometers which can separate the electrons and positrons [29,30] are placed in the directions where the events of e^-e^+ pairs are maximum.

The simulation of generating collimated γ-ray pulses is performed by using the particle-in-cell code EPOCH [37–39] with the parameters of the upcoming lasers [19,20]. The simulation setup can be found in Ref. [24]. In the simulation, more than 1.0×10^{14} γ-ray (>10 keV) photons with a divergence of 3° [Fig. 2(a)] are generated in a single pulse. After propagating a distance of $d_1 = 70\ \mu$m to the collision area, the γ-ray pulse duration is about 21 fs and the focal spot is about 25 μm in diameter. The brilliance of the

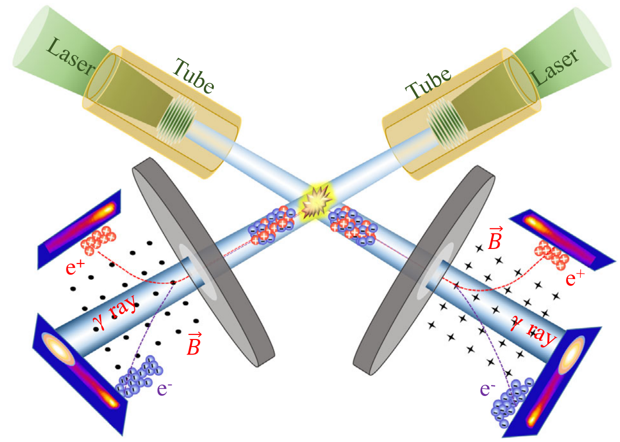

FIG. 1. The design of photon-photon collider. Two highly collimated γ-ray pulses are generated by focusing the 10-PW lasers into the narrow tube targets, whose length is $d = 200\ \mu$m, inner diameter is 4 μm, and thickness is 400 nm. The γ-ray pulses collide outside of the targets where e^-e^+ pairs can be created. The collision angle is θ_c and the distance from the tube target end to the collision point is d_1. The spectrometers, which have been used to detect the laser produced positrons, can be placed at more than 100 cm away from the collision area. A collimator (shielding) should be used to reduce the effect of the electrons with large spread angle on the image plates. The targets should be renewed each shot, as they will be destroyed by the main pulses.

γ-ray pulse is about 1.5×10^{25} photons s^{-1} mm^{-2} mrad^{-2} 0.1% BW (at 0.5 MeV). The luminosity of head-on colliding beams [40] for different d_1 is plotted in Fig. 2(b).

In modeling all the possible collisions between two photon beams of photon number 10^{14}, more than 10^{28} interactions are required. Such computation charges too large to be handled. The method of macroparticles, which is used in plasma simulations [41], can greatly reduce the computational requirement by merging a number of particles into one macroparticle. Here, we represent a large number of photons with similar energies and momenta as a macrophoton by dividing the spectral-angular distribution [Fig. 2(a)] into segments with steps of

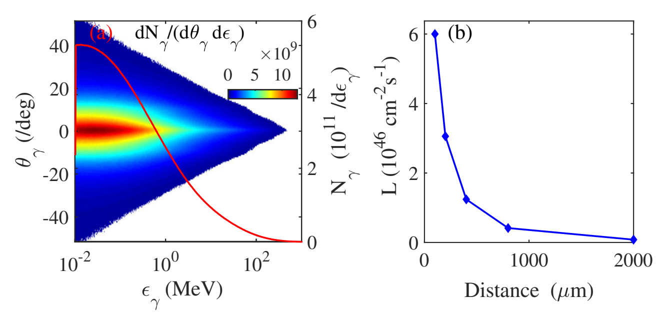

FIG. 2. (a) The spectral-angular distribution of the γ-ray pulse. The red line represents the energy spectrum. (b) The luminosity of head-on colliding beams with distance d_1. The collision rate is 1.43×10^{22} s^{-1}.

$d\gamma = (\{\log_{10}[\varepsilon(\mathrm{keV})]\} \times 100)$ and $d\theta_\gamma = 0.1°$. The weight of the macrophoton equals the number of photons in each bin. The energy and momentum of the macrophoton can be evaluated by averaging all the photons in the macrophoton. Then, one can handle all the possible two-photon BW processes between the macrophotons in two beams.

