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Effects of disorder on the drag rate in double quantum-wire systems

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Abstract

We study the Coulomb drag rate for electrons in a double quantum-wire structure in the presence of disorder. We use the particle number-conserving relaxation-time approximation to phenomenologically broaden the response functions entering the drag rate expression to account for the disorder effects. In contrast to the usual low-temperature regime investigated by various researchers, we focus our attention on the high-temperature drag rate to which plasmon modes are known to make substantial contribution. The full wave vector and frequency dependent random-phase approximation (RPA) at finite temperature and disorder strength is employed to describe the effective interlayer Coulomb interaction. The interplay between the screening effects and disorder at high temperature yields a nonmonotone behavior of the drag rate on the disorder parameter. The reduction in the interwire momentum transfer rate may be used as a probe to investigate localization properties of coupled quantum-wire systems.

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1. Introduction

Recent developments in the semiconductor growth and fabrication techniques have led to the production of high-quality quantum structures to study various aspects of electron-electron interactions in low-dimensional systems. Coupled quantum-well systems are especially well-suited to probe many-body effects because of the interplay between the in-layer and across the layer interaction strengths. A particular example is the Coulomb drag effect, when the well separation is large enough so that tunneling effects are not important, a current flowing in one layer induces a current or voltage in the other layer [1]. The origin of the effect lies in fact that the interactions between the charge carriers in different layers lead to momentum and energy transfer from the current carrying layer to the passive one. The initial experiments [2-5] performed at low temperature gave way to a surge of theoretical activity [6-10] to understand the transport properties of spatially separated electronic systems.

The temperature dependent behavior of the observed [2, 3] drag rate (viz., $\tau_D \sim T^2$) identifies the Coulomb interaction as the drag mechanism. However, deviations from the T^2-behavior in the drag rate led Gramila *et al* [3]. to suggest the exchange of virtual phonons as an alternative mechanism. When the high temperature behavior of the Coulomb drag rate was investigated [8] it was found that the collective mode effects influence the effective interlayer interaction significantly and the drag rate is enhanced compared to the low temperature regime. Recent experiments [11] support this view even if the role of correlation effects are not entirely clear.

The quasi-one-dimensional (Q1D) semiconductor structures provide another example to study the momentum and energy transfer between two electron gases of close proximity. The Coulomb drag effect for quantum wire systems was considered by Sirenko and Vasilopoulos [12] in their comparative study of dimensionality effects. In particular, their calculation for degenerate and nondegenerate systems distinguishes the regions of phase space contributing to the scattering process. Qin [13] used a cylindrical confinement model to determine the temperature and wire radius dependence of the momentum transfer rate. Relatively few works are devoted to the study of drag effect in double-wire systems. Since the level of sophistication of quantum wire fabrication is not as advanced as that of coupled quantum-wells, no experimental results on the drag rate for Q1D systems are reported.

In this paper, we study the effects of disorder on the Coulomb drag rate in coupled quantum wires in the plasmon dominated high temperature region. There are several motivations for investigating the disorder effects. The interplay between the electron-electron interactions and disorder has been a long standing subject of interest [14] accentuated with the recent observation of metal-insulator transitions [15] in Si metal-oxide-semiconductor field-effect transistors (MOSFETs) at zero magnetic field. The Coulomb drag effect in double-layer and double-wire systems offers an interesting probe in diagnosing the insulating phase as suggested by Shimshoni [16]. Since the drag rate is predicted to be enhanced by the plasmon modes the disorder effects would be more easily discerned at higher temperatures than the low temperature region where virtual phonon exchange mechanism is also believed to influence the observed behavior. Recent drag experiments [11] on double quantum-well systems at high temperature demonstrated the importance of collective modes and their careful treatment in the theoretical calculations. Similar effects should take place in double quantum-wire systems and we hope that our investigations will stimulate experimental work to test some of our predictions. Transport properties of coupled 1D systems are also interesting from the point of view of restoration of the Fermi-liquid behavior, as disorder-free, single quantum-wire systems are believed to be Luttinger liquids.

