High-energy $\gamma$-photon polarization in nonlinear Breit-Wheeler pair production and $\gamma$ polarimetry

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The interaction of an unpolarized electron beam with a counterpropagating ultraintense linearly polarized laser pulse is investigated in the quantum radiation-dominated regime. We employ a semiclassical Monte Carlo method to describe spin-resolved electron dynamics, photon emissions and polarization, and pair production. Abundant high-energy linearly polarized $\gamma$ photons are generated intermediately during this interaction via nonlinear Compton scattering, with an average polarization degree of more than 50%, further interacting with the laser fields to produce electron-positron pairs due to the nonlinear Breit-Wheeler process. The photon polarization is shown to significantly affect the pair yield by a factor of more than 10%. The considered signature of the photon polarization in the pair’s yield can be experimentally identified in a prospective two-stage setup. Moreover, with currently achievable laser facilities the signature can serve also for the polarimetry of high-energy high-flux $\gamma$ photons.

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Rapid advancement of strong laser techniques [1–4] enables experimental investigation of quantum electrodynamics (QED) processes during laser-plasma and laser-electron beam interactions. Nowadays, ultrashort ultraintense laser pulses can achieve peak intensities of about $10^{22} \text{ W/cm}^2$, with a duration of about tens of femtoseconds and an energy fluctuation $\approx 0.01$ [5–7]. In such laser fields, QED processes become nonlinear, involving multiphoton processes [8]: A $\gamma$ photon can be generated via nonlinear Compton scattering [9–11], or similarly a $\gamma$ photon can create an electron-positron pair in the interaction with a strong laser wave in the nonlinear Breit-Wheeler (BW) process [12]. These processes have been experimentally observed in Refs. [13–15] and recently were considered in all-optical experimental setups [16–20]. Presently, there are many theoretical proposals aiming at $\gamma$-ray and pair production with ultrashort laser fields of achievable or almost achievable intensities [21–28] and even avalanche-like electromagnetic cascades in future extreme laser intensities $\simeq 10^{24} \text{ W/cm}^2$ [29–36].

Recently, it has been realized that the radiation reaction due to $\gamma$ photon emissions in laser fields can be harnessed to substantially polarize electrons [37–43] or to create polarized positrons [44,45], while it has been known for a long time that an electron beam cannot be significantly polarized by a monochromatic laser wave [46–48]. Polarization properties of electrons, positrons, and $\gamma$ photons in ultrastrong laser-electron beam interaction have been investigated comprehensively in Refs. [41,44,49]. It is known that an efficient way of the polarization transfer from electrons to high-energy photons can be realized via linear Compton scattering; see, e.g., Refs. [50,51]. The extension of this technique into nonlinear regime is possible [47,52–54]. In the extreme nonlinear regime, it will allow us to obtain circularly polarized brilliant $\gamma$ rays via nonlinear Compton scattering from longitudinally spin-polarized electrons [49], highly sought in detecting schemes of vacuum birefringence in ultrastrong laser fields [55–57].

Significant efforts have been devoted to the investigation of pair production channels in ultrastrong laser-electron beam interaction [21,22,24–32]. General theory for the pair production by polarized photons in a monochromatic plane wave is given in Ref. [58]. A particular case of the multiphoton BW process with linearly polarized (LP) $\gamma$ photons of MeV energy and moderately strong x-ray laser field is considered in Ref. [59]. The role of the $\gamma$-photon polarization within the BW process in a constant crossed field is considered in Ref. [60], applying a spin-averaged treatment for the photon emission by an electron. While the latter gives a hint about the photon polarization effect, it is not straightforwardly extendible to the realistic setups with tightly focused laser beams. Most simple expressions for probabilities of the polarization effects in pair production process have been obtained in local constant field approximation (LCFA) [61,62]. They show that the pair production probability depends strongly on the photon polarization and that photons emitted via nonlinear
Compton scattering are, in general, polarized (the LCFAs probabilities have been successfully tested in experiments of pair production in channeling process, where the strong fields are produced within crystal plane and axes [63–65]). From the latter, one may expect that during the ultrastrong laser-plasma interaction the polarization of intermediate particles will strongly influence the pair production process. Therefore, we underline that for the quantitative correct predictions of pair production yields in laser-plasma interaction, the polarization-resolved treatment of intermediate particles is necessary.

