Electron-positron Pair Production from Vacuum in a Strong Rotating Electric Field

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Summary

By generalizing the **kinetic theory** of the electron-positron plasma (EPP) creation from vacuum from the case of linear (LP) to **arbitrary elliptic polarization** of the driving strong time dependent electric field, we obtain and discuss the following features of pair creation in **circularly** polarized (CP) field:

- substantial **decrease** of EPP production as compared to the case of LP[a];
- **radical change of the momentum distribution** function of created EPP stipulated by suppression of pair production in a small momentum region;
- appearance of the **macroscopic spin and magnetic moments** of the created EPP.

These features can be important in considerations of some observable effects: radiation from the EPP created in the focus spot of the colliding laser beams, impact of birefringence on the vacuum EPP, cascade processes, etc.

[a]Under the adopted normalization to the same **averaged** power over period.

Introduction

The **kinetic equation (KE) approach** is a **non-perturbative** consequence of QED (see [1, 2] and the latest reviews [3, 4] for details). Here we study electron-positron plasma (EPP) production under the action of an **elliptically polarized** (EP) field with a Gaussian envelop ($\tau \gg 2\pi/\omega$):

$$\begin{aligned} E_x(t) &= E_0 \exp(-t^2/2\tau^2)\cos(\omega t), \\ E_y(t) &= E_0 \exp(-t^2/2\tau^2)\cos(\omega t + \phi). \end{aligned} \tag{1}$$

Obviously, $\phi = 0$ corresponds to LP and $\phi = \pi/2$ to CP. To deal with such sort of fields we use a generalized version of KE's [5, 6, 7]. We evaluate numerically both the value of distribution function $f(\vec{p}=0, t; \phi)$ and, independently, the EPP spatial density

$$n(t;\phi) = 2g \int \frac{d^3p}{(2\pi)^3} f(\vec{p}, t; \phi),$$

where the degeneracy factor $g = 2$ for spinor QED and $g = 1$ for the scalar one.

Generalized KE (spinor QED)

In the case of **LP** field with the vector potential $A^\mu(t) = (0, 0, 0, A^3(t) = A(t))$ the KE for **spinor QED** have the well known form [1, 2]

$$\dot{f} = \frac{1}{2}\lambda u, \quad \dot{u} = \lambda(1-2f) - 2\varepsilon v, \quad \dot{v} = 2\varepsilon u, \quad \lambda = \frac{eE\varepsilon_\perp}{\varepsilon^2}, \tag{2}$$

where $\varepsilon(\vec{p}, t) = \sqrt{m^2 + \vec{P}^2}$, $\varepsilon_\perp = \sqrt{m^2 + p_\perp^2}$ and $\vec{P} = \vec{p} - e\vec{A}(t)$ are the quasienergy, transversal energy and quasi-momentum, respectively; and $\vec{E}(t) = -\dot{\vec{A}}(t)$ is the field strength.

Generalization to **arbitrary polarization** in the Hamilton gauge $A^\mu(t) = (A^0 = 0, \vec{A}(t))$ reads [5, 6, 7]

$$\begin{aligned} \dot{f} &= -2\vec{\lambda}_1\vec{u}, & \dot{\vec{f}} &= -2[\vec{f}\,\vec{\lambda}_2] + 2[\vec{v}\,\vec{\lambda}_1] - 2\vec{\lambda}_1 u, \\ \dot{u} &= 2\vec{\lambda}_1\vec{f} + 2\varepsilon v, & \dot{\vec{u}} &= \vec{\lambda}_1(2f-1) - 2[\vec{u}\,\vec{\lambda}_2] + 2\varepsilon\vec{v}, \\ \dot{v} &= -2\varepsilon u, & \dot{\vec{v}} &= -2[\vec{v}\,\vec{\lambda}_2] - 2\varepsilon\vec{u}, \end{aligned} \tag{3}$$

$$\vec{\lambda}_2 = \frac{e[\vec{P}\,\vec{E}]}{2\varepsilon(\varepsilon+m)}, \quad \vec{\lambda}_1 = \frac{\dot{\varepsilon}\vec{P}}{2\varepsilon(\varepsilon+m)} - \frac{e}{2\varepsilon}\vec{E}.$$

These KE are formulated in the Pauli representation, related to the spinor one $\hat{f} \sim f_{ss'}$, $\hat{u} \sim u_{ss'}$ and $\hat{v} \sim v_{ss'}$ by, e.g.,

$$f = \frac{1}{2}\mathrm{Sp}\,(\hat{f}), \quad \vec{f} = \frac{1}{2}\mathrm{Sp}\,(\vec{\sigma}\hat{f}). \tag{4}$$

Hence $f(\vec{p}, t)$ and $\vec{f}$ are the electron/positron scalar and spin **distribution functions**, while u, v and $\vec{u}, \vec{v}$ are the scalar and spin **vacuum anomalous averages**.