In two-photon interaction, the creation of the e^-e^+ pair is subject to the threshold condition $\varepsilon_{\gamma_1}\varepsilon_{\gamma_2}(1-\cos\theta_c) \geq 2(m_ec^2)^2$, where ε_{γ_1}, ε_{γ_2} are the energies of the photons, m_e is the electron mass at rest, and c is the light speed in vacuum. The cross section of the BW process is

$$\sigma_{\gamma_1\gamma_2} = \frac{\pi}{2} r_0^2(1-\beta^2)\left[(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right) - 2\beta(2-\beta^2)\right], \tag{1}$$

where r_0 is the classical electron radius, $\beta = (1-1/S)^{1/2}$, and $S = \varepsilon_{\gamma_1}\varepsilon_{\gamma_2}(1-\cos\theta_c)/2(m_ec^2)^2$. After the collision, the total energy of the two photons is equally distributed to the electron and the positron in the center-of-mass (c.m.) frame. In the c.m. frame, the energy of the electron ε_{ec} (positron ε_{pc}) can be expressed as

$$\varepsilon_{ec} = \varepsilon_{pc} = \frac{1}{2}\sqrt{2\varepsilon_{\gamma_1}\varepsilon_{\gamma_2}(1-\cos\theta_c)}, \tag{2}$$

and the electron (positron) momentum $\vec{p}_{ec}$ ($\vec{p}_{pc}$) has the following relation,

$$|p_{ec}| = |p_{pc}| = \sqrt{\frac{1}{4}\left[\left(\frac{\varepsilon_{\gamma_1}+\varepsilon_{\gamma_2}}{c}\right)^2 - (\vec{p}_{\gamma_1}+\vec{p}_{\gamma_2})^2\right] - (m_ec^2)^2}, \tag{3}$$

where $\vec{p}_{\gamma_1}$ and $\vec{p}_{\gamma_2}$ are the momenta of the γ-ray photons in the laboratory frame. The direction of the electron (positron) momentum is considered to be isotropic in the frame of the c.m., but $\vec{p}_{ec} = \vec{p}_{pc}$ must be satisfied. Through Lorentz transformation, one can get the electron (positron) energy ε_e (ε_p) and momentum $\vec{p}_e$ ($\vec{p}_p$) in the laboratory frame:

$$\varepsilon_{e,p} = \gamma_c(\varepsilon_{ec,pc} + \vec{v}_c \cdot \vec{p}_{e,p}), \tag{4}$$

$$\vec{p}_{e,p} = \vec{p}_{ec,pc} + \frac{\gamma_c - 1}{v_c^2}(\vec{v}_c \cdot \vec{p}_{ec,pc}) \cdot \vec{v}_c + \frac{\gamma_c \vec{v}_c \varepsilon_{ec,pc}}{c^2}, \tag{5}$$

where $\gamma_c = 1/\sqrt{1-(v_c/c)^2}$, the velocity of the c.m. $\vec{v}_c$ can be expressed as

$$\vec{v}_c = (\vec{p}_{\gamma_1} + \vec{p}_{\gamma_2})^2/(\varepsilon_{\gamma_1} + \varepsilon_{\gamma_2}). \tag{6}$$

In each interaction above the threshold, a macropair can be generated. The weight value of the macropair is $w_{\mathrm{pair}} = w_{\gamma_1}w_{\gamma_2}\sigma_{\gamma_1\gamma_2}/S_c$, where S_c is the cross area size of the photon beams, $\sigma_{\gamma_1\gamma_2}$ is the cross section of the BW process, and w_{γ_1} and w_{γ_2} are the weights of the macrophotons. This method can be easily extended to handle the photon-photon collider in full three dimensions if the spectral distribution in the other transverse direction is included in the spectral-angular distribution [Fig. 2(a)].