In this Rapid Communication, the BW pair production process in a realistic laser-electron beam interaction setup is investigated in the quantum radiation-dominated regime. An unpolarized ultrarelativistic electron beam is considered to head-on collide with an ultrastrong LP tightly focused laser pulse, which results in radiation of highly LP high-energy $\gamma$ photons via nonlinear Compton scattering. Further, generated polarized $\gamma$ photons interact with the laser fields creating electron-positron pairs within the nonlinear BW process; see the interaction scenario in Fig. 1(a). We apply a fully-polarization-resolved Monte Carlo simulation method developed in Refs. [41,49] to describe the spin-resolved electron dynamics, polarized photon emissions, and pair production by the latter (see also Ref. [66] for linear and weakly nonlinear regimes). We elucidate the substantial role of intermediate polarization of photons on the pair’s yield and show how the photon polarization signature can be detected in a two-stage setup, using laser fields of different linear polarizations and different intensities in these stages. Moreover, our results suggest an interesting application in high-resolution polarimetry of high-energy and high-flux LP $\gamma$ rays through the pair yield.

Note that the high-resolution polarimetry of high-energy $\gamma$ rays is an important problem in astrophysics and high-energy physics, which can be employed, e.g., to determine the nature of the emission mechanisms responsible for blazars, $\gamma$-ray bursts (GRBs), pulsars, and magnetars and to address problems in fundamental physics [67–70]. Current polarimetrices for high-energy $\gamma$ photons mainly employ the principles of Compton scattering and Bethe-Heitler pair production by the Coulomb fields of atoms, with an accuracy of about several percent [69,70]. The former is not efficient at photon energies larger than 100 MeV because of the kinematic suppression of the Compton rate at large scattering angles; in the latter the photon flux and polarimetry angular resolution are restricted by the convertor material (damage threshold and multiple scattering), because, in particular, multiple scattering in a convertor material decreases significantly the angular resolution of polarimetry [68–72]. Our polarimetry concept via nonlinear BW pair production working in a small duty cycle (determined by the laser pulse) is specifically designed for high-flux GeV $\gamma$ photons and provides a competitive resolution.

We consider the quantum radiation-dominated regime, which requires a large nonlinear QED parameter $\chi_e \equiv |e| \sqrt{- (F_{\mu\nu} F^{\mu\nu}) / m^2} \geq 1$ (for electrons and positrons) [8] and $R \equiv \omega_{0a} \chi_e \geq 1$ [73]. Significant BW pair production requires the nonlinear QED parameter $\chi_\gamma \equiv |e| \sqrt{- (F_{\mu\nu} k^\mu k^\nu) / m^2} \geq 1$ (for $\gamma$ photons) [8,74]. Here, $E_0$ and $\omega_0$ are the laser field amplitude and frequency, respectively, $p$ and $k_\gamma$ are the 4-momenta of electron (positron) and photon, respectively, $e$ and $m$ are the electron charge and mass, respectively, $F_{\mu\nu}$ is the field tensor, $\alpha$ is the fine structure constant, and $\omega_0 = |e| E_0 / m_0 c$ is the invariant laser field parameter. Relativistic units with $c = \hbar = 1$ are used throughout.