Owing to the present technology of producing quantum wires, the impurity effects such as surface roughness are expected to influence the transport properties. In the typical experiments high mobility samples are used. The Coulomb drag contribution to the observed momentum transfer rate or resistivity is then calculated with the assumption that intralayer impurity scattering is small and independent of energy [8, 9]. In the detailed derivation of Flensberg *et al.* [9] the necessary modifications to the drag resistivity in the case of energy-dependent electron-impurity scattering are discussed. Recently, Świerkowski *et al.* [17] presented a linear-response theory for transresistance in double-layer semiconductor structures. In their treatment the disorder scattering through the relaxation time approximation is accounted for. Our aim is to study the effects of the disorder on the Coulomb drag rate at high temperature. We calculate the interwire momentum transfer rate for a coupled quantum wire system by systematically increasing the strength of the disorder parameter. This amounts to decreasing the mobilities in each wire and can be achieved experimentally by taking more and more disordered samples in a systematic study. We find that the interplay between the disorder effects and effective electron-electron interactions gives rise to an increase in the drag rate for small values of the disorder parameter. As the strength of disorder is further increased we find that the drag rate decreases.

The rest of this paper is organized as follows. In the next section we outline the model we use for the description of coupled quantum-wire system, the drag rate expression, and the calculation of response functions in the presence of disorder. In Sec. III we present our results for the Coulomb drag rate, and provide comparisons with other theoretical works. We conclude with a brief summary.

2. Model and Theory

We consider two cylindrical quantum wires of radius R in parallel and infinite potential barriers [18]. The axes of the wires are separated by a distance d. We assume that only the lowest subband in each wire is occupied. The separation distance is assumed to be large enough to prevent interlayer tunneling. The bare Coulomb interaction between the electrons is written as $V_{ij}(q) = (2e^2/\epsilon_0)F_{ij}(q)$, in which the form factors $F_{ij}(q)$ describe the intra and interwire interactions [18]. The one-dimensional electron density N in each wire is related to the Fermi wave vector by $N = 2k_F/\pi$. We also define the dimensionless electron gas parameter $r_s = \pi/(4k_F a_B^*)$, in which $a_B^* = \epsilon_0/(e^2m^*)$ is the effective Bohr radius in the semiconducting layer with background dielectric constant ϵ_0 and electron effective mass m^*.

We adopt the Coulomb drag rate expression derived for double-layer systems to the present case of double wire problem [6-10]

$$\tau_D^{-1} = \frac{1}{4\pi m^* N T}\int_0^\infty dq\, q^2 \int_0^\infty d\omega \left|\frac{W_{12}(q,\omega)\,\mathrm{Im}\chi(q,\omega)}{\sinh(\omega/2T)}\right|^2 , \tag{1}$$

in which we have also assumed that the electron system in each wire has the same density N (we take $\hbar$ and k_B equal to unity). The above expression has been derived in a variety of approaches [6-10] from the Boltzmann transport theory to memory function formalism. It measures the rate of momentum transferred from one quantum-wire to the other. Here, $\chi(q,\omega)$ is the 1D dynamic susceptibility, describing the density-density response function of a single wire. We take $W_{12}(q,\omega)$ to be the dynamically screened effective interaction between electrons in quantum-wire 1 and 2. Within the random-phase approximation (RPA), the effective interlayer interaction is given by

$$W_{12}(q,\omega)=\frac{V_{12}(q)}{\varepsilon(q,\omega)}\,, \tag{2}$$

in which

$$\varepsilon(q,\omega)=[1-V_{11}(q)\chi(q,\omega)]^2-[V_{12}(q)\chi(q,\omega)]^2\,, \tag{3}$$

is the total screening function for the coupled quantum wire system. In this RPA expression, the bare intra and interwire electron-electron interactions V_{11} and V_{12} are used, thus the correlation effects are ignored. Recent numerical calculations [19, 20] indicate the importance of correlation effects in coupled quantum wire systems, and we discuss their influence on the drag rate in the next section. It is also assumed that only the lowest subband in each wire is occupied. Thus, the energy difference between the second and first subband levels $\Delta_{21}\approx 10(4/\pi)^2 r_s^2(R/a_B^*)E_F$ should be greater than the thermal energy T. For reasonable densities and wire radii of experimental interest, the single subband assumption holds.

