High-energy γ-photon polarization in nonlinear Breit-Wheeler pair production and γ-polarimetry

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(Dated: February 27, 2020)

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 γ photons are generated intermediately during this interaction via nonlinear Compton scattering, with an average polarization degree of more than 50%, which further interacting with the laser fields produce electron-positron pairs due to nonlinear Breit-Wheeler process. The photon polarization is shown to significantly affect the pair yield by a factor beyond 10%. The considered signature of the photon polarization in the pair's yield can be experimentally identified in a prospective two-stage setup. Moreover, the signature can serve also for the polarimetry of high-energy high-flux γ photons with a resolution well below 1% with currently achievable laser facilities.

Rapid advancement of strong laser technique enables experimental investigation of quantum electrodynamics (QED) processes during laser-plasma or laser-electron beam interactions. Nowadays, ultrashort ultrastrong laser pulses can achieve peak intensities of about 10^{22} W/cm^2, with a duration of about tens of femtoseconds and an energy fluctuation $\sim 1\%$ [1–7]. In such laser fields QED processes become nonlinear involving multiphoton processes [8]: a γ photon can be generated via nonlinear Compton scattering absorbing millions of laser photons [9–11], or similarly a γ photon can create an electron-positron pair in the interaction with a strong laser wave in nonlinear Breit-Wheeler (BW) process [12]. These processes have been first experimentally observed in [13–15] and recently considered in all-optical experimental setups [16–20]. Presently, there are many theoretical proposals aiming at γ ray and pair production with ultrastrong laser fields of achievable or soon-coming intensities [21–28] and even avalanche-like electromagnetic cascades in future extreme laser intensities $\gtrsim 10^{24}$ W/cm^2 [29–35].

Recently, it has been realized that the radiation reaction due to γ photon emissions in laser fields can be harnessed to substantially polarize electrons [36–42] or to create polarized positrons [43, 44], while it was known since long ago that an electron beam cannot be significantly polarized by a monochromatic laser wave [45–47]. Polarization properties of electrons, positrons and γ photons in ultrastrong laser-electron beam interaction have been investigated comprehensively in [40, 43, 48]. In particular, an efficient way of the polarization transfer from electrons to γ photons in such interaction has been identified, which will allow to obtain circularly polarized brilliant γ rays via nonlinear Compton scattering from longitudinally spin-polarized electrons [48], highly sought in detecting schemes of vacuum birefringence in ultrastrong laser fields [49, 50].

In spite of significant efforts in the investigation of pair production channels in ultrastrong laser-electron beam interaction [21, 22, 24–32], it still remains unclear how the polarization of intermediate particles influences the pair production process in ultrastrong focused laser beams. General theory for the pair production by polarized photons in a monochromatic plane wave is given in [51], obtaining unwieldy expressions for probabilities which, however, are not directly applicable for processes in tightly focused or multiple laser beams. A particular case of the multiphoton BW process with linearly polarized (LP) γ photons of a MeV energy and moderately strong x-ray laser field is considered in [52]. The role of the γ photon polarization within the BW process in a constant crossed field is considered in [53], applying a spin-averaged treatment for the photon emission by an electron. While the latter gives a hint on the photon polarization effect, it is not straightforwardly extendible to the realistic setups with tightly focused laser beams.

In this Letter, 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 γ photons via nonlinear Compton scattering. Further, generated polarized γ 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 [40, 48] to describe the spin-resolved electron dynamics, polarized photon emissions, and pair production by the latter. We elucidate the substantial role of intermediate polarization of photons on the pair's yield, and put forward a two-stage setup for detection of the photon polarization signature, 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 high-flux LP γ rays through the pair yield.

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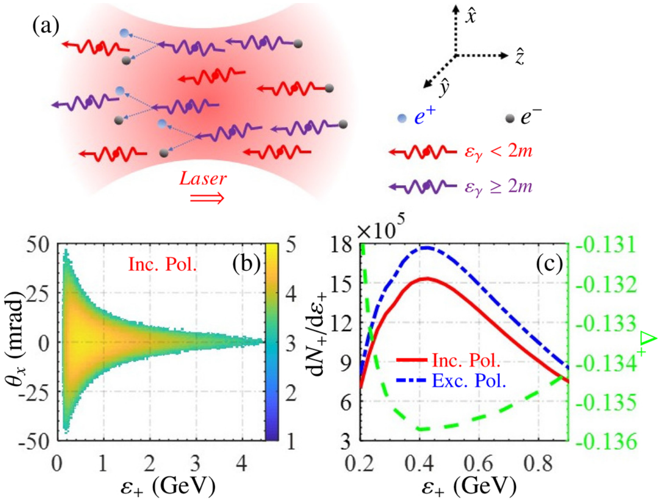

