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Collisional Transport in Nonneutral Plasmas*

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Recent experiments[1] on nonneutral plasmas have measured 3 coefficients of collisional transport (heat conduction, test particle diffusion, and viscosity) in the regime $r_c \ll \lambda_D$. The transport is from 10 to 10^4 times larger than predicted by classical theory. New guiding center theories of long-range collisional transport have been developed that agree with the measurements [2]. These results are applicable to both nonneutral and neutral plasmas, since electrons in neutral plasmas often fall in the regime $r_c \lesssim \lambda_D$. Our results may also provide insight into the anomalously large electron heat conductivity in fusion plasmas, as discussed below.

Nonneutral plasmas are excellent experimental systems for the study of collisional transport. The plasmas can be confined quiescently for long periods of time (weeks), so that collisional effects can be observed without being masked by the large fluctuation levels inherent in most laboratory neutral plasmas. The collisional transport causes a slow relaxation toward a confined thermal equilibrium in which the temperature and rotation frequency are spatially uniform (the plasmas rotate because of the ExB drift created by the unneutralized plasma space charge).

The classical theory of transport describes only short-range velocity-scattering collisions with impact parameters $\rho < r_c$. We verify experimentally that these short-range velocity-scattering collisions are responsible for Maxwellianization of the velocity distribution, and are correctly described by classical theory. However, in the regime $r_c \ll \lambda_D$ there are many more collisions with impact parameters in the range $r_c < \rho < \lambda_D$. These long-range interactions, which can be treated with guiding center theory, produce a larger (sometimes much larger) contribution to cross-field transport than do the short-range collisions.

1) Thermal conductivity has been measured in a pure ion plasma by creating a thermal gradient using a laser beam that heats (or cools) the ions locally. After the laser is turned off a second laser is employed to monitor the plasma temperature as the gradient relaxes through thermal diffusion. Thermal conductivities up to 200 times that of the classical theory are measured, but the measurements agree with the new guiding center theory. In the new theory guiding centers on well-separated field lines exchange energy associated with their motion parallel to the field, resulting in heat conduction that is *independent of magnetic field strength* B, as opposed to the classical result that scales as B^{-2}.

Furthermore, thermal energy can be exchanged over distances much larger than the Debye length by emission and absorption of lightly damped plasma waves. The new theory includes this mechanism, and future experiments may be able to observe this effect. This wave transport has been suggested as a possible explanation of anomalously large thermal conductivity in the electron channel in tokamak plasmas.[3]

2) In the process of test particle diffusion, long-range Coulomb interactions between guiding centers cause them to ExB drift across the magnetic field, giving enhanced diffusion compared to classical theory. Comparison with experiments led to the discovery of a significant new effect in kinetic theory: When a pair of guiding centers collides, interactions with surrounding particles act as a 'cage' causing multiple collisions between the guiding centers. This effect further enhances the diffusion by a factor of 3.

The coefficient of test particle diffusion has been measured in the same pure ion plasma as was employed in the heat conduction experiments. Ions are tagged via their electronic spins using a laser, and the tagged ions are then observed with a second laser as they diffuse across the magnetic field. The measured diffusion coefficient is ten times the classical prediction but agrees with the new guiding center theory over a wide range of temperatures, densities and magnetic field strengths.

3) In the process of viscous transport, a shear in the plasma rotation frequency is created, and then observed to relax due to viscous drag. Measurements of the coefficient of viscosity have been made in a device containing a pure electron plasma. In this plasma the motion of particles along the magnetic field is very rapid compared to the ExB drift timescale, so the plasma can be regarded as a collection of charged rods moving via 2D ExB drift dynamics. A recent theory of the transport for such a 2D system that explicitly takes into account the finite length of the plasma predicts viscosity that *increases like the first power of magnetic field strength* B, in reasonably good preliminary agreement with the experimentally measured viscosity. The viscosity is up to four orders of magnitude larger than the classical prediction, which scales as B^{-2}.

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