In this work, we retain the full wave vector, frequency, disorder, and temperature dependence of the dynamic susceptibility $\chi(q,\omega)$ which enters the numerator of the drag rate expression Eq. (1) as well as the screening function $\varepsilon(q,\omega)$. We account for disorder by considering an impurity scattering induced broadening γ which should be regarded as a phenomenological parameter. More explicitly, the real and imaginary parts of χ are given by

$$\mathrm{Re}[\chi(q,\omega;T)]=-\frac{m}{\pi q}\left[F(t,z_+,z_i)-F(t,z_-,z_i)\right], \tag{4}$$

$$\mathrm{Im}[\chi(q,\omega;T)]=\frac{m}{\pi q}\left[G(t,z_+,z_i)-G(t,z_-,z_i)\right], \tag{5}$$

where

$$F(t,z,z_i)=\frac{1}{4}\int_0^\infty\frac{dx}{\cosh^2(x-\tilde{\mu}/2)}\,\ln\left|\frac{(\sqrt{2tx}+z)^2+z_i^2}{(\sqrt{2tx}-z)^2+z_i^2}\right|, \tag{6}$$

$$G(t,z,z_i)=\pi f(z)+\frac{1}{2}\int_0^\infty\frac{dx}{\cosh^2(x-\tilde{\mu}/2)}\left[\tan^{-1}\left(\frac{z_i}{\sqrt{2tx}-z}\right)+\tan^{-1}\left(\frac{z_i}{\sqrt{2tx}+z}\right)\right], \tag{7}$$

in which we have used the scaled variables $t=T/E_F$, $\tilde{\mu}=\mu/T$, $z_\pm=(\Omega/\tilde{q}\pm\tilde{q})/2$, where $\Omega=\omega/E_F$ and $\tilde{q}=q/k_F$, and $z_i=\gamma/(2E_F\tilde{q})$. The chemical potential μ at finite temperature is calculated from the normalization integral $N=2\int(dk/2\pi)f(k)$, where $f(k)$ is the Fermi-Dirac distribution function for noninteracting electrons at finite temperature T. The quadrature formulae for $F(t,z,z_i)$ and $G(t,z,z_i)$ are the adaptation of Maldague's approach [21] to the 1D case. Screening properties of a 1D electron gas including both the thermal and collisional broadening effects were first calculated by Das

Sarma and Lai [22]. Once the finite temperature polarizability is obtained we impose the number-conserving approximation given by the Mermin formula [23]:

$$\chi_\gamma(q,\omega) = \frac{(\omega + i\gamma)\chi(q,\omega + i\gamma)}{\omega + i\gamma\chi(q,\omega + i\gamma)/\chi(q,0)} \,. \tag{8}$$

Thus, in the drag rate integral we use the above polarizability expression (after separating real and imaginary parts) which includes both the temperature and impurity scattering effects. In the limit q, $\omega \to 0$, the number-conserving approximation above gives the correct diffusive behavior for the response function

$$\chi_\gamma(q,\omega) \simeq -\frac{2m^*}{\pi k_F}\,\frac{Dq^2}{Dq^2 + i\omega}\,, \tag{9}$$

where $D = k_F^2/m^{*2}\gamma$ is the diffusion constant in a 1D system.

3. Results and discussion

We use the material parameters appropriate for a GaAs system for which the recent experiments [2-5, 11] on drag rate between coupled quantum-wells are performed. The static dielectric constant is given by $\epsilon_0 = 12.9$. The effective Bohr radius for GaAs is $a_B^* \approx 100\,\text{Å}$. For a typical linear electron density $N \sim 10^6\,\text{cm}^{-1}$, the electron gas parameter is $r_s \approx 0.5$. We first examine τ_D^{-1} at low temperatures. In coupled quantum wire systems with a single filled subband, the drag rate τ_D^{-1} is dominated by back scattering ($q \sim 2k_F$). At low temperatures ($T \ll T_F$), the use of approximate expressions for the response function $\chi(q,\omega)$ of a clean system, and neglecting the screening effects result in a linear temperature dependence [12, 24]

$$\tau_D^{-1} \sim \frac{|W_{12}(2k_F)|^2\, m^{*2}\, T}{k_F^2}\,. \tag{10}$$

In the presence of disorder, the diffusive limit of $\chi(q,\omega)$ gives rise to a different ω and q behavior of the integrand, and we find to leading order

$$\tau_D^{-1} \sim \frac{|W_{12}(2k_F)|^2\, m^{*5}\, T^2\, \gamma^2}{k_F^8}\,. \tag{11}$$

In two-dimensional systems, Zheng and MacDonald [6], using similar approximations, have found a logarithmic correction to the low-temperature drag rate. Kamenev and Oreg [9] have also reached similar results, and in particular have shown that for extremely dirty samples the drag resistivity goes as $\rho_D \sim T\gamma$.