FIG. 1. (a) Scenario of nonlinear BW pair production. A LP laser pulse, polarized in x direction and propagating along $+z$ direction, head-on collides with an electron beam, generating LP γ photons, and further these pairs. "e^+" and "e^-" indicate positron and electron, respectively. (b) Angle-resolved positron density $\log_{10}(d^2N_+/d\varepsilon_+ d\theta_x)$ (GeV^{-1}·mrad^{-1}) vs the deflection angle $\theta_x = p_x/p_z$ and the positron energy ε_+, with accounting for the photon polarization. (c) Positron density $dN_+/d\varepsilon_+$ vs ε_+ in the cases of including (red-solid) and excluding (blue-dash-dotted) the photon polarization, respectively. The green-dashed curve shows the relative deviation $\Delta_+ = [(dN_+/d\varepsilon_+)^{Inc.Pol.}\text{-}(dN_+/d\varepsilon_+)^{Exc.Pol.}]/(dN_+/d\varepsilon_+)^{Exc.Pol.}$. The laser and electron beam parameters are given in the text (in the paragraph beginning below Eq. (1)).

Note that the high-resolution polarimetry of high-energy γ rays is an important problem in astrophysics and high-energy physics [54–57]. Current polarimetries for high-energy γ 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 percents [56, 57]. 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, and in the latter the photon flux is restricted severely by the convertor materials [58, 59]. Our polarimetry concept via nonlinear BW pair production is specifically designed for high-flux GeV γ photons and provides a competitive resolution.

We consider the quantum radiation-dominated regime, which requires a large nonlinear QED parameter $\chi_e \equiv |e|\sqrt{-(F_{\mu\nu}p^\nu)^2}/m^3 \gtrsim 1$ (for electrons and positrons) [8] and $R \equiv \alpha a_0 \chi_e \gtrsim 1$ [60]. Significant BW pair production requires the nonlinear QED parameter $\chi_\gamma \equiv |e|\sqrt{-(F_{\mu\nu}k_\gamma^\nu)^2}/m^3 \gtrsim 1$ (for γ photon) [8, 61]. Here, E_0 and ω_0 are the laser field amplitude and frequency, respectively, p and k_γ the 4-momenta of electron (positron) and photon, respectively, e and m the electron charge and mass, respectively, $F_{\mu\nu}$ the field tensor, α the fine structure constant, and $a_0 = eE_0/m\omega$ 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, photon emission and pair production quantum mechanically in the local constant field approximation [8, 61–63], valid at $a_0 \gg 1$. At each simulation step, the photon emission is calculated following the common algorithms [64–66], and the photon polarization following the Monte Carlo algorithm [48]. The photon Stokes parameters (ξ_1, ξ_2, ξ_3) are defined with respect to the axes $\hat{\mathbf{e}}_1 = \hat{\mathbf{a}} - \hat{\mathbf{v}}(\hat{\mathbf{v}}\hat{\mathbf{a}})$ and $\hat{\mathbf{e}}_2 = \hat{\mathbf{v}} \times \hat{\mathbf{a}}$ [67], with the photon emission direction $\hat{\mathbf{n}}$ along the ultrarelativistic electron velocity $\mathbf{v}$, $\hat{\mathbf{v}} = \mathbf{v}/|\mathbf{v}|$, and the unit vector $\hat{\mathbf{a}} = \mathbf{a}/|\mathbf{a}|$ along the electron acceleration $\mathbf{a}$. After the photon emission the electron spin state is determined by the spin-resolved emission probabilities [40, 68]. Between photon emissions, the spin precession is governed by the Thomas-Bargmann-Michel-Telegdi equation [69–71]. The polarized photon conversion to electron-positron pair is described by the probabilities of the pair production. The latter, summing over the pair spins, is derived in the leading order contribution with respect to $1/\gamma_e$ via the QED operator method of Baier-Katkov [72]:

$$\frac{d^2W_{pair}}{d\varepsilon_+ dt} = \frac{\alpha m^2}{\sqrt{3}\pi\varepsilon_\gamma^2}\left\{\mathrm{IntK}_{\frac{1}{3}}(\rho) + \left(\frac{\varepsilon_+^2+\varepsilon_-^2}{\varepsilon_+\varepsilon_-} - \xi_3\right)\mathrm{K}_{\frac{2}{3}}(\rho)\right\}, \quad (1)$$

where, ε_- and ε_+ are the energies of created electron and positron, respectively, with the photon energy $\varepsilon_\gamma = \varepsilon_- + \varepsilon_+$, $\rho \equiv 2\varepsilon_\gamma^2/(3\chi_\gamma\varepsilon_+\varepsilon_-)$, $\mathrm{IntK}_{\frac{1}{3}}(\rho) \equiv \int_\rho^\infty dx \mathrm{K}_{\frac{1}{3}}(x)$, and K_n is the n-order modified Bessel function of the second kind. In this relativistic setup the emitted γ photon is assumed to propagate along the radiating electron momentum, and the pair along the parent γ photon momentum. Note that averaging over the photon polarization one obtains the known pair production probability $W_{pair}^{Exc.Pol.}$ [61], and $W_{pair} = W_{pair}^{Exc.Pol.} - \xi_3 W_\xi$. When including polarization in Eq. (1), the Stokes parameters are transformed from the photon emission frame $(\hat{\mathbf{e}}_1, \hat{\mathbf{e}}_2, \hat{\mathbf{n}})$ to the pair production frame $(\hat{\mathbf{e}}_1', \hat{\mathbf{e}}_2', \hat{\mathbf{n}})$, where $\hat{\mathbf{e}}_1' = [\mathbf{E} - \hat{\mathbf{n}} \cdot (\hat{\mathbf{n}} \cdot \mathbf{E}) + \hat{\mathbf{n}} \times \mathbf{B}]/|\mathbf{E} - \hat{\mathbf{n}} \cdot (\hat{\mathbf{n}} \cdot \mathbf{E}) + \hat{\mathbf{n}} \times \mathbf{B}|$ and $\hat{\mathbf{e}}_2' = \hat{\mathbf{n}} \times \hat{\mathbf{e}}_1'$, with the electric and magnetic field components $\mathbf{E}$ and $\mathbf{B}$; see [73].

The impact of the photon polarization on the BW pair production is quantitatively demonstrated in Figs. 1(b) and (c). The employed laser and electron beam parameters are the following. A realistic tightly-focused Gaussian LP laser pulse [73, 74] propagates along $+z$ direction (polar angle $\theta_l = 0°$), with peak intensity $I_0 \approx 3.45 \times 10^{21}$ W/cm^2 ($a_0 = 50$), wavelength $\lambda_0 = 1$ μm, pulse duration $\tau = 15T_0$ with period T_0, and focal radius $w_0 = 5$ μm. A cylindrical unpolarized electron beam propagates along $-z$ direction (polar angle $\theta_e = 180°$), with initial kinetic energy $\varepsilon_0 = 10$ GeV, angular divergence $\Delta\theta = 0.3$ mrad, energy spread $\Delta\varepsilon_0/\varepsilon_0 = 0.06$, beam radius $w_e = \lambda_0$, beam length $L_e = 5\lambda_0$, emittance $\epsilon_e \approx 3 \times 10^{-4}$ mm·mrad, electron number $N_e = 5 \times 10^6$, and density $n_e \approx 3.18 \times 10^{17}$ cm^{-3} with a transversely Gaussian and longitudinally uniform distribution. The electron beam parameters are typical for laser-plasma acceleration [75]. The pair production and radiation reaction are significant at these parameters as $\chi_e \approx 2.47$, Max$(\chi_\gamma) \approx 2.34$ and $R \approx 1$, while avalanche-like cascades are suppressed.

