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Relativistic laser pulse dynamics in dense quantum plasma by QED approach

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Abstract
Utilizing the covariant Lagrangian function and Euler-Lagrange equation, a set of Dirac equations has been derived to elucidate the interaction between strong electromagnetic waves and spin-polarized plasmas. Analysis reveals that relativistic effects significantly impact the interaction process, manifesting through three key factors: self-energy, vacuum polarization, and radiation reaction. In this specific research paper, a quantum electrodynamical approach has been employed to formulate a set of relativistic kinetic equations accommodating both spin +1/2 and -1/2 particles. The model explicitly incorporates quantum electrodynamical characteristics within defined energy ranges and considers the effects influenced by particle spin. Employing this model, investigations into the interaction of lasers with electric fields of varying amplitudes have yielded valuable insights into this dynamic phenomenon.

Keywords: Lagrangian function, vacuum polarisation, quantum electrodynamical, radiation reaction

Introduction

Quantum plasma plays a crucial role in understanding various phenomena, encompassing experiments involving high-intensity lasers with solid plasmas [1-4], dense astrophysical plasmas [5, 6], nanostructures utilized as electronic components [7], metal nanostructures [8], quantum free electron lasers [9], and more. The complete comprehension of particle dynamics in any given phenomenon necessitates analysis across a broad range of velocities, from zero to the speed of light. The relativistic treatment of quantum plasma enhances predictions, accentuates known effects, and sometimes unveils entirely new outcomes, particularly relevant in the domain of high-energy physics [10].

Traditionally, Dirac equations and quantum field theory methods were primarily developed for processes occurring in vacuum, rendering them distinct from the kinetic methods employed in classical plasma physics. This disparity creates a gap in language, understanding, and methodologies between classical and quantum plasma science [11-14]. The model presented herein aims to bridge this gap. Quantum plasmas manifest in diverse environments, including the Earth's interior [15], giant planets [16-21], brown and white dwarf stars [22-24], and the outer crust of neutron stars [25, 26]. They hold promise for applications in nanoscale systems [27] such as quantum wells [28], ultracold plasmas [29], laser fusion plasmas [30], high-intensity light sources [31], plasmonic devices [32], ultrasmall electronic devices [33-38], nanophotonics, nanowires [39-42], quantum diodes [43-45], picoseconds superluminescence [46-48], acousto-electronic devices [49], biophotonics [50], and electron beam pumped semiconductor lasers [51-56]. Additionally, quantum plasma effects are observed in laser-produced plasmas, metal clusters, thin metal films, spintronics, compression-based high-density plasma experiments, and quantum x-ray free-electron lasers [57-59].

In high-energy-density plasmas, where the number density of electrons can reach exceedingly high values, relativistic motion effects become significant. The physical nature of such plasmas is that of relativistic quantum plasmas (RQP), necessitating the establishment of a relativistic quantum model to elucidate the underlying physical processes [60]. Quantum electrodynamics offers a robust framework for investigating the properties and dynamics of RQP by integrating principles from quantum mechanics and relativity. This approach facilitates a profound understanding of the interplay between quantum and relativistic effects in plasma systems, driving advancements in theoretical and experimental plasma physics and unlocking new avenues for practical applications.

For field strengths below the critical threshold, quantum fluctuations have been studied using the quantum electrodynamical (QED) approach. Research has explored phenomena such as circularly polarized waves propagating along external magnetic fields and low-frequency circularly polarized electromagnetic waves in electron-positron plasmas, considering QED effects involving photon-photon scattering. Simulations of relativistic quantum plasmas using real-time lattice scalar QED have also been conducted.

Theory and Methodology

The theoretical framework for modeling the propagation of relativistic laser pulses in high-density quantum plasma using the quantum electrodynamics (QED) approach involves several crucial components.

Maxwell's Equations: Maxwell's equations govern the behavior of electromagnetic fields and are indispensable for describing laser pulse propagation. Coupled with appropriate boundary conditions, these equations dictate the evolution of laser pulses in both space and time.

Quantum Field Theory: Quantum Electrodynamics (QED) is a quantum field theory that elucidates the interaction between charged particles and electromagnetic fields. It treats particles as excitations of quantum fields and incorporates their interactions via the exchange of virtual photons.

Dirac Equation: The Dirac equation, a relativistic wave equation, characterizes the behavior of fermionic particles like electrons and positrons in electromagnetic fields. It amalgamates quantum and relativistic effects, providing a fundamental depiction of their dynamics.

QED Vacuum Polarization: Intense electromagnetic fields induce vacuum polarization, where virtual electron-positron pairs are created and annihilated. This phenomenon alters the refractive index of quantum plasma, resulting in nonlinear effects such as self-focusing and self-phase modulation.

