Mesoscopic fluctuations of Coulomb drag of composite fermions

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We report the observation of mesoscopic fluctuations of Coulomb drag in a system with two layers of composite fermions, which are seen when either the magnetic field or carrier concentration are varied. These fluctuations cause an alternating sign of the average drag. We study these fluctuations at different temperatures to establish the dominant dephasing mechanism of composite fermions.

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Coulomb drag is a powerful technique for measuring the strength of electron-electron (e-e) interaction. Coulomb drag studies are performed on two closely spaced but electrically isolated layers, where a current is driven through one (active) layer and the voltage drop is measured along the other (passive) layer. The origin of this voltage is a momentum transfer between the charge carriers in the two layers via e-e interaction. Coulomb drag is well-studied theoretically[1–5] and has been investigated in a range of experimental systems.[6–14]

A specific case in Coulomb drag occurs in the presence of strong magnetic fields when all electrons are contained within the lowest Landau level and the filling factor ν has a value of 1/2. Under these conditions the strongly interacting electrons can be described by composite-fermion (CF) quasiparticles, each of which representing an electron coupled with two magnetic flux quanta $\Phi_0=h/e$.[15] In previous theoretical[16] and experimental[11] studies, the Coulomb drag in CF systems has been shown to be strongly enhanced and have a different temperature dependence compared with the case of $B=0$.

Recently, it has been shown that Coulomb drag in disordered systems can demonstrate the interplay of e-e interactions and quantum interference.[17] This was observed as reproducible fluctuations of the drag.[14] These have a similar origin as conductance fluctuations in single-layer systems[18] that arise from the interference between electrons in each layer. Unlike the conductance fluctuations, the fluctuations of the drag are remarkable in that they can exceed the average value, resulting in random changes in the sign of the drag as the carrier concentration and magnetic field are varied.

The properties of CFs around $\nu=1/2$ are similar to those of normal noninteracting electrons at small B field.[19] Indeed, there has been a theoretical prediction that a fluctuating drag is also expected in a system of CFs.[20] Here we report the observation of the fluctuations of the Coulomb drag between CFs. Despite the significant increase in the magnitude of drag of CFs relative to that of normal electrons, the fluctuations of the drag can still exceed the average, resulting in an alternating sign of the drag.

The studied samples are AlGaAs-GaAs double-layer structures,[21] where the carrier concentration of each layer can be independently controlled by gate voltage over the range of $n=0.4\times10^{11}$–2.0×10^{11} cm^{-2} with a corresponding change in the mobility from 1.2 to 6.7 $\times10^5$ cm^2 V^{-1} s^{-1}. The GaAs quantum wells are 200 Å in thickness and are separated by an $Al_{0.33}Ga_{0.67}As$ layer of thickness 300 Å. Each layer has a Hall-bar geometry, 60 μm in width and with a distance between the voltage probes of 60 μm. The measurement circuit of the drag voltage V_2 is shown in Fig. 1(A). The drag resistance R_D is found from the ratio of the drag voltage to the current I_1 passed through the active layer, $R_D=-V_2/I_1$.

The drag resistance as a function of magnetic field, $\rho_D(B)$, is shown in Fig. 1 for various temperatures in the vicinity of $\nu=1/2$. Values of drag taken at a fixed B field are plotted in Fig. 1(B). The solid line is a plot, without adjustable parameters, of the expected value of the drag resistance of CFs (Ref. 16) in a macroscopic sample