In our Monte Carlo method, we treat spin-resolved electron dynamics semiclassically and photon emission and pair production quantum mechanically in LCFAs [8,74–76], valid at $a_0 \gg 1$ (for the emitted photon energies in the region $k_- \gg \chi_e / a_0^2 p_-$, with $k_- = \omega - k_z$ and $p_- = \epsilon - p_z$ being the photon and electron light-cone energies, respectively [77]). At each simulation step, the photon emission is calculated following the common algorithms [78–80] and the photon polarization following the Monte Carlo algorithm [49]. The photon Stokes parameters $(\xi_1, \xi_2, \xi_3)$ are defined with respect to the axes $\hat{e}_1 = \hat{a} - \hat{v} (\hat{v} \times \hat{a})$ and $\hat{e}_2 = \hat{v} \times \hat{a}$ [81], with the photon emission direction $\hat{n}$ along the ultrarelativistic electron velocity $\hat{v}$, $\hat{v} = v / |v|$, and the unit vector $\hat{a} = a / |a|$ along the electron acceleration $\mathbf{a}$. After the photon emission, electron spin state is determined by the spin-resolved emission probabilities [41]. Between photon emissions, the spin precession is governed by the Thomas-Bargmann-Michel-Telegdi equation [82–84]. The electron spin dynamics simulated by our method is in accordance with the results of the CAIN code [66], applicable for simulating the electron-laser as well as beam-beam collisions. Note that the latter use a slightly different Monte Carlo algorithm for spin evolution (the spin...
quantization axis after the photon emission is chosen along the average spin direction, with further quantum mechanical spin rotation due to the probability of no photon emissions).

We describe the polarized photon conversion to electron-positron pair by the probabilities of the pair production. The latter, summing over the pair spins, is derived in the leading-order contribution with respect to 1/γ, via the QED operator method of Baier-Katkov [62]:

$$\frac{d^2W_{\text{pair}}}{de_\gamma dt} = \frac{\alpha m^2}{\sqrt{3\pi}\epsilon_\gamma} \left\{ \text{IntK}_1(\rho) + \left( \frac{e_+^2 + e_-^2}{e_+ e_-} - \xi_3 \right) \text{K}_2(\rho) \right\},$$

(1)

where $e_-$ and $e_+$ are the energies of created electron and positron, respectively, with the photon energy $\epsilon_\gamma = e_+ + e_-$, $\rho \equiv 2e_\gamma^2/(3\chi_\gamma e_+ e_-)$, $\text{IntK}_1(\rho) \equiv \int_0^\infty d\xi \text{K}_1(\xi)$, and $\text{K}_n(\xi)$ is the $n$-order modified Bessel function of the second kind. In this relativistic setup, the emitted $\gamma$ photon is assumed to propagate along the radiating electron momentum, and the pair is assumed to do so along the parent $\gamma$-photon momentum. Note that by averaging over the photon polarization one obtains the known pair production probability $W_{\text{pair}}^{\text{Exc.Pol.}}$ [74] and $W_{\text{pair}} = W_{\text{pair}}^{\text{Exc.Pol.}} - \xi_3W_0$. When including polarization in Eq. (1), the Stokes parameters are transformed from the photon emission frame ($\hat{\epsilon}_1$, $\hat{\epsilon}_2$, $\hat{n}$) to the pair production frame ($\hat{\epsilon}_1$, $\hat{\epsilon}_2$, $\hat{n}$), where $\hat{\epsilon}_1 = [E - \hat{n} \cdot (\hat{n} \cdot E)] + \hat{n} \times \hat{B}/[E - \hat{n} \cdot (\hat{n} \cdot E)] + \hat{n} \times \hat{B}$ and $\hat{\epsilon}_2 = \hat{n} \times \hat{\epsilon}_1$, with the electric and magnetic field components $E$ and $B$; see Ref. [85].