Our simulations show that radiated γ photons are dominantly LP with an average polarization of $\overline{\xi_3} \approx 55.64\%$. The further produced pairs are characterized in Fig. 1(b). The transverse

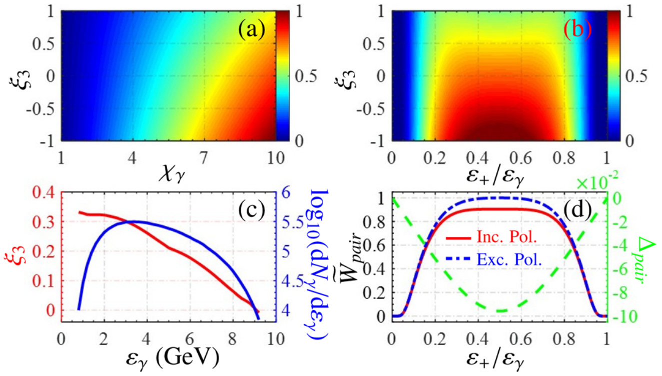

FIG. 2. (a) Normalized pair production probability $\widetilde{W}_{pair}$, integrating over ε_+ and scaled by its maximal value at (χ_γ, ξ_3) = (10, -1) in the demonstrated parametric region, vs χ_γ and ξ_3. (b) $\widetilde{W}_{pair}$ with $\chi_\gamma = 2.34$ (corresponding to $\overline{\chi}_\gamma$ of Fig. 1), scaled by its maximal value at $(\varepsilon_+/\varepsilon_\gamma, \xi_3)$ = (0.5, -1) in the demonstrated parametric region, vs $\varepsilon_+/\varepsilon_\gamma$ and ξ_3. (c) ξ_3 (red) and density $\log_{10}(dN_\gamma/d\varepsilon_\gamma)$ (blue) of emitted γ photons, which eventually split to pairs, vs ε_γ. (d) $\widetilde{W}_{pair}$ vs $\varepsilon_+/\varepsilon_\gamma$ 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 $\Delta_{pair} = (\widetilde{W}^{Inc.Pol.}_{pair} - \widetilde{W}^{Exc.Pol.}_{pair})/\widetilde{W}^{Exc.Pol.}_{pair}$. Other laser and electron beam parameters are the same as those in Fig. 1.

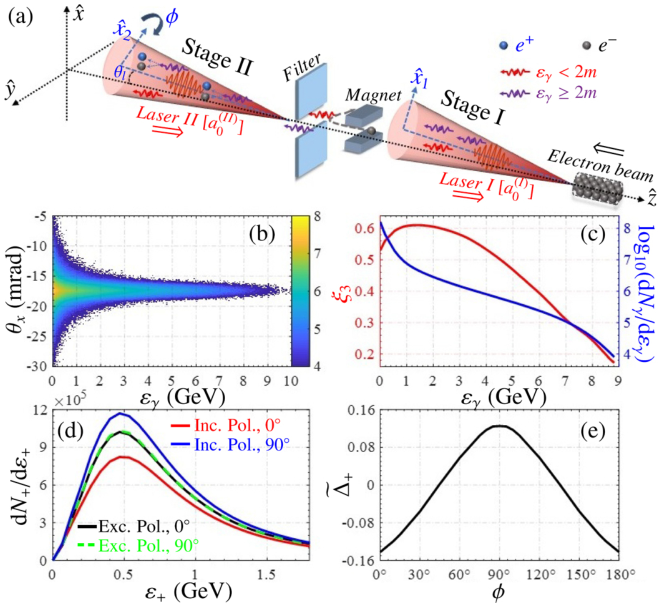

FIG. 3. (a) Two-stage scenario for detection of the considered effect of the photon polarization. In Stage I and Stage II the laser fields have different LP along $\hat{x}_1$ and $\hat{x}_2$, and different intensities, $a_0^{(I)} = 20$ (Max$(\chi_\gamma) \approx 0.91$) and $a_0^{(II)} = 50$, respectively; ϕ is the rotation angle of the polarization $\hat{x}_2$ with respect to $\hat{x}_2$. (b) $\log_{10}(d^2N_\gamma/d\varepsilon_\gamma d\theta_x)$ vs θ_x and ε_γ, generated in Stage I. (c) $\log_{10}(dN_\gamma/d\varepsilon_\gamma)$ (blue), calculated by integrating $d^2N_\gamma/d\varepsilon_\gamma d\theta_x$ in (b) over θ_x from -25 mrad to -10 mrad, and the corresponding ξ_3 (red) vs ε_γ. (d) $dN_+/d\varepsilon_+$ vs ε_+, produced in Stage II, in the cases of including polarization with $\phi = 0°$ (red-solid, $\hat{x}_2 \parallel \hat{x}_1$) and 90° (blue-solid, $\hat{x}_2 \perp \hat{x}_1$) and excluding polarization with $\phi = 0°$ (black-solid) and 90° (green-dashed), respectively; (e) $\widetilde{\Delta}_+$ vs ϕ. Other laser and electron beam parameters are the same as those in Fig. 1.