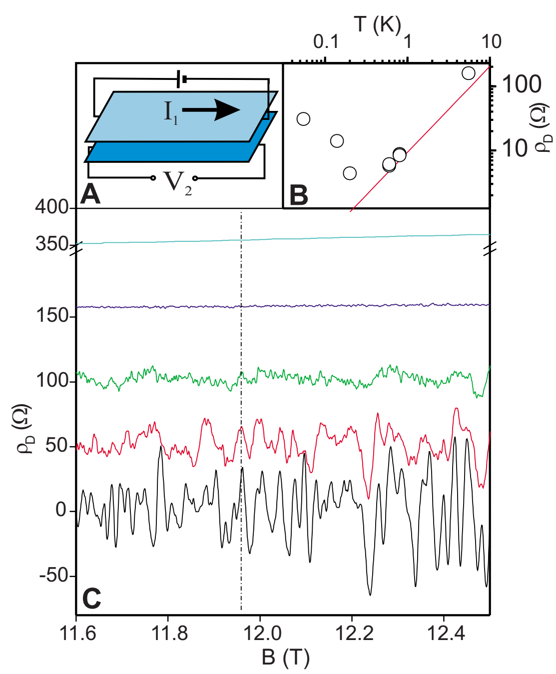

FIG. 1. (Color online) Panel A: schematic of the measurement circuit used to measure the Coulomb drag. Panel B: the drag resistivity as a function of temperature, at a fixed B field of 11.96 T. The solid line is Eq. (1). Panel C: drag resistivity as a function of magnetic field for different temperatures; T=0.05, 0.14, 0.2, 0.8, 5.6 K, from bottom to top. The graphs are offset from each other by 50 Ω for clarity. The concentration of each layer is $n=1.45\times10^{11}$ cm^{-2} such that $\nu=1/2$ at $B_{1/2}=12$ T. The vertical line corresponds to the B field at which the points plotted in panel B were measured.

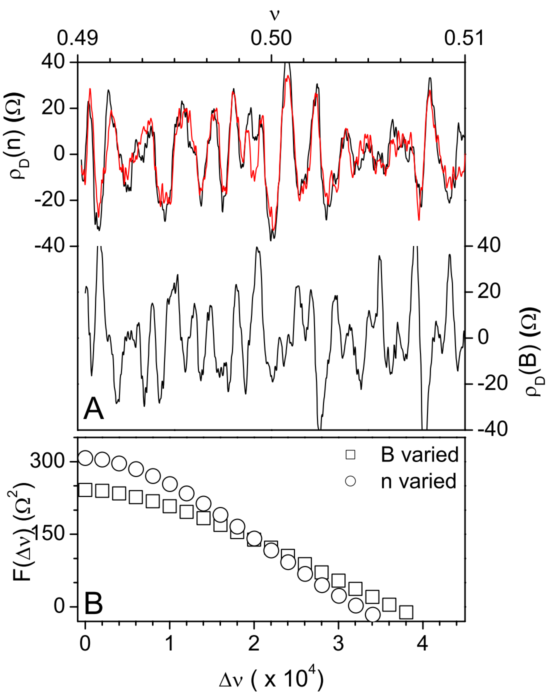

FIG. 2. (Color online) Panel A: comparison of the fluctuations of the drag resistivity as a function of ν when n and B are varied. The similarity of their periods in ν is proof that the drag is arising between interfering CFs. A repeat measurement of $\rho_D(n)$ is shown to give an indication of the reproducibility of fluctuations. T =50 mK. Panel B: the autocorrelation functions of the fluctuations shown in the top panel for $\rho_D(B)$ (squares) and $\rho_D(n)$ (circles).

$$\rho_D = 0.825(h/e^2)(T/T_0)^{4/3}. \tag{1}$$

Here $T_0 \approx \pi e^2 nd/\epsilon = 330$ K, ϵ is the dielectric constant, and $d=500$ Å is the spacing between layers. One can see that at high temperatures, $T>1$ K, the drag resistance is in good agreement with Eq. (1), and its T dependence is similar to that seen in Ref. 11 where the average drag of CFs was measured. However, as T is decreased the temperature dependence changes: as T decreases ρ_D can either decrease or increase as in Fig. 1(B), depending on the carrier concentration. This nonmonotonic T dependence can be accounted for by the competition between the average drag and mesoscopic effects. The average drag dominates at high T and decreases with decreasing T while the amplitude of the fluctuations of ρ_D increases with decreasing T and dominates at low temperatures.