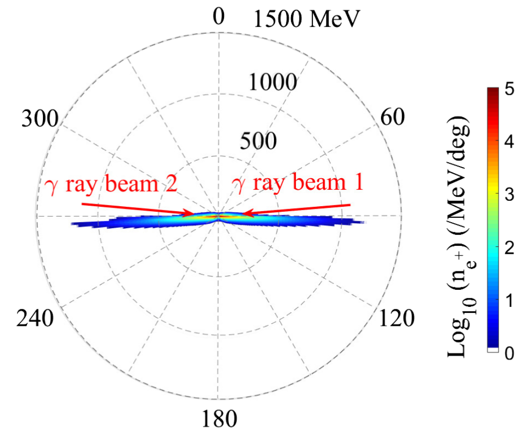

FIG. 3. The angular-spectrum distribution of the positrons from the photon-photon collider with a collision angle $\theta_c = 170°$ and $d_1 = 70$ μm. The directions of the positron bunches, which are directed between two γ-ray pulses, are ~0.4° off the direction of the γ-ray pulses.

Here is an example of the calculation. Double γ-ray pulses [Fig. 2(a)] are employed in the photon-photon collider, in which the collision angle is assumed to be $\theta_c = 170°$, and the distance from the tube target end to the collision point is $d_1 = 70$ μm. More than 8.7×10^{10} (3.2×10^8) macropairs (e^-e^+ pairs) can be created in a single shot. Figure 3 shows the spectral-angular distribution of the positrons (almost the same as that of the electrons) from the calculation. The low energy positrons are distributed in full angle while the energetic positrons are better collimated (Fig. 3). It is noted that most of the positrons are collimated into a divergence angle of 7°. More than 1.4×10^6 positrons can be emitted within an angle of 2.5 mrad, which is roughly 100 times higher than the detectable threshold of the spectrometers [29,30]. Consulting with the previous experiments [14,29,30], the allowed maximum distance from the source to the image plate is 282 cm. In addition to the generation of e^-e^+ pairs, ~1000 photon-photon scattering events and ~1.0 muon-antimuon pair can be produced in each shot.

In the two-photon BW process, the pair direction is determined by the c.m. direction. For the collision between monoenergetic beams, most of the positrons are directed in the middle of the two beams [11]. If photon beams of wide bandwidth are used, most of the e^-e^+ pairs are created in the collisions of photons with unequal energies: a high energy photon [the tail of distribution in Fig. 2(a)] from one beam collides with a less energetic photon in the other beam. The positrons are directed close to the direction of the γ-ray pulse and better collimated if higher energy photons are involved in collisions (more details can be found in the Supplemental Material [42]). Hence, the γ-ray pulse of wide bandwidth and better collimated at higher energy [Fig. 2(a)] could be a perfect choice to create collimated e^-e^+ pairs as shown in Fig. 3.

In the design (Fig. 1), additional e^-e^+ pairs can be generated from the Trident [14], Bethe-Heitler [14,29,43,44], and Triplet processes [45,46], due to the presence of the tube and the energetic electrons from the other side. All of the additional positrons are considered to be noise in this work. During the stage of γ-ray generation in the 400-nm-thick gold tube, the processes of Bethe-Heitler, Triplet, and Trident result in 1.4×10^7, 4.0×10^6, and 2.7×10^6 positrons, respectively. The methods to calculate the above positron productions can be found in the Supplemental Material [42]. The positrons which move out of the tube wall due to initial transverse momenta are deflected off the collision area by the transverse electric field (1.4×10^{14} V/m) near the outer surface of the tube target (for more details, see Supplemental Material [42]). Thus, the positrons generated from the narrow tube target could be safely ignored. The electron-electron scattering [2] of the primary energetic electrons could affect the detected electrons only, since the electrons and positrons are separated by the magnetic field. In the collision area, an electron cloud from the other side will interact with the γ-ray pulse, and the triplet positrons [45,46] is the only noise source that will be detected by the spectrometers. The density, width, and charge of the electron cloud are about $1.5 \times 10^{27} \mathrm{m}^{-3}$, 25 μm, and <1000 nC, respectively. The maximum production of the triplet positrons is 6.4×10^4 only if all the electrons are involved in the interaction. The divergence of the triplet positrons, which is determined by the high energy photons, is about 3°. Hence, the BW signal is more than 3 orders of magnitude higher than the noise level.

