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Modulation effect in multiphoton pair production

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ABSTRACT

We investigate the electron–positron pair production process in an oscillating field with modulated amplitude in the quantum kinetic formalism. By comparing the number density in the oscillating field with and without modulation, we find that the pair production rate can be enhanced by several orders when the photon energy just reaches the threshold with the help of shifted frequency due to modulation. We also detect the same effect in a pulse train with subcycle structure. We demonstrate that the frequency threshold can be lowered by the frequency of the pulse train due to the modulation effect. We also find that the momentum distribution for a N-pulse train can reach N^2 times the single pulse at the maximum value and the number density as a function of pulse number follows the power law with index 1.6 when the modulation effect is maximized.

1. Introduction

The electron–positron pair production from vacuum under a strong external field is one of the remarkable predictions of the quantum electrodynamics (QED). After pioneering works of Sauter [1], Heisenberg and Euler [2], and Schwinger [3] a large number of investigations are dedicated to study on the vacuum pair production through employing different methods such as proper time technique [4–6], Wentzel–Kramers–Brillouin (WKB) approximation [7], worldline instanton technique [8,9], quantum field theoretical simulation [10,11] as well as the quantum kinetic method [12–16]. The experimental verification of vacuum pair production is still unavailable so far due to Schwinger threshold of the external electric field $E_{cr} = m^2c^3/e\hbar = 1.32 \times 10^{18}$ V/m, m and $-e$ are mass and charge of electron, respectively, is too high to achieve in the laboratory at present.

On the other hand, with the rapid development of laser technology in recent years, it is expected that the field strength of experimental facility may be more approaching to the Schwinger threshold in the near future, for example, the European extreme-light-infrastructure (ELI) program is now advancing [17]. Motivated by this, various schemes have been proposed to support the upcoming possible experiments in recent years. A strongly enhanced pair production rate was presented in dynamically assisted Schwinger mechanism where a rapid oscillating electric field is superimposed onto a slowly varying one [18–20]. The study on time-domain multiple-slit interference effect in an alternating sign N-pulse electric field [21] showed that the maximum of central longitudinal momentum can reach N^2 times the single pulse value. The pair production in a short pulse with subcycle structure was studied [22] to present the momentum spectrum extremely sensitive to subcycle dynamics. The accurate study on the pair production in a pulsed electric field with subcycle structure [23] detected the signature of effective mass of the electrons and positrons in the given strong electric field, where the frequency threshold of a multiphoton process rises due to the effective mass which is heavier than the real mass. These findings and schemes advance greatly the topic of pair production in strong field, more details can be seen in [24–30].

In present letter we introduce a scheme where the amplitude of a high frequency oscillating electric field is modulated. Amplitude modulating changes the dynamics of the oscillating field in the following two aspects. On the one hand the frequency of the oscillating field is shifted up by the modulation frequency, which may have a positive influence on the production rate, on the other hand the field strength is decreased so that it suppresses the production rate in the multiphoton regime. Therefore it is desirable to show overall influence of the amplitude modulation on the pair production process. Here we study the production rate and momentum distribution for different parameters in a high frequency

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oscillating field with amplitude modulated by a sinusoidal signal. The aim of study is to highlight how the modulation effect influences the pair production. Furthermore, we investigate how the modulation effect can lower the frequency threshold in a more realistic field configuration, i.e. a pulse train with subcycle structure. The quantum Vlasov equation is employed in the study and the natural units ($\hbar = c = 1$) are used.

The paper is organized as follows. In Sec. 2 we introduce our method based on the quantum Vlasov equation. In Sec. 3 we get the numerical results and necessary theoretical analysis. In the last section we provide a brief conclusion.

2. Theoretical formalism based on quantum Vlasov equation

The spectral information of created particles in an external field is encoded in the distribution function $f(\mathbf{p},t)$. The equation of motion for $f(\mathbf{p},t)$ can be derived from canonical quantization with fully quantized spinor and the electromagnetic field as a classical background [14]. We are only interested in subcritical field strength regime $E \ll E_{cr}$ where created particle density is so low that the collision effect and self consistent field current due to created particles can be neglected. Since the achievable spatial focusing scale is orders of magnitude larger than the Compton wavelength of electrons we ignore any spatial dependence, and we also ignore the magnetic field. With these simplifications, the quantum Vlasov equation for $f(\mathbf{p},t)$ reads:

$$\dot{f}(\mathbf{p},t) = \frac{1}{2}q(\mathbf{p},t)\int_{-\infty}^{t} dt' q(\mathbf{p},t')[1-2f(\mathbf{p},t')]\cos[2\Theta(\mathbf{p},t',t)], \tag{1}$$

where $f(\mathbf{p},t)$ accounts for both spin directions due to absence of magnetic fields. Here, $q(\mathbf{p},t) = eE(t)\varepsilon_\perp/\omega^2(\mathbf{p},t)$ and $\Theta(\mathbf{p},t',t) = \int_{t'}^{t}\omega(\mathbf{p},\tau)d\tau$ with quantities as the electron/positron momentum $\mathbf{p} = (\mathbf{p}_\perp, p_\parallel)$, transverse energy squared $\varepsilon_\perp^2 = m^2 + p_\perp^2$, the total energy squared $\omega^2(\mathbf{p},t) = \varepsilon_\perp^2 + p_\parallel^2$, and the longitudinal momentum $p_\parallel = P_3 - eA(t)$. This equation may be expressed as a linear, first order, ordinary differential equation system (ODEs) [15] for the convenience of numerical treatment:

$$\dot{f}(\mathbf{p},t) = \frac{1}{2}q(\mathbf{p},t)g(\mathbf{p},t), \tag{2}$$

$$\dot{g}(\mathbf{p},t) = q(\mathbf{p},t)[1-2f(\mathbf{p},t)] - 2\omega(\mathbf{p},t)w(\mathbf{p},t), \tag{3}$$

$$\dot{w}(\mathbf{p},t) = 2\omega(\mathbf{p},t)g(\mathbf{p},t). \tag{4}$$

The term $g(\mathbf{p},t)$, i.e. the integral part of Eq. (1) constitutes an important contribution to the source of pair production, where the quantum statistics character is represented by the term $[1 - 2f(\mathbf{p},t)]$ due to the Pauli exclusive principle. The term $w(\mathbf{p},t)$ denotes a countering term to pair production, which is associated to the pair annihilation in pair creation process to some extent. The last one of ODEs means that the more pairs are created, the more pairs are annihilated. Note that the studied system has a typical non-Markovian character.

By numerically solving this ODEs with the initial conditions $f(\mathbf{p},-\infty) = g(\mathbf{p},-\infty) = w(\mathbf{p},-\infty) = 0$, we can obtain the momentum space distribution $f(\mathbf{p},t)$ of the created particles for any given spatially homogeneous, time-dependent electric field. The number density $n(t)$ of created particles can be obtain easily from $f(\mathbf{p},t)$:

$$n(\infty) = 2\int \frac{d^3\mathbf{p}}{(2\pi)^3} f(\mathbf{p},\infty), \tag{5}$$

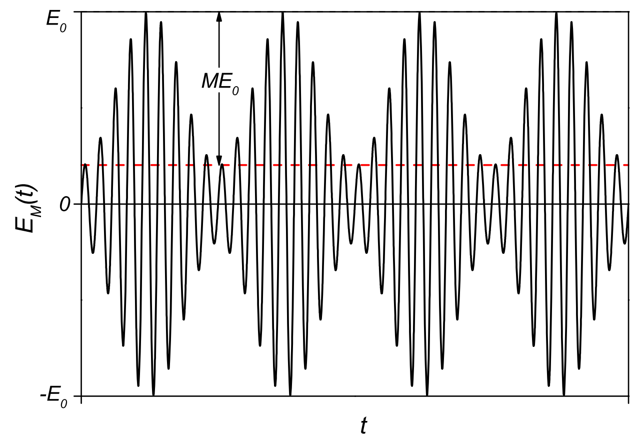

Fig. 1. A typical case of high frequency field with the amplitude modulated by a sinusoidal signal with modulation degree $0 < M < 1$.

where the factor 2 comes from the degeneracy of electrons. It is necessary to remind that there is no clear interpretation of $f(\mathbf{p},t)$ in the presence of an external field. At finite times it cannot be considered as distribution function of real particles but only as a mixture of real and virtual excitations. Consequently, $f(\mathbf{p},t)$ might be interpreted as the momentum distribution for real particles only at asymptotic times $t = \pm\infty$, when the external field is switched off [31,32].

3. Numerical results

In order to reveal the physical mechanism briefly as well as for the simplicity of numerical calculations, we just consider the problem in the one-dimensional momentum space for the created electron–positron pair.

3.1. Pair production in a high frequency oscillating field with amplitude modulated by a sinusoidal signal

The spatially homogeneous, time-dependent electric field in a given direction can be expressed as $\mathbf{E}(t) = -\dot{\mathbf{A}}(t) = (0,0,E(t))$. The transverse momentum of created particles which is perpendicular to the electric field is fixed as $p_\perp = 0$ as mentioned above. We introduce a high frequency oscillating field which has a carrier frequency as ω_c and an amplitude as E_0, meanwhile, this amplitude is modulated by a sinusoidal signal with the modulation frequency as ω_m ($\omega_m \ll \omega_c$), i.e.

$$E_M(t) = (1 - M\frac{1+\cos(\omega_m t)}{2})E_0\sin(\omega_c t), \tag{6}$$

where $0 \le M \le 1$ denotes the modulation degree. Obviously $M = 0$ and $M = 1$ correspond to the no-modulation and full modulation, respectively. A typical case of $0 < M < 1$ is displayed in Fig. 1.

Now Eq. (6) can be expanded as $E_M(t) = (1 - \frac{M}{2})E_0\sin(\omega_c t) - \frac{M}{4}E_0\sin(\omega_+ t) - \frac{M}{4}E_0\sin(\omega_- t)$, where $\omega_\pm = \omega_c \pm \omega_m$. It indicates that modulating amplitude results in frequency shift, from which one can expect a possible positive influence on the pair production rate. On the other hand the average power of the electric field is suppressed by a factor of $\int_0^{2\pi/\omega_m} E_M^2(t)dt / \int_0^{2\pi/\omega_m} E_0^2(t)dt = \frac{3}{8}(\frac{4}{3} - M)^2 + \frac{1}{3}$ due to modulation, which may have a negative influence on the pair production rate.

To investigate the overall influence of amplitude modulation on the pair production rate, we compare the produced number density with and without modulation for full frequency space. We find that the pair production rate can be enhanced due to modulation for the carrier frequency near the frequency threshold of