In Fig. 1(C) it is seen that at high temperatures the drag resistance does not contain visible fluctuations, but at lower temperatures fluctuations appear and below $T \sim 200$ mK the fluctuations dominate the drag resistivity. Note that the magnitude of these fluctuations is greatly enhanced, by a factor of ~ 1000, in comparison to those seen in weak B fields,[14] where fluctuations were on the order of 20 mΩ.

Figure 2 shows how the fluctuations in ρ_D are also observed when the concentration of both layers is varied simultaneously, upper curve in panel A. The lower graph shows the fluctuations of the drag resistance while B is varied and n is held constant. It is clear that the fluctuations are of a similar amplitude in both experiments. It is also interesting to note that when the fluctuations are plotted as a function of filling factor ν (using the relation for the filling factor of electrons in one layer $\nu = nh/eB$) they have a similar "period" $\Delta\nu_c$. This characteristic scale is determined by finding the autocorrelation function of the fluctuations, $F(\Delta\nu) = \langle \rho_D(\nu)\rho_D(\nu+\Delta\nu)\rangle$, and then taking the half width of the half maximum of the peak of this function. The autocorrelation functions of the fluctuations in Fig. 2 are shown in panel B.

The close value of $\Delta\nu_c$ found from $\rho_D(n)$ and $\rho_D(B)$ is an important result that is expected from the flux attachment of $2\Phi_0$ to each electron and is a proof that the charge carriers in our system are CFs. Mesoscopic fluctuations are caused by both changes in the Fermi energy and the magnetic field. Composite fermions experience a reduced effective magnetic field that is dependent on the external magnetic field and the concentration of carriers: $B^*(n) = B - 2\Phi_0 n$. Consequently, mesoscopic fluctuations with varying carrier concentration will result not only from the change in the Fermi energy ΔE_F but also from the change in the effective B field: $\Delta B^*(n) = 2\Phi_0 \Delta n$.[20] Fluctuations due to the shift in E_F occur over a scale of $\Delta n_c \approx (k_B T)\varrho \approx g_{cf}/L_T^2$,[22] where ϱ is the density of states of CFs, g_{cf} is their dimensionless conductance (in units of e^2/h), $L_T = \sqrt{\hbar D/k_B T}$ is the thermal length and D is the diffusion coefficient. The second mechanism results in fluctuations on a scale of $\Delta n_c = \Delta B_c^*/2\Phi_0 = 1/2L_\phi^2$, where L_ϕ is the coherence length. Thus, comparing the two scales we find that fluctuations due to changes in E_F occur over a scale of Δn which is $\approx g_{cf}^2$ times larger than fluctuations due to the change in $B^*(n)$, so that the second mechanism dominates and $\Delta n_c \approx 1/2L_\phi^2$.

The effect of varying the external B field is the same for CFs as it is for conventional electrons in weak B fields: the correlation magnetic field ΔB_c corresponds to one magnetic flux quantum through a coherent area L_ϕ^2. This results in the relationship between the correlation magnetic field and correlation concentration near $\nu = 1/2$: $\Delta B_c/\Delta n_c = 2\Phi_0$. [This relation has been seen in the case of a single-layer system in which conductance fluctuations were measured near $\nu = 1/2$ (Ref. 23)]. This also explains why the fluctuations in $\rho_D(n)$ and $\rho_D(B)$ have the same period when plotted as a function of $\nu = nh/eB$.