Generalized KE (scalar QED)

In order to better understand the spin effects, we compare the results of numerical solution of KE's (3) with that of **scalar QED**, with KE's of the form (e.g., [2, 8]):

$$\dot{f} = \frac{1}{2}\lambda u, \quad \dot{u} = \lambda(1+2f) - 2\varepsilon v, \quad \dot{v} = 2\varepsilon u, \quad \lambda = \frac{eE\vec{P}}{\varepsilon^2}. \tag{5}$$

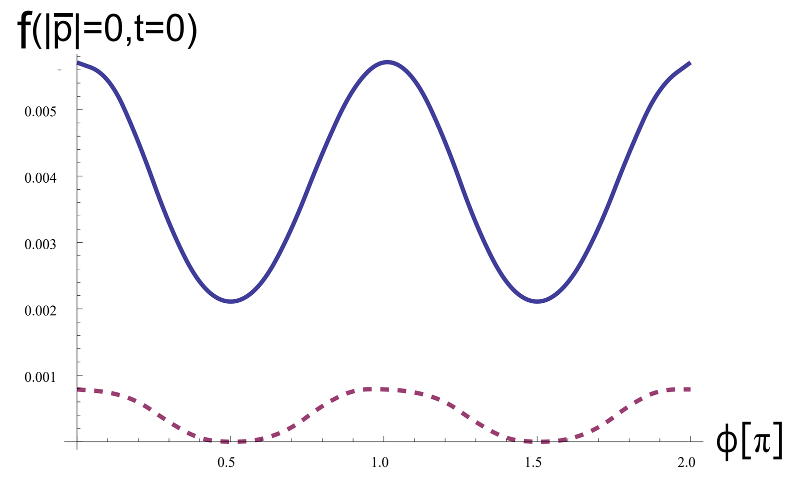

Figure 1: Dependence of the distribution function on phase shift ϕ for spinor and scalar QED. Values $\phi = 0, \pi, 2\pi$ correspond to LP while $\phi = 0.5\pi, 1.5\pi$ to CP.

Shape of momentum distribution

All calculations are made for the same parameters: $E_0 = 0.2E_c$, $\omega = 0.5$, $\tau = 16$, where $E_c = m^2/e$ is the Schwinger critical field, the units $c = \hbar = 1$ are used, and the energy scale is fixed by $m = 1$. In Figs. 1, 2 and 4 the solid and dashed lines correspond to spinor and scalar QED, respectively. Fig. 1 demonstrates suppression of **quasiparticle** creation at the point $\vec{p} = 0$ of the momentum space at $t = 0$ (when the field is maximal) upon transition from LP to CP. This is typical for both the scalar and spinor QED.

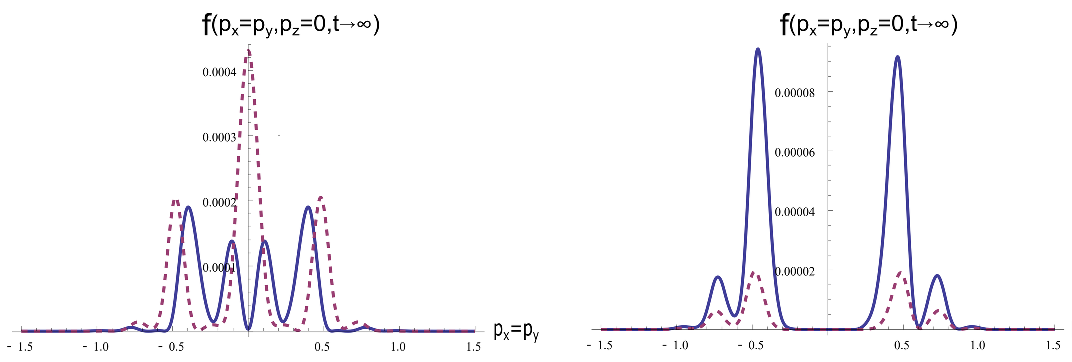

Figure 2: Distribution function along the line $p_x = p_y, p_z = 0$ of momentum space after passing the pulse (1). Left panel: LP; Right panel: CP.