The impact of the photon polarization on the BW pair production is quantitatively demonstrated in Figs. 1(b) and 1(c). The employed laser and electron beam parameters are the following. A realistic tightly focused Gaussian LP laser pulse [85,86] propagates along $+z$ direction (polar angle $\theta_0 = 0^\circ$), with peak intensity $I_0 \approx 3.45 \times 10^{11} \text{ W/cm}^2$ ($\alpha_0 = 50$), wavelength $\lambda_0 = 1 \mu\text{m}$, pulse duration $\tau = 15\tau_0$ with period $\tau_0$, and focal radius $w_0 = 5 \mu\text{m}$. A cylindrical unpolarized electron beam propagates along the $-z$ direction (polar angle $\theta_e = 180^\circ$), with initial kinetic energy $e_0 = 10 \text{ GeV}$, angular divergence $\Delta\theta = 0.3 \text{ mrad}$, energy spread $\Delta e_0/e_0 = 0.06$, beam radius $w_e = \lambda_0$, beam length $L_e = 5\lambda_0$, emittance $\epsilon_e \approx 3 \times 10^{-4} \text{ mm rad}$, electron number $N_e \approx 5 \times 10^6$, and density $n_e \approx 3.18 \times 10^{17} \text{ cm}^{-3}$ with a transversely Gaussian and longitudinally uniform distribution. The electron beam parameters are typical for laser-plasma acceleration [87]. The pair production and radiation reaction are significant at these parameters as $\chi_\gamma \approx 2.47$, $\max(\chi_\gamma) \approx 2.34$, and $R \approx 1$, while avalanche-like cascades are suppressed.

Our simulations show that radiated $\gamma$ photons are dominantly LP with an average polarization of $\xi_3 \approx 55.64\%$. The further produced pairs are characterized in Fig. 1(b). The transverse angular spread of the positrons is about 90 mrad, and the energies are mainly in the region of $0.2 \text{ GeV} \leq \epsilon_+ \leq 4.4 \text{ GeV}$. Integrating over the angular distribution, we show the energy distribution of positrons in Fig. 1(c). When the intermediate photon polarization is accounted for, the pair (positron) yield decreases. The relative difference reaches the maximum of $\Delta_+ \approx 13.6 \%$ at $\epsilon_+ \approx 0.4 \text{ GeV}$, and the average relative deviation $\Delta_+ = (N_{\text{Inc.Pol.}} - N_{\text{Exc.Pol.}})/N_{\text{Exc.Pol.}} \approx -13.44\%$. For the given parameters, the positron number is $N_{\text{Inc.Pol.}} \approx 1.36 \times 10^6 \approx N_e \times 27.2\%$, and thus, the deviation of about $13.44\%$ is remarkable but cannot be directly measured in an experiment. We propose the experimental observation of the discussed effect in a two-stage setup discussed below.

The physical reason for the intermediate polarization effect is analyzed in Fig. 2. According to Eq. (1), $W_{\text{pair}}$ depends on the parameters $\xi_3$, $\chi_\gamma$, and $e_+/e_\gamma$. As illustrated in Figs. 2(a) and 2(b), $W_{\text{pair}}$ continuously decreases (increases) with the increase of $\xi_3$ ($\chi_\gamma$), and has a symmetric distribution with respect to $e_+/e_\gamma$. Intermediate $\gamma$ photons, which are radiated by the electrons and eventually split to pairs, are LP with an average polarization $\xi_3 \approx 25.91\%$ (lower than that of all emitted $\gamma$ photons), as demonstrated in Fig. 2(c), and the corresponding pair production probability is smaller than that excluding polarization, in particular, in the region of $0.2 \leq e_+/e_\gamma \leq 0.8$ in Fig. 2(d). Consequently, the pair yield of consistently including the photon polarization is much smaller than that with averaging over the polarization, as shown in Fig. 1(c).

This photon polarization effect is robust with respect to the laser and electron beam parameters. As the laser field parameter $\alpha_0$ varies from 40 to 60, the laser pulse duration from 12 to 18 cycles, and the initial kinetic energy of the electron beam $e_0$ from 8 to 10 GeV, the pair production parameter $\Delta_+$ changes less than 10% [85]. It stays almost identical for the cases of larger angular divergence of $\Delta\theta = 1$ mrad, larger energy spread $\Delta e_0/e_0 = 0.1$, and different colliding angle $\theta_e = 175^\circ$ [85]. In the case of employing a circularly polarized laser pulse, the average polarization of emitted $\gamma$ photons by the unpolarized electron beam is rather small, and consequently, the considered effect cannot be identified [85].