In Ref. 20 the variance of the drag fluctuations in the "diffusive" regime of drag (where the mean free path is much shorter than the distance between the layers, $l \ll d$) is predicted to be

$$\langle \rho_D^2 \rangle \approx \frac{h^2}{e^4} \frac{1}{g_{cf}^4 (\kappa d)^2} \left(\frac{L_\phi^{cf}}{L} \right)^2, \tag{2}$$

where κ is the inverse Thomas-Fermi screening length, L_ϕ^{cf} is the coherence length of CFs, and L is the size of the square sample. Near $\nu = 1/2$ the effective magnetic field B^* is small and g_{cf} is simply related to the inverse of the longitudinal resistance: $g_{cf} = (h/e^2)(R_{xx})^{-1} = 4.4$. This results in a CF mean free path of $l_{cf} = g_{cf}/k_F = 46$ nm, where $k_F = \sqrt{2\pi n}$. Thus, while the normal-electron properties infer that the Coulomb drag in our structures is "ballistic," with $l/d = 200$, the prop-

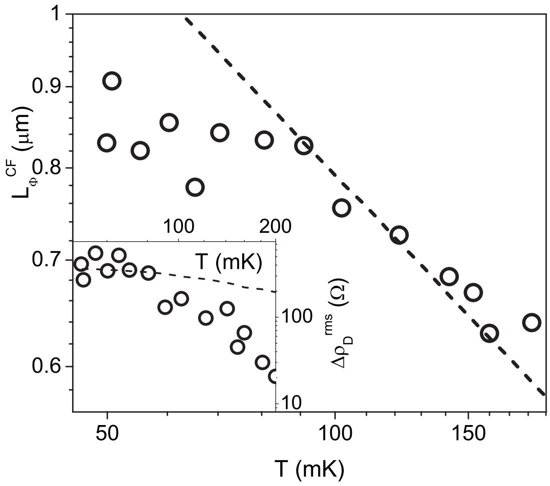

FIG. 3. T dependence of L_ϕ found from the correlation concentration of the drag resistivity fluctuations. Dashed line is a plot of the calculated values of L_ϕ^{cf} assuming dephasing is dominated by e-e scattering (Ref. 25) and using α=1.7. Inset: the amplitude of drag resistivity fluctuations plotted against T; $n=1.45\times10^{11}$ cm^{-2}. Dashed line is a theoretical plot of the amplitude using Eq. (2) and introducing a prefactor of 20.

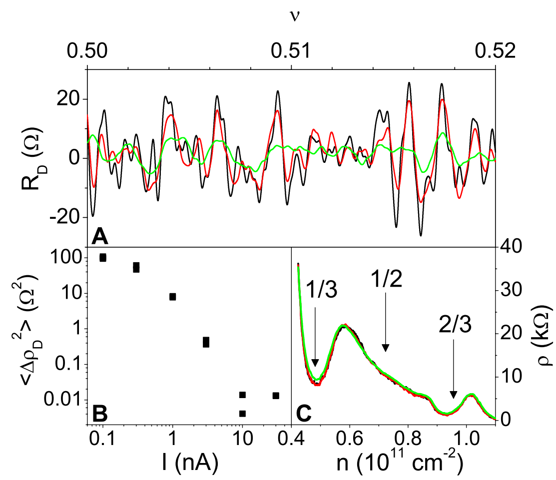

FIG. 4. (Color online) Panel A: drag resistivity as a function of filling factor measured with different active-layer currents: I=0.1, 0.3, and 1 nA. Panel B: variance of the drag resistance fluctuations as a function of driving current; T=50 mK and n=1.45 $\times10^{11}$ cm^{-2}. Panel C: single-layer resistivity as a function of carrier concentration measured at the same three currents, at T =50 mK and $n=0.57\times10^{11}$ cm^{-2}.

erties of CFs suggest that the drag will be in the intermediate regime with l_{cf}/d=0.92.

