Landau damping of Langmuir waves in a semiclassical plasma

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Landau damping has been known as one of the most fundamental phenomena of waves in plasma physics. Such collisionless damping of Langmuir waves was first theoretically predicted by Landau [1] and later experimentally verified by Malmberg and Wharton [2]. Since then, the Landau damping in plasmas has been a topic of important research [3, 4]. However, in most of these investigations Landau damping has been considered classically. When quantum effects come into the picture, there appear new length scale and new coupling parameter, as well as new collective modes. Although, there are some developments of Landau damping in nonlinear regimes [4], however, many of these have not yet been explored, especially in the quantum or semiclassical regime.

In this work, we study the effects of nonlinear Landau damping on Langmuir wave envelopes (WEs) in an electron-positron (EP) pair plasma in the weak quantum regime (i.e., when the Langmuir wavelength is larger than the typical thermal de Broglie wavelength of EPs). Our starting point is the Wigner-Moyal distribution function $f_\alpha(x, v, t)$ for electrons $(\alpha = e)$ and positrons $(\alpha = p)$ which satisfies the following evolution equation

$$\frac{\partial f_\alpha}{\partial t} + v\frac{\partial f_\alpha}{\partial x} + \frac{e_\alpha m_\alpha}{2i\pi\hbar^2}\int\int dx_0 dv_0 e^{im_\alpha(v-v_0)x_0/\hbar} \times \left[\phi\left(x+\frac{x_0}{2}\right) - \phi\left(x-\frac{x_0}{2}\right)\right] f_\alpha(x, v_0, t) = 0, \quad (1)$$

where the potential $\phi(x, t)$ satisfies the Poisson equation:

$$\frac{\partial^2\phi}{\partial x^2} = -4\pi\sum e_\alpha \int f_\alpha dv. \quad (2)$$

Using the multiple scale technique as in Refs. [4, 5], we obtain the following nonlinear Schrödinger (NLS)-like equation for Langmuir wave envelopes in EP pair plasmas.

$$i\frac{\partial\phi}{\partial\tau} + P\frac{\partial^2\phi}{\partial\xi^2} + Q|\phi|^2\phi + \frac{R}{\pi}\mathcal{P}\int\frac{|\phi(\xi',\tau)|^2}{\xi-\xi'}d\xi'\phi + iS\phi = 0, \quad (3)$$

where the coefficients of the group velocity dispersion (P), the cubic (Q) and the nonlocal (R) nonlinearities as well as the Landau damping coefficient (S) are significantly modified by the quantum parameter H (the ratio of plasmon energy to thermal energy densities) associated with the particle dispersion. The nonlocal term appears due to the wave-particle resonance.

The NLS equation (3) is used to study the modulational instability (MI) [Fig. 1] and the evolution of WEs in EP plasmas. The effects of H are examined on the Landau damping rate, frequency shift and the energy transfer rate [Fig. 2], as well as on the MI and evolution of Langmuir WEs. It is found that the Landau damping rate and the decay rate of the solitary wave amplitude are significantly reduced compared to the classical case $(H = 0)$.

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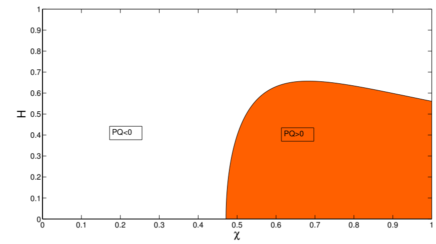

Figure 1: Contour plot of $PQ = 0$ to show the regions for $PQ > 0$ and $PQ < 0$ in the $\chi - H$ plane. $\chi = k/k_d$ is the nondimensional carrier wave number.

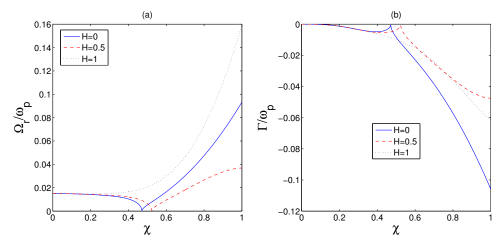

Figure 2: The frequency shift Ω_r/ω_p and the energy transfer rate Γ/ω_p are shown against χ for different values of H as in the legends.

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