FIG. 2. (a) Normalized pair production probability $\tilde{W}_{\text{pair}}$, integrating over $\epsilon_\gamma$ and scaled by its maximal value at $(\chi_\gamma, \xi_3) = (10, -1)$ in the demonstrated parametric region, vs $\chi_\gamma$ and $\xi_3$. (b) $W_{\text{pair}}$ with $\chi_\gamma = 2.34$ (corresponding to $\chi_\gamma$ of Fig. 1), scaled by its maximal value at $(\xi_3/e_\gamma, \xi_3) = (0.5, -1)$ in the demonstrated parametric region, vs $\xi_3/e_\gamma$ and $\xi_3$. (c) $\xi_3$ (red) and density $\log_{10}(dn_e/d\epsilon_e)$ (blue) of emitted $\gamma$ photons, which eventually split to pairs, vs $\epsilon_\gamma$. (d) $\tilde{W}_{\text{pair}}$ vs $\xi_3/e_\gamma$ for the cases of including polarization with $\xi_3 = 25.91\%$ (red solid) and excluding polarization (i.e., $\xi_3 = 0$, blue dash-dotted), respectively. The green dashed curve indicates the relative deviation of the pair creation probabilities $\delta_{\text{pair}} = (\tilde{W}_{\text{Inc.Pol.}} - \tilde{W}_{\text{Exc.Pol.}})/\tilde{W}_{\text{Exc.Pol.}}$. Other laser and electron beam parameters are the same as those in Fig. 1.
FIG. 3. (a) Two-stage scenario for detection of the considered effect of the photon polarization. In stages I and II, the laser fields have different LP along $\hat{x}_I$ and $\hat{x}_2$, and different intensities, $a_0^{\text{LP}} = 20$ (Max(x) ≈ 0.91) and $a_0^{\text{HI}} = 50$, respectively; $\phi$ is the rotation angle of the polarization $\hat{x}_2$ with respect to $\hat{x}_I$, $0^\circ$, $90^\circ$ generated in stage I. (c) $dN/d\xi_2$ of $dN/d\xi_2$, produced in stage II, in the cases of including polarization with $\phi = 90^\circ$ (red solid), $\hat{x}_3 \parallel \hat{x}_1$ and $90^\circ$ (blue solid), $\hat{x}_3 \perp \hat{x}_1$ and excluding polarization with $\phi = 0^\circ$ (black solid) and $90^\circ$ (green dashed), respectively; (d) $\Delta_3$ vs $\phi$. Other laser and electron beam parameters are the same as those in Fig. 1.

Experimental verification of the intermediate photon polarization can be carried out in a all-optical two-stage setup, which is similar to those generally used to probe vacuum birefringence [55,56], and a similar setup has been realized with crystals [63–65]. In both stages of our setup, LP laser pulses are used, but with different polarization directions. In stage I, a relatively low laser intensity $a_0^{\text{LP}} = 20$ (Max(x) ≈ 0.91) is used for $\gamma$-photon production via nonlinear Compton scattering [see Fig. 3(b)], which can produce much higher flux $\gamma$ rays than the linear Compton scattering and suppress the pair creation, while in stage II a higher laser intensity $a_0^{\text{HI}} = 50$ is used for pair production via the nonlinear bremsstrahlung process [49]. Then, the laser polarization first is fixed along the $x$ direction, and the positron (pair) yield $N_+|_{\phi=0^\circ}$ is measured. Then, the laser polarization is rotated by $90^\circ$, and again $N_+|_{\phi=90^\circ}$ is measured, which is different from $N_+|_{\phi=0^\circ}$ since $\xi_3$ changes with the rotation of the laser polarization; see similar interpretation in Fig. 3. Thus, $\xi_3$ can be deduced by an asymmetry parameter