angular spread of the positrons is about 90 mrad, and the energies are mainly in the region of 0.2 GeV $\lesssim \varepsilon_+ \lesssim$ 4.4 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 $\varepsilon_+ \approx 0.4$ GeV, and the average relative deviation $\widetilde{\Delta}_+ = (N_+^{Inc.Pol.} - N_+^{Exc.Pol.})/N_+^{Exc.Pol.} \approx -13.44\%$. For the given parameters the positron number is $N_+^{Inc.Pol.} \approx 1.36\times10^6 \approx N_e \times 27.2\%$, thus, the deviation of about 13.44% is remarkable and can be measured with current experimental techniques [76–78].

The physical reason for the intermediate polarization effect is analyzed in Fig. 2. According to Eq. (1), W_{pair} depends on the parameters ξ_3, χ_γ and $\varepsilon_+/\varepsilon_\gamma$. As illustrated in Figs. 2(a) and (b), W_{pair} continuously decreases (increases) with the increase of ξ_3 (χ_γ), and has a symmetric distribution with respect to $\varepsilon_+/\varepsilon_\gamma$. Intermediate γ photons, which are radiated by the electrons and eventually split to pairs, are LP with an average polarization $\overline{\xi_3} \approx 25.91\%$ (lower than that of all emitted γ 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 $0.2 \lesssim \varepsilon_+/\varepsilon_\gamma \lesssim 0.8$ 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 a_0 varies from 40 to 60, the laser pulse duration from 12 to 18 cycles, and the initial kinetic energy of the electron beam ε_0 from 8 GeV to 10 GeV, the pair production parameter $\widetilde{\Delta}_+$ changes less than 10% [73]. It keeps almost identical for the cases of larger angular divergence of $\Delta\theta = 1$ mrad, larger energy spread $\Delta\varepsilon_0/\varepsilon_0 = 0.1$ and different colliding angle $\theta_e = 175°$ [73]. In the case of employing a circularly polarized laser pulse, the average polarization of emitted γ photons by the unpolarized electron beam is rather small, and consequently, the considered effect can not be identified [73].

For experimental verification of the considered effect of the photon polarization, we introduce an all-optical two-stage method. In both stages LP laser pulses are used, however, with different polarization directions. In Stage I, a relatively low laser intensity $a_0^{(I)} = 20$ (Max$(\chi_\gamma) \approx 0.91$) is used for γ photon production via nonlinear Compton scattering (see Fig. 3(b)) and suppressing the pair creation, while in Stage II a higher laser intensity $a_0^{(II)} = 50$ for pair production via the nonlinear BW process. When the laser polarization direction in Stage II is parallel to that in Stage I ($\phi = 0°$, $\hat{x}_2 \parallel \hat{x}_1$), the pair yield of including polarization is much smaller than that excluding polarization, $N_+^{Inc.Pol.} < N_+^{Exc.Pol.}$, with $\widetilde{\Delta}_+ \approx -14.23\%$; see Fig. 3(d), because ξ_3 in this frame is positive with $\overline{\xi_3} \approx 55.54\%$; see Fig. 3(c). When the polarization direction in Stage II is rotated by $\phi = 90°$, ξ_3 of γ photons in the rotated frame becomes negative, $\overline{\xi_3} \approx -55.54\%$. Consequently, we have $N_+^{Inc.Pol.} > N_+^{Exc.Pol.}$, with $\widetilde{\Delta}_+ \approx 12.52\%$; see Fig. 3(d). It is clear that in the case of neglecting the photon polarization,

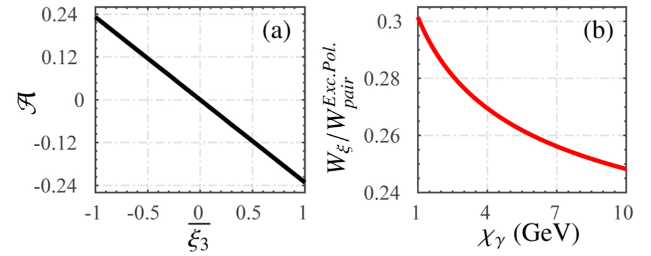

FIG. 4. Polarimetry for high-flux high-energy γ photons. (a) The asymmetry parameter $\mathcal{A}$, defined in the text, vs $\overline{\xi_3}$. (b) $W_\xi/W_{pair}^{Exc.Pol.}$ vs χ_γ by summing over $\varepsilon_+/\varepsilon_\gamma$. The average energy of γ photons $\overline{\varepsilon_\gamma} = 4.32$ GeV (corresponding to $\overline{\varepsilon_\gamma}$ in Fig. 1), with an angular divergence $\Delta\theta_\gamma = 0.3$ mrad and an energy spread $\Delta\varepsilon_\gamma/\varepsilon_\gamma = 6\%$. The scattering laser parameters are the same as those in Fig. 1.

