Drag Effect in Double-Layer Dipolar Fermi Gases

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Abstract. We consider two parallel layers of two-dimensional spin-polarized dipolar Fermi gas without any tunneling between the layers. The effective interactions describing screening and correlation effects between the dipoles in a single layer (intra-layer) and across the layers (inter-layer) are modeled within the Hubbard approximation. We calculate the rate of momentum transfer between the layers when the gas in one layer has a steady flow. The momentum transfer induces a steady flow in the second layer which is assumed initially at rest. This is the drag effect familiar from double-layer semiconductor and graphene structures. Our calculations show that the momentum relaxation time has temperature dependence similar to that in layers with charged particles which we think is related to the contributions from the collective modes of the system.

1. Introduction

Ultracold gases of polar atoms or molecules with their anisotropic long-range interaction are of great interest in recent years. [1, 2] Single and multi-layer structures of two-dimensional (2D) bosons or fermions are being studied from the point of view of their quantum phases, Fermi liquid properties, collective excitations, and formation of density waves. [3, 4, 5, 6, 8, 9, 10, 11, 12] Ground-state properties of 2D dipolar fermions have been investigated in a number of works [13, 14, 15]. Transport properties on the other hand are much less studied [16]. In this work, we address a transport property in dipolar fermion gases in analogy to a similar effect observed in electronic systems.

In electronic bilayer systems a transport phenomenon known as the drag effect has been studied for a long time. In the drag effect when a current is applied to one of the layers the electrons in the second will be dragged resulting in an interlayer resistivity which is related to the momentum transfer between the layers. [18, 19] Interestingly, the newly discovered 2D electronic systems such as graphene also exhibit this phenomenon [20].

In this paper, we consider the drag effect in a double-layer dipolar system of polarised fermions. It is assumed that a flow is established in one of the layers while We adapt the Hubbard approximation to describe the correlation effects between the dipoles within the same layer and use the random-phase approximation (RPA) to account for the interactions across the layers. We assume that the Femi gases in the parallel layers are in normal state so that the transfer of momentum from one layer to another gives rise to a friction-like effect. This is in contrast to the so-called dissipationless drag predicted for the same system when the fermions are in a superfluid state [21].

2. Model

We consider two infinite parallel layers of 2D spin-polarized dipolar Fermi gas, separated by a distance d. We assume that an external field aligns the dipoles perpendicularly to the to the laters, so that the intra-layer interaction is purely repulsive and isotropic and given by $V_{11}(r) = C_{dd}/(4\pi r^3)$. The inter-layer bare interaction on the other hand is $V_{12}(r) = (C_{dd}/4\pi)(r^2 - 2d^2)/(r^2 + d^2)^{5/2}$. The Fourier transform of the intra-layer interaction is not well-defined, therefore a cut-off parameter related to the width of the layer is used in various applications. [11, 12]

In this work we adapt the Hubbard approximation for the intra-layer interaction which is a familiar approach from electronic systems. [22] The Hubbard approximation allows us to obtain the intra-layer interaction in Fourier space free of any cut-off parameter and it may be regarded as an effective interaction. For the inter-layer interaction we use the bare Fourier transform as no cut-off is required in this case. Therefore, in Fourier space the intra-layer interaction $V_{11}(q)$ within a single layer and the inter-layer interaction $V_{12}(q)$ across the layers are given by [21]

$$V_{11}(q) = \frac{C_{dd}}{2}\left[\sqrt{k_F^2 + q^2} - q\right] \quad \text{and} \quad V_{12}(q) = -\frac{C_{dd}}{2}q\exp(-qd), \tag{1}$$

where the indices 1 and 2 indicate different layers and C_{dd} is the dipole-dipole coupling constant.

As a result of the momentum transfer caused by inter-layer dipole-dipole interactions, an applied current in one layer drives a current in the other one. This momentum transfer constitutes the Coulomb drag rate in the system, given by [?, 19]

$$\tau_D^{-1} = \frac{\hbar^2}{8mnk_BT\pi^2}\int_0^\infty dq\ q^3 \int_0^\infty d\omega\ \frac{|W_{12}(q,\omega)|^2 \operatorname{Im}\chi_1(q,\omega) \operatorname{Im}\chi_2(q,\omega)}{\sinh^2(\hbar\omega/(2k_BT))}, \tag{2}$$

where k_B is the Boltzmann constant and $\chi(q,\omega)$ is the 2D polarization function. In addition, m is the mass of a dipole and n is the density of a single layer. Here, W_{12} is the dynamically screened effective interaction, defined by

$$W_{12} = \frac{V_{12}}{\epsilon(q,\omega)} \tag{3}$$

in which the dielectric function is written as

$$\epsilon(q,\omega) = [1 - V_{11}(q)\chi_1(q,\omega)]\,[1 - V_{22}(q)\chi_2(q,\omega)] - [V_{12}(q)]^2\,\chi_1(q,\omega)\chi_2(q,\omega), \tag{4}$$

in terms of the intra- and inter-layer interactions and non-interacting dynamic susceptibility of the ith layer $\chi_i(q,\omega)$ for spin-polarised fermions.