Next, we evaluate numerically the Coulomb drag rate τ_D^{-1} using the effective interaction obtained for a double-wire system as a function of temperature. We retain the full wave vector, frequency, disorder, and temperature dependence in $\chi(q,\omega)$ and $\varepsilon(q,\omega)$, using the formalism outlined in the previous section. Similar to the double quantum-well system [8, 11], at high temperature, the drag rate is dominated by collective excitation modes described by the zeros of the dielectric function $\varepsilon(q,\omega)$. The plasmon dispersion $\omega_{\rm pl}(q)$ in a double wire system has two branches, both lying above the particle-hole continuum. As the temperature increases, the particle-hole continuum embodying the single-particle excitation region broadens to render coupling between the collective modes more feasible, and the drag rate is enhanced. The effect of phenomenological broadening to simulate disorder effects on the plasmon dispersions is such that $\omega_{\rm pl}(q)$ is depressed [25, 26].

In Figs. 1-2 we show the scaled drag rate τ_D^{-1}/T as a function of temperature for two different coupled wire systems. That τ_D^{-1}/T exhibits a broad enhancement for $T \gtrsim 0.3\,E_F$ indicates a much stronger T-dependence at high temperature. The phenomenological disorder parameter γ/E_F is taken to be 0 (clean system), 0.05, 0.1, and 0.5. We observe, that with increasing disorder (for small γ) the drag rate τ_D^{-1} increases in magnitude and shifts towards the low temperature side. This effect is more visible in coupled quantum-wire systems with larger radius. However, at the largest disorder parameter considered ($\gamma/E_F = 0.5$) the drag rate is actually lower than that of a clean system ($\gamma = 0$). This may be due to the breakdown of weak-disorder approximation adopted in our formalism. When the density of electrons in each wire is lowered, the correlations are expected to become more effective. The drag rate τ_D^{-1} in the low-density case ($r_s = 1.5$) is peaked at a higher temperature with increasing magnitude. In contrast, small radius quantum wires are better suited to observe this effect.

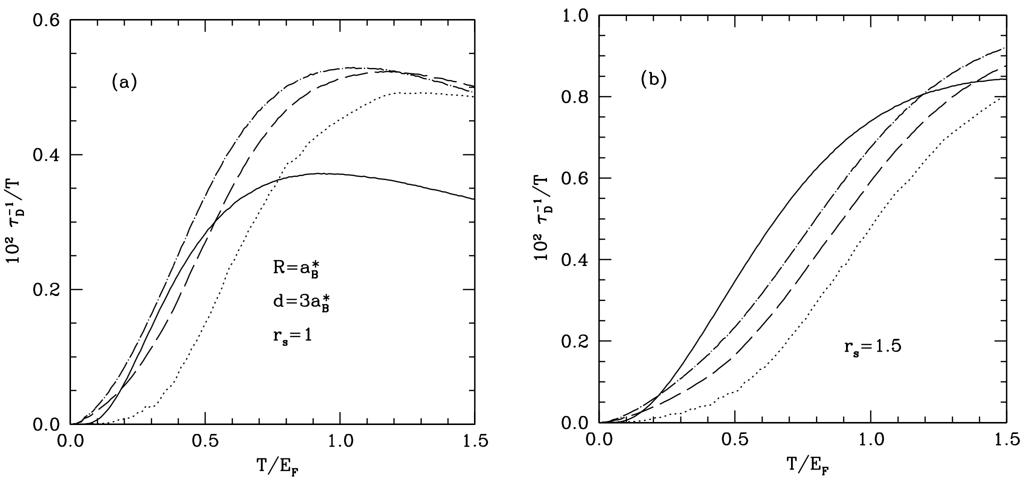

Figure 1. The scaled drag rate τ_D^{-1}/T within the RPA as a function of temperature for a double quantum-wire system with $R = a_B^*$, $d = 3\,a_B^*$, at (a) $r_s = 1$ and (b) $r_s = 1.5$. The dotted, dot-dashed, dashed, and solid lines are for $\gamma/E_F = 0$, 0.05, 0.1, and 0.5, respectively.