the rotation of the laser polarization in Stage II would not affect the pair yield. We can explain also why the absolute value $|\widetilde{\Delta}_+|$ in the case of $\phi = 0^\circ$ is slightly larger than that of $\phi = 90^\circ$. The reason is that the pair production probability is $W_{pair} = W_{pair}^{Exc.Pol.} - \xi_3 W_\xi$ in a single formation length, but within n formation lengths it is $W_n = 1 - (1 - W_{pair})^n = 1 - [1 - (W_{pair}^{Exc.Pol.} - \xi_3 W_\xi)]^n$, which is asymmetric with respect to ξ_3. Thus, the dependence of $\widetilde{\Delta}_+$ on the rotation angle ϕ demonstrated in Fig. 3(e) can be a measurable experimental signature of the considered photon polarization effect.

Finally, we suggest a new polarimetry method for high-flux multi-GeV γ photons by employing the polarization properties within the nonlinear BW pair production process. A γ photon beam head-on collides with an ultrastrong LP laser pulse, and the interaction scenario is similar to Stage II in Fig. 3(a). The procedure of determining the LP Stokes parameters $\overline{\xi_1}$ and $\overline{\xi_3}$ of the given photon beam is the following. For the $\overline{\xi_3}$ determination, the laser polarization first is fixed along x direction, and the positron (pair) yield $N_+|_{\phi=0^\circ}$ is measured. Then, the laser polarization is rotated by 90°, and again $N_+|_{\phi=90^\circ}$ is measured, which is different from $N_+|_{\phi=0^\circ}$ since $\overline{\xi_3}$ changes with the rotation of the laser polarization; see similar interpretation in Fig. 3. Thus, $\overline{\xi_3}$ can be deduced by an asymmetry parameter

$$\mathcal{A} = \frac{N_+|_{\phi=0^\circ} - N_+|_{\phi=90^\circ}}{N_+|_{\phi=0^\circ} + N_+|_{\phi=90^\circ}}, \tag{2}$$

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

The resolution of the polarization measurement can be estimated via the statistical uncertainty $\delta\mathcal{A}/\Delta\mathcal{A} = 1/(\Delta\mathcal{A}\sqrt{N_+})$ [79], where the total number of pairs $N_+ = \mathcal{R}_{pair}N_\gamma$ is determined by the pair production rate $\mathcal{R}_{pair} \approx 37.98\%$ and $\Delta\mathcal{A} =$ Max($\mathcal{A}$) - Min($\mathcal{A}$) ≈ 0.4634, calculated with the given parameters. For instance, in the case of the laser-driven polarized γ rays [48], we have $N_\gamma \sim 10^6$, and the resolution is about 0.35%. As the photon flux increases, the resolution increases accordingly. The resolution improves as well with the increase of the pair yield, which takes place when increasing χ_γ (see analysis in Fig. 2), and with the increase of the asymmetry parameter $\Delta\mathcal{A} \sim W_\xi/W_{pair}^{Exc.Pol.}$. The latter, however, decreases with larger χ_γ (see Fig. 4(b)). Due to opposite behaviours of N_+ and $\Delta\mathcal{A}$ with the variation of $\chi_\gamma \propto a_0\varepsilon_\gamma$, the resolution is quite stable with respect to the changes of the laser intensity and the γ 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 $\Delta\varepsilon_\gamma/\varepsilon_\gamma = 0.1$, a larger angular divergence $\Delta\theta_\gamma = 1$ mrad, and a different colliding angle $\theta_\gamma = 175^\circ$ [73].

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 above 13%. We put forward an all-optical method to experimentally determine the considered signature of the photon polarization. Moreover, we provide a new polarimetry method for high-flux high-energy γ-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.

This work is supported by the National Natural Science Foundation of China (Grants Nos. 11874295, 11875219 and 11905169), and the National Key R&D Program of China (Grant No. 2018YFA0404801).

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