Quantum Kinetic Equations: Quantum kinetic equations, like the Wigner equation or the quantum Vlasov equation, describe the collective behavior of plasma particles. These equations trace the evolution of the particle distribution function, accounting for collisions and quantum statistics.

In the realm of high-energy and high-density plasmas, relativistic effects are paramount. Relativistic Quantum Plasma (RQP) pertains to plasmas where both quantum and relativistic effects are significant. Classical approaches founded on Maxwell's equations and classical statistical mechanics fall short in such extreme conditions, necessitating a quantum field theory approach.

The QED framework offers a unique advantage in addressing RQP as it seamlessly incorporates both quantum and relativistic effects. QED's relativistic nature aptly captures the high-energy behavior of plasma constituents, while its quantum aspects facilitate the depiction of particle interactions and fluctuations at the microscopic level [61, 62]. Moreover, QED furnishes a solid foundation for understanding the interplay between quantum and statistical properties in plasmas [63-65]. To interpret the dynamic behavior of quantum plasmas, four mathematical models are commonly employed: the Wigner-Poisson (WP) model, the Schrödinger-Poisson model, the quantum hydrodynamic (QHD) model, and the quantum electrodynamics (QED) approach. While hydrodynamic models offer ease of computation with acceptable accuracy, kinetic models utilizing the QED approach yield precise results albeit at the cost of complexity and computational time. To address this, we propose developing a new relativistic QED model that combines quantum and relativistic concepts. This model, applicable across all energy regimes, will employ Dirac's equation in tensor form to formulate the term of least action [66, 67], incorporating QED, quantum, and relativistic effects. This equation of motion will be analyzed using the time slices technique [68]. Notably, our model will introduce a novel aspect where laser field amplitudes evolve in space and time, applicable to lasers of all strengths, including those surpassing the Schwinger limit [69-72].

Numerical Modeling

The Lagrangian function of electromagnetic (EM) field can be written as.

$$L = L_O + L_F + L_S \tag{1}$$

where

$$L_O = -mc^2 / \gamma \tag{2}$$

is the Lagrangian function of free electron. m, c, ϒ, are the rest mass of electron, the light speed in vacuum and the relativistic factor of electron respectively.

$$L_F = \frac{-e}{\gamma c} U_\alpha A^\alpha \tag{3}$$

is the ordinary electron- EM wave interaction Lagrangian, e is the electron quantity of an electron, U_α is the 4-velocity of electron and A^α is the 4-potential.

$$L_S = \sigma_\mu (\dot{\sigma}^\mu - \alpha F^{\mu\upsilon} \sigma_\upsilon) \tag{4}$$

Is the spin – e.m. field interaction Lagrangian, $\alpha = e/mc$ and Lande factor g=2 is presumed. σ_μ is the 4-vector spin and $F^{\mu\upsilon}$ is the Maxwell electromagnetic field tensor. The ions are viewed as a uniformly positive background.

$$m\frac{du^\alpha}{d\tau} = e/c\, F^{\alpha\beta} U_\beta + \frac{\partial}{\partial x_\alpha} (\alpha \sigma_\mu F^{\mu\upsilon} \sigma_\upsilon) \tag{5}$$

$$\frac{d\sigma^\alpha}{d\tau} = \alpha F^{\alpha\upsilon} \sigma_\upsilon \tag{6}$$

Equation (5) and (6) are the motion equations of single electron. The microscopic four dimensional velocity and spin density in the rest frame are also defined as $\nu^\mu = u^\mu - U^\mu$ and $\Sigma^\mu = \sigma^\mu - S^\mu$, respectively.

Taking the ensemble average we get,

$$U^\beta \partial_\beta U^\alpha = \frac{e}{mc} F^{\alpha\beta} U_\beta + \frac{e}{m^2 c} \frac{\partial}{\partial x_\alpha} (S_\mu F^{\mu\upsilon} S_\upsilon) - < \nu^\beta \partial_\beta \nu^\beta > + \frac{e}{m^2 c} < \frac{\partial}{\partial x_\alpha} (\Sigma_\mu F^{\mu\upsilon} \Sigma_\upsilon) > - U^\beta < \partial_\beta \Sigma^\alpha > \tag{7}$$

and

$$U^{\beta}\partial_{\beta}S^{\alpha} = \frac{e}{mc}F^{\alpha\upsilon}S_{\upsilon} - < \nu^{\beta}\partial_{\beta}\Sigma^{\alpha} > -U^{\beta} < \partial^{\beta}\Sigma^{\alpha} > \quad (8)$$