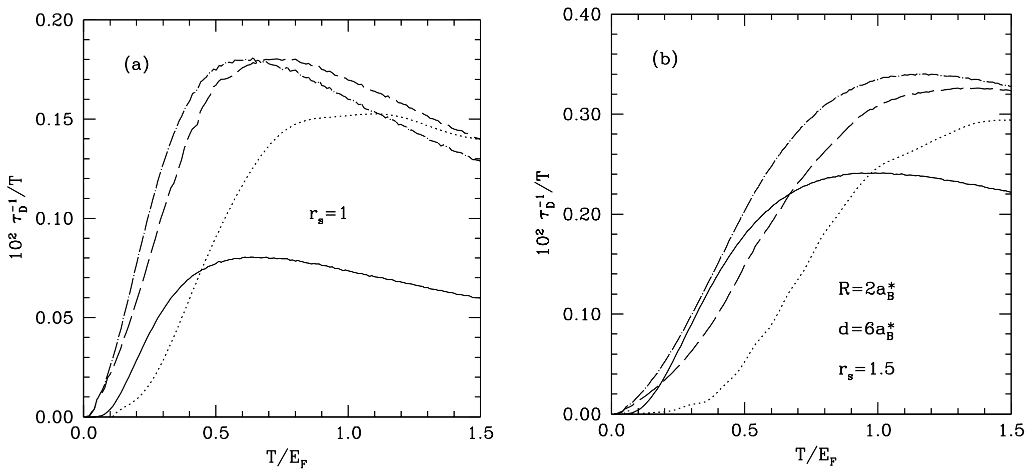

Figure 2. The scaled drag rate τ_D^{-1}/T within the RPA as a function of temperature for a double quantum-wire system with $R = 2\,a_B^*$, $d = 6\,a_B^*$, at (a) $r_s = 1$ and (b) $r_s = 1.5$. The dotted, dot-dashed, dashed, and solid lines are for $\gamma/E_F = 0$, 0.05, 0.1, and 0.5, respectively.

To trace the origin of dependence on the disorder parameter γ of the momentum transfer rate we investigate the integrand of Eq. (1) in detail. After performing the frequency integral, we end up with $\tau_D^{-1} \sim \int dq\, q^2\, F(q)$ which we plot in Fig. 3 as a function of q. Specializing to the coupled wire system with parameters $R = a_B^*$ and $d = 3\,a_B^*$, at $r_s = 1$ and $T = E_F$, we observe that the peak position in the integrand is shifted towards the long-wavelength side as γ increases. However, the peak height of the integrand after increasing for low disorder ($\gamma \approx 0.1\,E_F$), starts to decease for greater disorder compared to its value of the clean system. In Fig. 4 we show the frequency dependence of the response function $\mathrm{Im}[\chi(q,\omega)]$. Figure 4a shows $\mathrm{Im}[\chi(q,\omega)]$ for $\gamma = 0$, 0.1, and $0.5\,E_F$, denoted by the dotted, dashed and solid lines, respectively. The calculated behavior shows similar trends as those treated by Das Sarma and Hwang [25]. In the same figure shown by the thick lines are the dynamically screened response functions, i.e. $\mathrm{Im}[\chi(q,\omega)]/|\varepsilon(q,\omega)|$. Again we observe a steady decrease as the disorder parameter γ increases. However, at a smaller wave vector ($q = 0.1\,k_F$) we find in Fig. 4b, a rather different behavior for the screened quantity $\mathrm{Im}[\chi(q,\omega)]/|\varepsilon(q,\omega)|$. As the integral over q and ω is performed in the calculation of τ_D^{-1} the observed nonmonotone behavior manifests itself.