The calculation of the expected variance in Eq. (2) depends on the knowledge of the dephasing length of the CFs L_ϕ^{cf}. However, the matter of the dephasing length in CF systems is a nontrivial one. Dephasing occurs not only via e-e interaction but also via interactions between electrons and the Chern-Simons gauge field (see, e.g., Ref. 24 and references therein). In theory[20] phase breaking is assumed to be dominated by the latter mechanism: scattering of CFs by thermal fluctuations of the gauge field. The resulting dephasing length is $L_\phi \approx \sqrt{2\pi e^2 d/k_B T\epsilon}$, in contrast to the usual expression for the dephasing length of $L_\phi^{cf} = \alpha\sqrt{D\hbar g_{cf}/k_B T \ln g_{cf}}$, which comes from dephasing by e-e scattering at low temperatures.[25]

The measured L_ϕ^{cf} (found from the correlation concentration $\Delta n_c = 1/2L_\phi^2$) is shown as a function of T in Fig. 3. If one uses the expression for L_ϕ that comes from fluctuations of the gauge field then one obtains the correct temperature dependence, but the values are an order of magnitude too big compared with experiment. Our result is in agreement with the predictions of Ref. 24 on dephasing in CF systems where, in the presence of long-range interactions, L_ϕ is expected to be well described by e-e scattering in the limit of low temperatures, $T \ll 100/g_{cf}^2\tau_{cf}$, which for our system (with a low conductance of CFs) applies below 35 K.

Using the measured values of L_ϕ^{cf} we calculate the expected variance of the drag resistivity fluctuations using Eq. (2), which is plotted as the dashed line in the inset in Fig. 3, multiplied by 20 for the sake of comparison. We see that the magnitude of the fluctuations is underestimated when calculated using Eq. (2), and the temperature dependence is poorly described at higher temperatures. However, this discrepancy between the experiment and the predictions of the diffusive drag theory in Ref. 20 is less than that previously seen for the case of Coulomb drag of normal electrons,[14] where fluctuations were four orders of magnitude larger in amplitude than that expected theoretically. This can be accounted for by our system being closer to the diffusive limit, $l_{cf}/d < 1$.

The found value of L_ϕ is seen to deviate at low temperatures from that expected from e-e scattering, Fig. 3. It is possible that this effect is related to a nonlinearity of the drag fluctuations that we have observed at low temperatures. The fluctuations of the drag at $\nu=1/2$ are found to be strongly nonlinear, unlike in the case of weak magnetic fields, where both the average drag resistance and the fluctuations of the drag resistance were seen to be independent of the active-layer current.[14] The drag resistivity as a function of ν measured using different currents is shown in Fig. 4(A). The amplitude of the fluctuations increases by four times in decreasing the current from 1 to 0.1 nA. The nonlinearity of the fluctuations is stronger at higher currents, as demonstrated in Fig. 4(B), where the variance of the fluctuations is plotted as a function of current. This nonlinearity is not simply due to Joule heating, as the single-layer resistance is seen to be independent of driving current below 1 nA [Fig. 4(C)]. All of the measurements we present in this paper were performed using a 0.1 nA driving current, where the nonlinearity is weak [Fig. 4(B)]. A strong nonlinearity of the Coulomb drag of CFs was also seen in previous measurements of the average drag resistance.[11] The origin of this nonlinearity deserves further investigation in the future.

To summarize, we have seen reproducible fluctuations of the Coulomb drag between composite fermions when varying carrier concentration in the two layers and magnetic field. There is a large enhancement in the size of fluctuations relative to that seen in drag between normal electrons, as was predicted theoretically. At low temperatures the magnitude of the fluctuations exceeds the average drag, such that the sign of the drag changes randomly with varying n and B. The decoherence length found from the quasiperiod of the drag fluctuations is close to that described by e-e scattering. The magnitude of the drag fluctuations exceeds that expected from the theory developed for the diffusive regime, though to a lesser extent than that seen in the case of drag fluctuations between normal electrons, due to the shorter mean free path of composite fermions. For a full quantitative comparison, a theory for the variance in the regime which is intermediate between diffusive and ballistic is required.

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