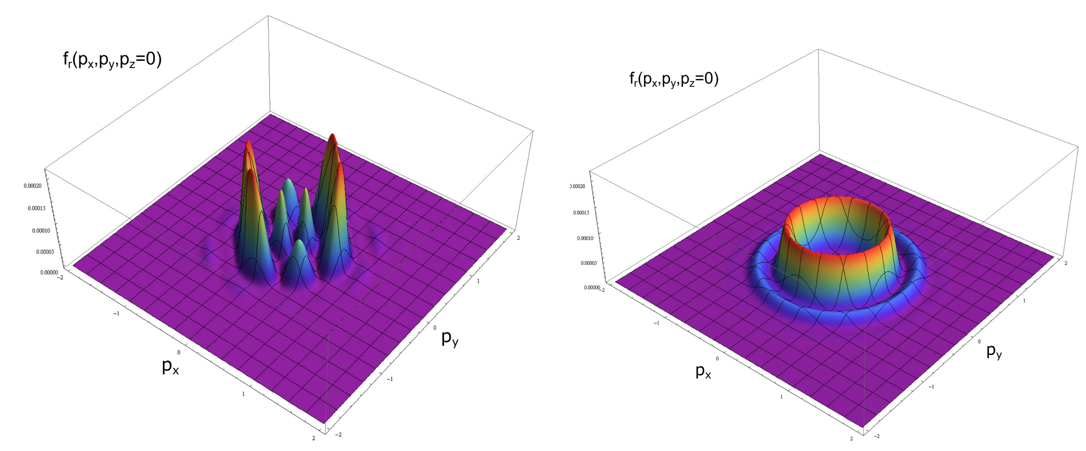

Figure 3: Distribution function for spinor QED over the plane $p_z = 0$ in momentum space. Left panel: LP; Right panel: CP.

Saturated EPP density

Suppression of EPP production in a **small transverse momenta region** results in formation of the out-state with **3D ring-type structure** and a frozen core oriented along the field rotation axis (Figs. 2, 3). Similar 2D structures were observed in graphene [9]. According to Fig. 4 the overall efficiency of EPP production decreases monotonically with ϕ, and is greater in spinor QED than in the scalar one.

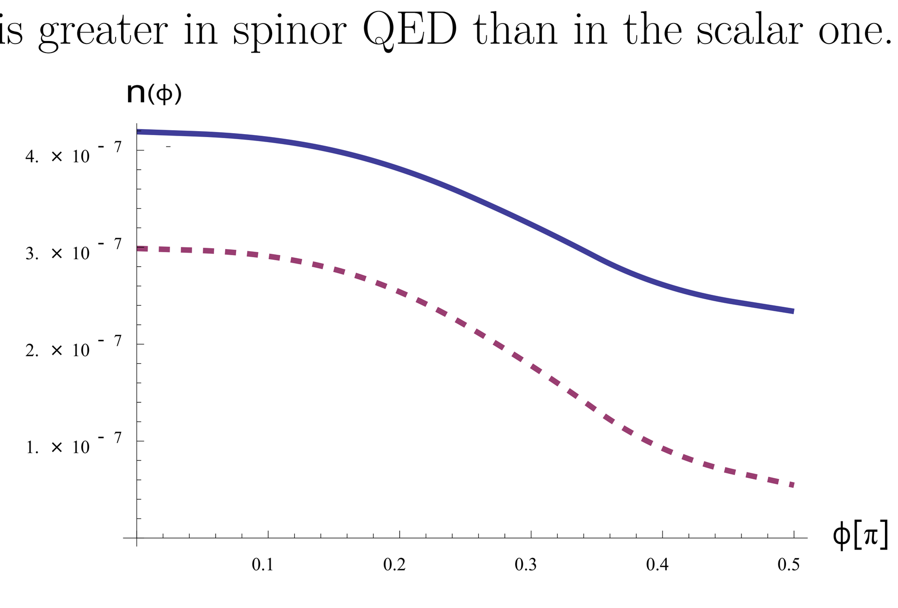

Figure 4: EPP density $n(t = 64, \phi)$ for spinor and scalar QED.

Spin polarization effects

One can judge about **appearance of the macroscopic spin moment** by using the diagonal elements of the density matrix $f_{ij} \sim \hat{f}$. According to the definition (4) $f_{11} = f + f_3$ and $f_{22} = f - f_3$. For LP ($\phi = 0$) we have $f_{11} = f_{22}$ and hence $f_3 = 0$, but for $\phi \neq 0$ this degeneracy is removed, $f_{11} \neq f_{22}$, see Fig. 5. When the field rotation direction is reversed ($\phi \to -\phi$), $f_{11} \leftrightarrow f_{22}$ and $f_3 \to -f_3$ (Fig. 6).