We have based our systematic study of disorder scattering effects on the drag rate, on the theoretical formalism developed by Świerkowski *et al.* [17]. In this approach momentum-independent relaxation-time approximation is used to phenomenologically broaden the response function $\chi(q,\omega)$. A number of theoretical calculations are devoted to the low temperature behavior of drag rate for coupled quantum-wells in the presence of disorder. By splitting the contributions of ballistic and diffusive regimes Zheng and MacDonald [6] calculated the correction to the interlayer scattering rate due to disorder enhanced interactions. Similar enhancement in the drag resistivity ρ_D was also calculated by Kamenev and Oreg [9] who used diagrammatic perturbation theory methods. In a recent paper, Shimshoni [16] considered the Coulomb drag between two parallel layers in the Anderson insulating state, treating the Mott and Efros-Shklovskii types separately. In his low-temperature analysis, Shimshoni [16] found that ρ_D is suppressed for a Mott insulator with decreasing localization length (i.e. increasing disorder). In all these attempts the disorder has the effect of enhancing the drag rate τ_D^{-1} of the resistivity ρ_D as a function of T. In the Boltzmann equation theory based calculation of the drag rate Flensberg and Hu [8] found that the charged impurities located a distance s away from the quantum wells influenced τ_D^{-1} significantly for $s \lesssim 400\,\text{Å}$. Classical simulations to determine the influence of ionized impurities on Coulomb drag has also been performed [27]. We also point out that disorder effects in Coulomb drag problems are gaining attention recently in a variety of related contexts [28].

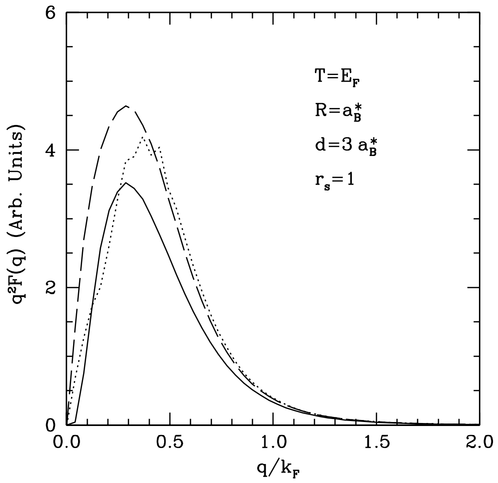

Figure 3. The integrand of Eq. (1) after the ω-integration is carried out. The system parameters are $R = a_B^*$, $d = 3\,a_B^*$, $r_s = 1$, and $T = E_F$. The dotted, dashed, and solid lines are for $\gamma/E_F = 0$, 0.1, and 0.5, respectively.

Our approach is different than considered by Shimshoni [16] in that we assume from the outset that the electronic state of quantum wires are metallic. The phenomenological disorder parameter has the effect of lowering the mean free path of electrons as the magnitude of γ increases. Thus, the density fluctuations described by $\text{Im}[\chi(q,\omega)]$ in the numerator of Eq. (1), and $\varepsilon(q,\omega)$ appearing in the denominator are nontrivially altered at higher temperatures. Taking the mean-free path and localization length in a 1D system to be the same, we estimate $lk_F = 2E_F/\gamma \approx 4$ for the largest value of the disorder parameter used, which is close to the weak to strong localization crossover. Our results indicate that coming from the metallic phase, the drag rate may potentially signal the localization properties of coupled quantum-wire systems.