3. Results

We calculate the drag rate τ_D^{-1} between the layers of dipolar gases using Eq. (2) as a function of temperature. Note that the temperature dependence comes from various occurrences of χ's in the integrand. The dimensionless interaction strength parameter is defined as $\lambda = k_F a_0$ where a_0 denotes the characteristic length scale, obtained by $a_0 = mC_{dd}/(4\pi\hbar^2)$. Here, m is the mass of a dipole, $k_F = \sqrt{4\pi n}$ is the Fermi wave number and n is the density of a single layer.

Figures 1 and 2 show the drag rate for various values of the interaction strength λ and layer separation distance d. In general, as the distance d gets larger inter-layer interactions are weakened and the drag rate decreases. As the coupling strength λ increases, both the intra- and inter-layer interactions become stronger which results in an increased drag rate. However, we
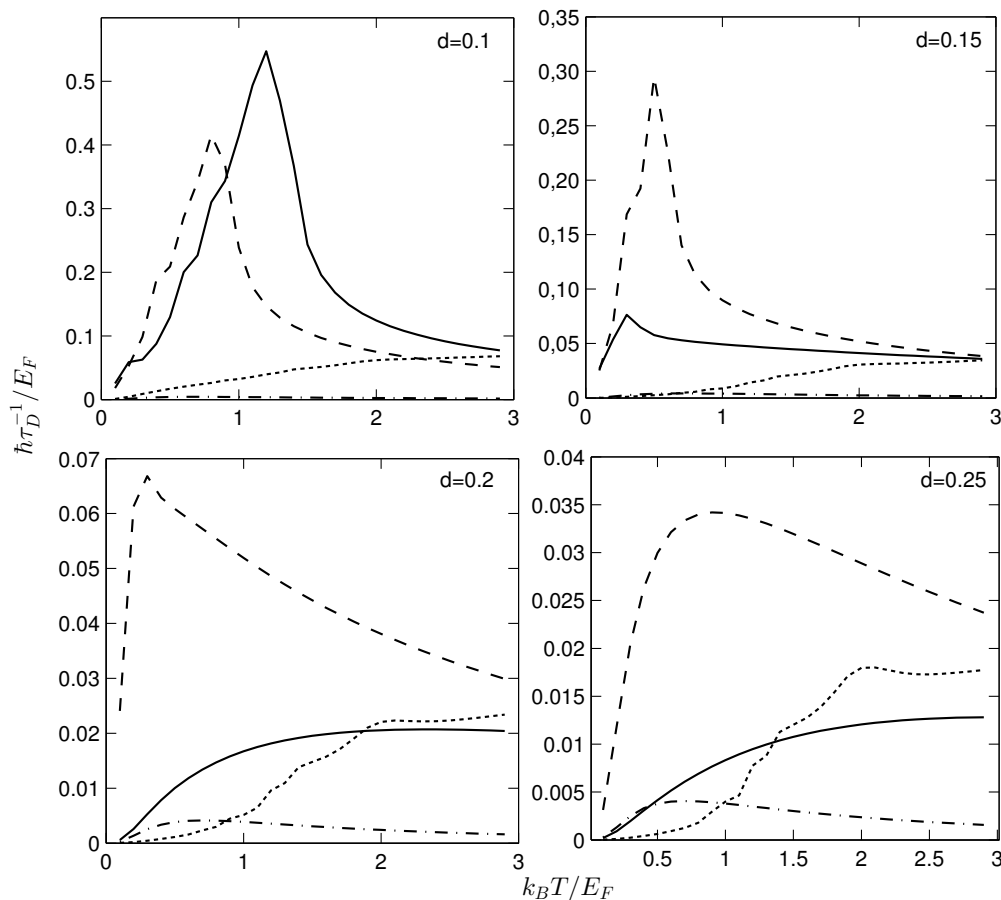
Figure 1. The dimensionless drag rate τ_D^{-1} as a function of temperature for different values of the interaction strengths, indicated by λ, as $\lambda = 0.2$ (dashed-dotted lines), $\lambda = 2.0$ (dashed lines), $\lambda = 4.0$ (solid lines) and $\lambda = 8.0$ (dotted lines). Here, the graphs are obtained for the systems with the well separation distances $d = 0.1, 0.15, 0.2,$ and 0.25, respectively.

