9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Plasma kinetic model of nonlinear scalar QED particles in high-intensity laser pulse

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In recent high-intensity laser experiments, nonlinear quantum electrodynamics (QED) processes have become important [1]. QED is the U (1) gauge theory for electrons, positrons, and photons. An EM field of a laser pulse is associated with a coherent state, and ``nonlinear'' QED is the model of QED including a coherent EM field [2]. The verification experiments of the scattering cross-sections of nonlinear QED processes have been performed at several high-intensity laser facilities. Such activities aim to study single scattering processes in nonlinear QED. However, the energy spectrum broadening of scattered particles was expected, meaning multiple scattering. For example, the Monte Carlo calculation predicted 23 events of nonlinear Compton scattering on average in a collision of a 600 MeV electron and a focused laser pulse at 1×10^{22} W/cm^2 [3]. Such multiple scattering of nonlinear QED processes is significant for the collective effects of nonlinear QED particles in high-intensity laser experiments. It is expected that those effects follow plasma kinetic theory.

One considers relativistic kinetic theory of electrons in a high-intensity laser pulse, the transport equation might be

$$\left[p^{\mu}\frac{\partial}{\partial x^{\mu}} + F^{\mu}\frac{\partial}{\partial P^{\mu}}\right]\mathcal{N}(x,p) = (\text{quantum collision term})\,. \qquad (1)$$

We employed the 4-vector expression. The vector $F^{\mu} = -\mathcal{F}^{\mu\nu}p_{\nu}/m$ is the laser Lorentz force. We usually substitute a nonlinear QED cross-section for the collision term. Is that treatment correct? The list of issues is as follows:

1. How should we define the distribution function f from a quantum field fundamentally?
2. The LHS of Eq. (1) explains the advection effects in the classical domain. The RHS estimates quantum collision. The physical regimes are different. Is it OK to use Eq. (1)?
3. Quantum field theory doesn't treat forces essentially. How do we formulate the Lorentz force?

Substituting the cross-section for the transport equation is not enough for quantum collision processes. Now consider the following question: can we directly construct kinetic theory from nonlinear QED? We can expect a positive answer to that. How do we demonstrate that? The notable method was explained by de Groot, et. al. [4] who regarded the Wigner function $\mathcal{N}_W$ of a quantum field as a distribution function. Their transport equation was,

$$p^{\mu}\frac{\partial}{\partial x^{\mu}}\mathcal{N}_W(x,p) = (\text{quantum collision term}) \qquad (2)$$

As the third issue, $F^{\mu}\partial\mathcal{N}_{\mathrm{W}}/\partial p^{\mu}$ is absent. For the plasma driving by an EM field, that term is necessary. For that recovery, we propose to use the coherent state of a laser EM field with nonlinear QED formalism. This method can introduce a classical laser EM field in quantum field theory and formulate the term with the Lorentz force in the transport equation. We discuss the above with the charged scalar particle model.

This work was supported by JSPS KAKENHI Grants-in-Aid for Scientific Research (C) JP24K06990, the Institute of Laser Engineering, Osaka University, through Joint Research Project No. 2023B2-076 and 2024B2-028SETO.

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