Therefore, eq. (7) can be written in the vectorial form as

$$\frac{d(\gamma_f mc^2)}{dt} = eU \cdot E + \frac{e}{\gamma_f m}\frac{\partial}{\partial t}\Psi_s + \frac{P_c}{\gamma_f} \quad (9)$$

$$\frac{d(\gamma_f mU)}{dt} = e(E + \frac{U}{c} * B) + \frac{e}{\gamma_f mc}\nabla\Psi_s - \frac{1}{\gamma_f \eta}\nabla \cdot \Pi + \frac{P_c}{\gamma_f} \quad (10)$$

where

$$\Psi_s = \gamma_f S \cdot (B - \frac{U}{c} \times E) - \frac{2\gamma_f^{\ 2}}{\gamma_f + 1} S^0 (\frac{U}{c} \cdot B) \quad (11)$$

Equations (9) and (10) are the time and special components of (7) respectively. Ψ_s Is the spin potential and in the nonrelativistic limit, it is equivalent to the corresponding item in reference. Π Is the pressure tensor?

$$\frac{dS^0}{d\tau} = \frac{e}{\gamma_f mc} S \cdot E + \frac{P}{\gamma_f} \quad (12)$$

and

$$\frac{dS}{d\tau} = \frac{e}{\gamma_f mc}(S^0 E + S \times B) - \frac{1}{\gamma_f m\eta}\nabla \cdot K + \frac{\Xi_s}{\gamma_f} \quad (13)$$

Equations (12) and (13) are the time and special components. K is the coupling tensor of thermal-spin are the nonlinear corrections to the spin evolution caused by the microscopic four dimensional velocity and spin density in the rest frame. The continuity equation becomes.

$$\frac{\partial}{\partial t}(\eta\gamma) + \nabla \cdot (\eta\gamma U) = 0 \quad (14)$$

Eqs. (9), (10), (12), (13) and (14) form a full set of macroscopic electrodynamical equations. Comparing with the nonrelativistic limit results. It is easy to know to know that the relativistic effects mainly affect the interaction processes by three factors: firstly the self-energy secondly vacuum polarization and thirdly radiation reaction. Lastly the velocity-field coupling as shown in equation. This set of equation can be used to discuss the spin effects of relativistic plasma which exist widely in astrophysics, high energy laser plasma system and so on.

Discussion

Relativistic effects have a profound impact on the linear and nonlinear behavior of plasma waves. Relativistic quantum plasmas have significant potential, serving as injectors for conventional accelerators in fields such as x-ray and nuclear physics. Moreover, they could play a role in igniting controlled thermonuclear fusion reactions. Advancements in laser technology are enabling access to new physical phenomena and enhancing the precision of high-field measurements. Techniques like compression and amplification of laser pulses using plasma gratings hold promise for increasing the maximum power density of intense lasers, overcoming limitations imposed by material damage in conventional chirped pulse amplification systems.

At intensities surpassing approximately 10^{20} W/cm², the production of positrons outpaces their annihilation, potentially leading to the creation of dense electron–positron plasmas. Such exotic plasmas, akin to those found at the horizons of black holes, hold relevance for astrophysics. Understanding this new regime is crucial for advancing ultra-high-intensity laser-matter experiments and their applications, including high-energy ion, electron, positron, and photon sources for fundamental physics research, as well as next-generation radiography for homeland security and industrial applications.

This research endeavors to develop a quantum electrodynamical model for relativistic spin plasma based on the covariant Lagrangian function of electrons. This model enables the exploration of the effects of strong relativistic plasma spin. Analysis indicates that relativistic effects influence the interaction process through three primary aspects: self-energy, vacuum polarization, and radiation reaction. The model, being covariant and derived from quantum field theory, encompasses various quantum effects. It inherently incorporates significant spin effects, making it suitable for conditions where plasma temperature significantly exceeds the Fermi temperature and the force induced by the Bohm potential is much smaller than the spin force.

The model's application involves examining the spin contribution to the ponderomotive force exerted by strong electromagnetic waves on magnetized plasma. Numerical techniques will be employed to analyze results for different parameter sets relevant to the problem at hand. These results will be compared with those obtained using alternative models, and simulation studies will provide insights into realistic scenarios.

In this portion, the main problem, selected in the study should be discussed with the relevant earlier literature and the proposed method or solution. Proper references should be used in support to the content.

Conclusion

The study of quantum plasma, particularly relativistic quantum plasmas (RQP), marks a significant advancement across astrophysical, high-energy physics, and nanoscale systems. Integrating quantum electrodynamics (QED) with plasma physics provides a robust framework, bridging classical and quantum approaches. The proposed relativistic quantum model offers a comprehensive solution, incorporating Maxwell's equations, quantum field theory, and QED vacuum polarization. Numerical techniques, supported by SERB, DST funding, deepen our understanding of relativistic spin plasma's dynamics. This interdisciplinary research promises insights into fundamental physics, laser-matter interactions, and controlled fusion, shaping future advancements in scientific exploration and technological innovation.

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