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Quantum Kinetic Theory for Plasmas

Spin, exchange, and particle dispersive effects

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Abstract

This thesis is about developing and studying quantum mechanical models of plasmas. Quantum effects can be important at high densities, at low temperatures, and in strong electromagnetic fields, in various laboratory and astrophysical systems. The focus is on the electron spin, the intrinsic magnetic moment; exchange interactions, a purely quantum mechanical effect arising from particles being indistinguishable; and particle dispersive effects, essentially the Heisenberg uncertainty principle. The focus is on using phase-space formulations of quantum mechanics, namely Wigner and Q-functions. These methods allow carrying over techniques from classical plasma physics and identifying quantum as opposed to classical behavior.

Two new kinetic models including the spin are presented, one fully relativistic and to first order in $\hbar$, and one semi-relativistic but to all orders in $\hbar$. Among other example calculations, for the former, conservation laws for energy, momentum, and angular momentum are derived and related to "hidden momentum" and the Abraham-Minkowski dilemma. Both models are discussed in the context of the existing literature.

A kinetic model of exchange interactions, formally similar to a collision operator, is compared to a widely used fluid description based on density functional theory, for the case of electrostatic waves. The models are found to disagree significantly.

A new, non-linear, wave damping mechanism is shown to arise from particle dispersive effects. It can be interpreted as the simultaneous absorption or emission of multiple wave quanta. This multi-plasmon damping is of particular interest for highly degenerate electrons, where it can occur on time scales comparable to or shorter than that of linear Landau damping.

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