$$\mathcal{A} = \frac{N_+|_{\phi=0^\circ} - N_+|_{\phi=90^\circ}}{N_+|_{\phi=0^\circ} + N_+|_{\phi=90^\circ}},$$

and the relation of $\mathcal{A}$ to $\xi_3$ is shown in Fig. 4(a). In the same way, the Stokes parameter $\xi_1$ is determined via another asymmetry parameter $\mathcal{A}'$, first fixing the laser polarization along the axis of $\phi = 45^\circ$ and then rotating by $90^\circ$ ($\phi = 135^\circ$).

The resolution of the polarization measurement can be estimated via the statistical uncertainty $\delta \mathcal{A}/\Delta \mathcal{A} = 1/(\Delta \mathcal{A} \sqrt{N_+})$ [88], where the total number of pairs $N_+ = N_+^{\text{pair}} N_\gamma$ is determined by the pair production rate $R^{\text{pair}} N_\gamma \approx 37.98\%$ and $\Delta \mathcal{A} = \Delta(\mathcal{A}) - \min(\mathcal{A}) \approx 0.4634$, calculated with the given parameters. For instance, in the case of the laser-driven polarized $\gamma$ rays [49], we have $N_+ \approx 10^6$, and the resolution is about 0.35%. As the photon flux increases, the resolution decreases accordingly. The resolution improves as well with the increase of the pair yield, which takes place when increasing $X_\gamma$ (see analysis in Fig. 2), and with the increase of the asymmetry parameter $\Delta \mathcal{A} \sim W_\xi/W_{\text{Exc. Pol.}}$. The latter, however, decreases with larger $X_\gamma$ [see Fig. 4(b)]. Because of the opposite behaviors of $N_+$ and $\Delta \mathcal{A}$ with the

FIG. 4. Polarimetry for high-flux high-energy $\gamma$ photons. (a) The asymmetry parameter $\mathcal{A}$ defined in the text, vs $\xi_3$. (b) $W_\xi/W_{\text{Exc. Pol.}}$ vs $X_\gamma$, by summing over $\xi_3$. The average energy of $\gamma$ photons $\overline{E_\gamma} = 4.32$ GeV (corresponding to $\xi_3$ in Fig. 1), with an angular divergence $\Delta \theta_\gamma = 0.3$ mrad and an energy spread $\Delta E_\gamma/E_\gamma = 6\%$. The scattering laser parameters are the same as those in Fig. 1.
variation of $\chi_p \propto a_0 \delta_2 \gamma$, the resolution is quite stable with respect to the changes of the laser intensity and the $\gamma$-photon energy. Moreover, the resolution does not vary much and remains well below 1% with a shorter or longer laser pulse, a larger energy spread $\Delta \epsilon_\gamma / \epsilon_\gamma = 0.1$, a larger angular divergence $\Delta \theta_e = 1$ mrad, and a different colliding angle $\theta_e = 175^\circ$ [85]. The proposed polarimetry based on the BW process avoids limitations of $\gamma$-ray polarimetry via the BH process [68–72] with respect to the $\gamma$-ray flux and angular resolution, imposed by the convertor material in the latter.

In conclusion, the impact of intermediate photon polarization on nonlinear BW pair production during LP laser-electron beam interaction is investigated in the quantum radiation-dominated regime. The photon polarization is shown to significantly affect the pair yield by a factor of more than 13%. Thus, for accurate Monte Carlo simulations of laser-electron beam interaction it is crucial to treat the electron spin and polarization of intermediate particles, even for simulations of those processes where the polarization of the final particles is not in the center of interest. Our analysis suggests that the considered signature of the photon polarization is experimentally detectable in a two-stage all-optical setup. Moreover, we provide a polarimetry method specifically designed for high-flux high-energy $\gamma$ rays in the GeV range, which provides competitive resolution with currently feasible laser facilities, and is likely to be useful in astrophysics and high-energy physics.

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