Figure 4(a) shows the e^-e^+ pair production N_p for different collision angles θ_c, from which one can see that more pairs can be created at larger θ_c since more photons of low energy can satisfy the threshold condition of e^-e^+ pair creation. Meanwhile, the positron divergence angle θ_p strongly depends on θ_c (the angular distribution of the positron for different collision angles θ_c can be found in the Supplemental Material [42]). The tendency of θ_p is completely different from the previous results with mono-energetic mega-electron-volt photon sources [10,11], due to the huge difference on photon energy spectra. For all the listed collision angles [Fig. 4(a)], the positron signal is several orders of magnitude higher than the noise level.

The relation between the γ-ray beam incident angle and the e^-e^+ pair emergence angle is also considered, with the results plotted in Fig. 4(a) (blue line). The positron direction, which is directed between two γ-ray pulses, is

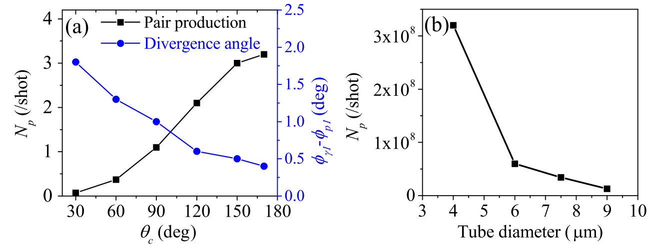

FIG. 4. The distance d_1 is 70 μm and $\theta_c = 170°$. (a) The effect of the collision angle θ_c on the e^-e^+ pair production N_p (black line) and the relations between the incident angle of the γ-ray beam 1 $\phi_{\gamma 1}$ and the pair emergence angle ϕ_{p1} (blue line). (b) The influence of tube inner diameter on pair production N_p under the same laser power of 10 PW while changing the tube inner diameter from 4 to 9 μm.

0.4°–2.0° off the incident γ-ray pulse direction. For larger θ_c, the pair direction is much closer to the direction of the incident γ-ray pulse, as shown in Fig. 4(a). We also check the effect of the distance d_1 on the e^-e^+ pair production. It is found that the pair production decreases with the enhancement of d_1. In the case of $\theta_c = 170°$, a maximal value of d_1 is allowed to ~1.8 mm considering the detectable threshold of the spectrometers [29,30].

In practice, one can use much thicker tubes with the same inner diameter since the tube thickness does not affect the results of the γ-ray pulse. However, the targets need to be renewed each shot as they will be destroyed by the main pulses. The prepulse, which is inevitable, can result in the expansion of the target. In a simulation using a preexpand target with a scale length of 15 nm, there are no drops on the photon production and collimation. Such target expansion could result from prepulses with contrast less than 10^{-10} about 5–10 ps before the main pulse, which is readily available in a 10-PW laser by employing pulse cleaning techniques [47]. We also check the requirement on pointing stability during the generation of the γ-ray pulse by irradiating the laser 1 μm off the axis. The photon divergence angle increases to 5° and photon production is enhanced by a factor of 0.33. Using such γ-ray pulses, the scheme is still realizable since the e^-e^+ pair production only drops by a factor of ~0.6.

The divergence angle and energy conversion efficiency of the γ-ray pulse, both of which are affected by the tube inner diameter and laser power density [24], would significantly impact the results of a photon-photon collider. Figure 4(b) shows the effects of tube inner diameter on the e^-e^+ pair production N_p. From the figure, one can see that enlarging the tube inner diameter to ~10 μm, better for a laser pulse injecting into the tube, can still ensure the detection by the spectrometers. The effect of the laser power on pair production is also considered (for more details, see Supplemental Material [42]). It is found that a laser power of ~4 PW is allowed to realize the scheme without any further design on the spectrometers [29,30].

In conclusion, a novel approach to experimentally demonstrate the creation of electron-positron pairs from the two-photon Breit-Wheeler process is proposed by employing the highly collimated γ-ray pulses with wide bandwidth generated from the interaction between 10-PW laser pulses and narrow tubes. Theoretical calculations suggest that more than 3.2×10^8 pairs can be created in a single shot, the pairs are well collimated with a divergence angle of 7°, and the signal-to-noise ratio is higher than 10^3. This method, which is robust for a wide range of parameters, can realize the observation of two-photon interaction in the laboratory with the upcoming 10-PW laser facilities.

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