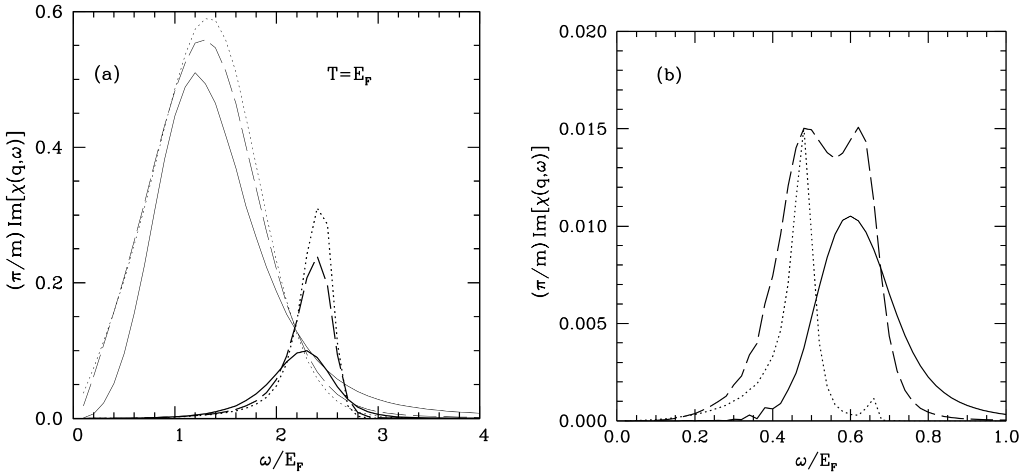

Figure 4. The frequency dependence of the imaginary part of the response function for a $R = a_B^*$, $d = 3\,a_B^*$ double wire system at $r_s = 1$ and $T = E_F$. (a) Thin lines are for the non-interacting system $\mathrm{Im}[q,\omega)$, whereas the thick lines denote $\mathrm{Im}[\chi(q,\omega)/|\varepsilon(q,\omega)|$ at $q = 0.5\,k_F$. (b) $\mathrm{Im}[\chi(q,\omega)/|\varepsilon(q,\omega)|$ for the same parameters at $q = 0.1\,k_F$.

As the electron density in each wire is lowered the exchange-correlation effects become stronger. The RPA employed to screen the bare interwire interaction becomes inadequate. In the detailed studies of drag resistivity and drag rate in double-layer systems it has been found important to include correlation effects beyond those described by the RPA to achieve agreement with experimental data at low densities [17, 29]. We incorporate the correlation effects in an approximate way using local-field corrections within the self-consistent STLS scheme [30]. In a recent calculation [19] of intra and interwire correlation effects in double quantum wire systems, we have accounted for the disorder effects through the use of Eq. (8). In this number-conserving approximation with γ acting as a parameter throughout the self-consistent evaluation of the correlation effects, we find that the local-field factors are slightly modified. Figure 5 shows the intrawire (thick lines) and interwire (thin lines) local-field corrections for two different coupled quantum wire systems. It is found that the phenomenological disorder parameter γ changes $G_{ij}(q)$ for $q/k_F \gtrsim 1$. It has the general effect of increasing the intrawire correlations and decreasing the interwire correlations. Recently, Thakur and Neilson [26] have combined the STLS scheme and mode-coupling theory to treat the disorder and correlation effects self-consistently. It would be interesting to apply their method to a coupled quantum wire system to obtain a more realistic assessment of the disorder effects in a strongly correlated system. In the STLS scheme the bare Coulomb interactions are replaced by $V_{ij}(q) \to V_{ij}(q)[1 - G_{ij}(q)]$. A calculation by Świerkowski *et al.* [17] shows that the G_{12} affects the transresistivity in double-layer electron systems very little. However, the short-range intra-layer correlations built in via the self-consistent scheme yield a substantial increase. Similar behavior in double-wire systems is also seen to hold. In Fig. 6, we show the drag rate with (thick lines) and without (thin lines, RPA) the local-field corrections for $r_s = 1$ (Fig. 6a) and $r_s = 1.5$ (Fig. 6b). In general, the correlation effects increase the calculated drag rate. The peak position in τ_D^{-1}/T due to plasmon enhancement also shows a slight shift, but we have not systematically studied this effect. We note that the local-field corrections used in the present calculation are temperature independent. Although it would be interesting to develop more accurate temperature dependent local-field corrections [31], we conjecture that their effect would be small in the temperature regime of interest. Finally, we mention that Das Sarma and Hwang [25] have criticized the use of local-field factor, arguing that the vanishing of vertex corrections to the polarizability renders the RPA exact in 1D systems. It would be most useful to have experimental results on the strongly correlated double quantum-wires to resolve some of these issues. Controlled experiments would also be helpful in distinguishing the non-Fermi liquid (i.e. Luttinger liquid) manifestations thought to occur in strongly coupled 1D systems [32].