do see some anomalies especially at larger values of λ. We surmise that this is because of the Hubbard approximation model we use for the intra-layer interactions and improved interaction models are necessary for further explorations. The overall shape of the drag rate as a function of temperature (up to $3T_F$ resembles that of electronic double-layer structures. [23] Therefore, it is natural to associate the peak around T_F with the collective excitation modes of double-layer dipolar fermions in a similar manner. These are in essence collective density excitations which may be associated with in-phase and out-of-phase oscillations in the double layer system. [21] The peak position in the drag rate also depends on the separation distance d and coupling strength λ. As λ increases the collective modes become less energetic (dispersion is softened) and it becomes easier to excite the modes. This results in a decrease in the overall shape of the drag rate as a function of temperature and a shift in the peak position towards low temperature. With some irregularities we observe this general behaviour. To understand the discrepancies we need to resort to improved interaction models. It would be interesting to calculate the drag rate due to collective excitations only to understand the origin of enhancement at high temperatures.
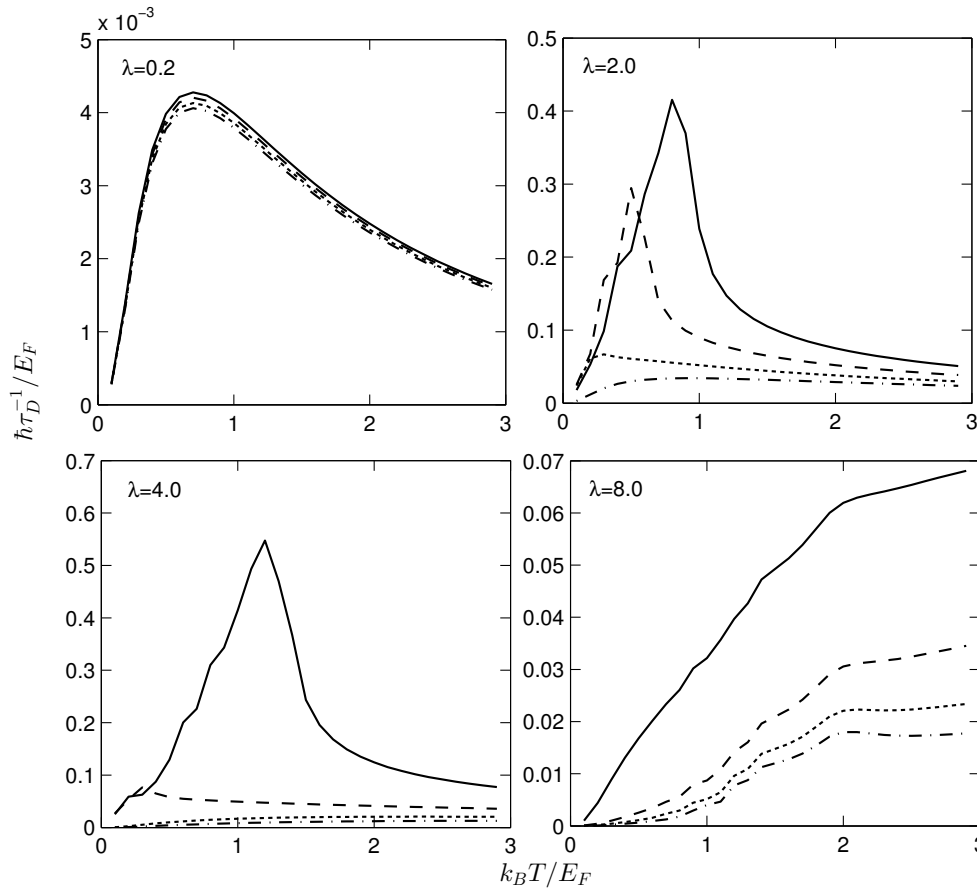
Figure 2. Temperature dependence of the dimensionless drag rate τ_D^{-1} for the corresponding values of the interaction strengths, $\lambda = 0.2, 2.0, 4.0, 8.0$. The solid, dashed, dotted and dashed-dotted lines define the well separation distances for $d = 0.1, 0.15, 0.2, 0.25$, respectively.

4. Conclusion

In conclusion we have calculated the drag rate between two layers of dipolar Fermi gas. We have found that for typical layer separation distances and moderate interaction strengths the drag rate shows a peaked behaviour as a function of temperature. We believe that this is due to the collective mode excitations in the double-layer structure similar to that encountered in electronic systems. More sophisticated screened interaction models are needed to study the strongly correlated regime (large λ). It would also be interesting to explore the effects of density imbalance in the layers.

Acknowledgments

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