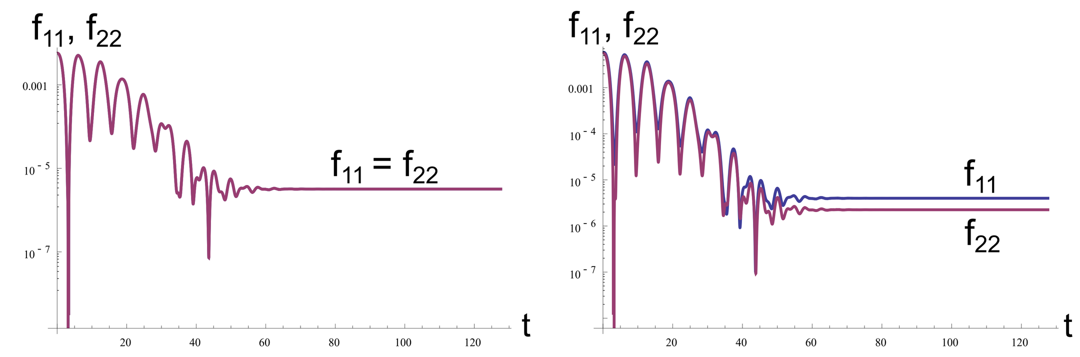

Figure 5: Evolution of diagonal spinor correlators during $0 < t < 120$ at the point $\vec{p} = 0$. Left panel: LP; Right panel: EP ($\phi = 0.05\pi$).

In the CP case ($\phi = \pi/2$) one direction of the macroscopic spin polarization is almost totally suppressed (e.g., $f_{11} \gg f_{22}$) and all the created EPP is **strongly polarized** (Fig.7),

$$n_{22} \ll n_{11} \approx n, \quad S \approx \frac{1}{2}n, \quad \Sigma \approx \mu_0 n, \tag{6}$$

where $\mu_0 = e/2m$ is the Bohr magneton.

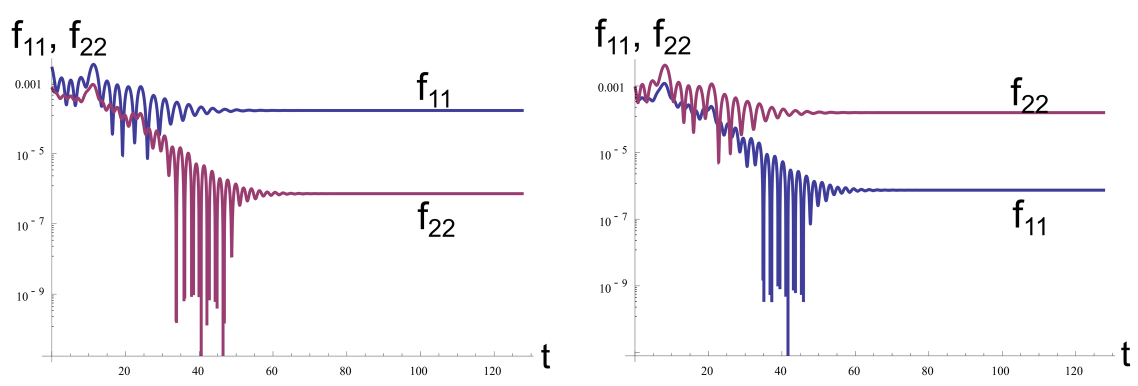

Figure 6: Evolution of diagonal spinor correlators during $0 < t < 120$ at the point $p_x = p_y = 0.49, p_z = 0$ in a rotating field. Left panel: CW rotation ($\phi = 0.5\pi$); Right panel: CCW rotation ($\phi = -0.5\pi$).

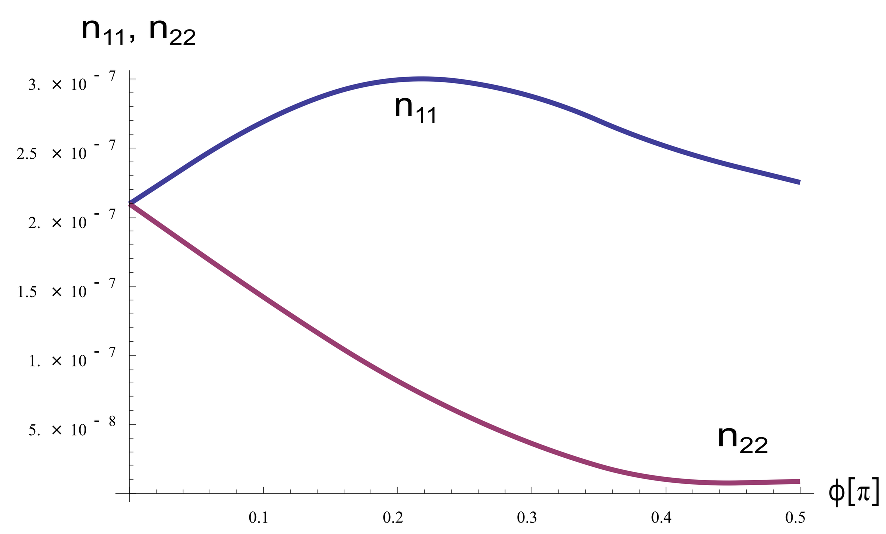

Figure 7: Spin degeneracy removal by transition to $\phi \neq 0$.

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