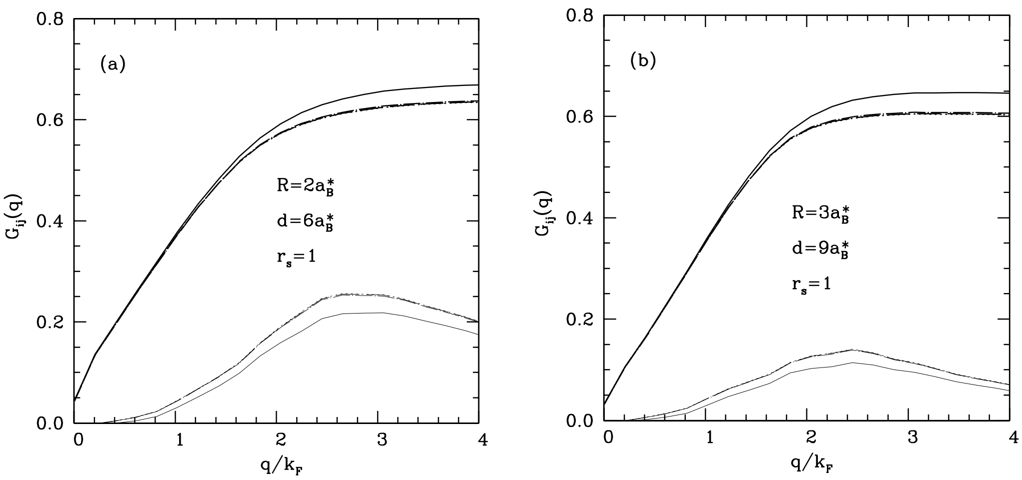

Figure 5. The intrawire (thick lines) and interwire (thin lines) local-field corrections in the presence of disorder in a coupled quantum-wire system. The system parameters are (a) $R = 2\,a_B^*$, $d = 6\,a_B^*$ (b) $R = 3\,a_B^*$, $d = 9\,a_B^*$ at $r_s = 1$. The dotted, dashed and solid lines are for $\gamma/E_F = 0$, 0.1, and 0.5, respectively. The interwire local-field factors are multiplied by a factor 10 to enhance visibility.

In summary, we have considered the Coulomb drag effect between two parallel quantum-wires in the presence of disorder treated phenomenologically. The temperature dependence of the drag rate is known to be significantly enhanced at high temperature when a dynamically screened effective interlayer interaction is used [8]. This enhancement is due to the collective density fluctuations (plasmons) in the double quantum-wire system. We find that at small values of the disorder parameter, the drag rate is further increased. At larger values of the disorder parameter, the density fluctuations are suppressed with a reduced localization length and the drag rate is reduced. Thus, the drag rate τ_D^{-1} exhibits a non-monotonous behavior with respect to the strength of disorder, and may be used as a possible probe to understand the localization properties in Coulomb coupled systems. Similar effects are also expected to take place in double-layer structures. So far, the experiments [2-5, 11] measuring the Coulomb drag rate were carried out with high-mobility samples. A systematic study with varying degrees of disorder, should in principle be able to test some of our predictions.

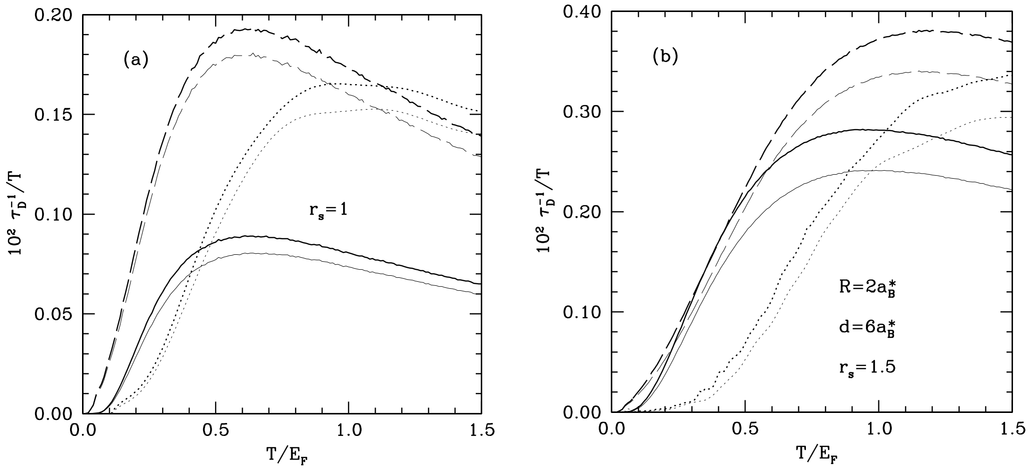

Figure 6. The scaled drag rate τ_D^{-1}/T with (thick lines) and without (thin lines, RPA) the local-field corrections as a function of temperature for a double quantum-wire system with $R = 2\,a_B^*$, $d = 6\,a_B^*$, at (a) $r_s = 1$ and (b) $r_s = 1.5$. The dotted, dot-dashed, dashed, and solid lines are for $\gamma/E_F = 0$, 0.05, 0.1, and 0.5, respectively.

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