Coulomb Drag in the Extreme Quantum Limit

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Coulomb drag resulting from interlayer electron-electron scattering in double layer 2D electron systems at high magnetic field has been measured. Within the lowest Landau level the observed drag resistance exceeds its zero magnetic value by factors of typically 1000. At half-filling of the lowest Landau level in each layer ($\nu = 1/2$) the data suggest that our bilayer systems are much more strongly correlated than recent theoretical models based on perturbatively coupled composite fermion metals.

Double layer two-dimensional electron systems (2DES) have been the subject of intense recent interest, especially at high magnetic fields, owing to the diversity of many-body phenomena they exhibit which are not found in ordinary single layer systems. These new phenomena arise from the interplay of the intra- and interlayer Coulomb interactions and the tunneling amplitude in the system. A particularly interesting case arises when the individual 2D layers are at Landau level filling fraction $\nu = 1/2$. If the separation between the layers is large the system behaves as two independent 2DES's, each of which is widely believed to be a Fermi liquid-like state of Chern-Simons composite particles. On the other hand, when the layers are close together they behave as a single system and exhibit a ferromagnetic quantized Hall state at total Landau filling factor $\nu_{tot} = 1/2 + 1/2 = 1$. The nature of this remarkable transition from two gapless Fermi liquids to a single gapped quantum Hall phase is not well understood and remains a frontier topic in the field [1].

The strength of the Coulomb interaction between electrons in opposite layers is obviously a key ingredient of the physics. Recently a technique has been developed which provides a simple way to directly obtain the interlayer electronic momentum relaxation rate and thereby assess the strength of these critical interactions. In this technique the frictional drag between the two 2DES's is measured by observing the voltage which develops in one layer when a current is driven through the other. This voltage, which exists even though the two layers are electrically isolated, is directly proportional to the interlayer momentum relaxation rate arising from the scattering of electrons in one layer off those in the other. At zero magnetic field drag studies have yielded a quantitative measure of the Coulomb scattering rate between electrons in the two layers [2], provided evidence for momentum relaxation due to the exchange of phonons [3], and revealed the predicted plasmon enhancement of the drag [4–7]. Recent drag experiments performed in magnetic fields large enough to induce the integer quantized Hall effect have given evidence for the oscillatory screening effects expected from Landau quantization [8,9].

In this paper we report the first Coulomb drag results from the extreme quantum limit, focussing especially on the situation where in each 2D layer the lowest Landau level is half-filled. Our measurements show that even though the separation between the two layers is too large to yield the $\nu_{tot} = 1$ quantized Hall state, the drag is considerably stronger than recent theories predict for weakly coupled composite fermion (CF) liquids.

The samples employed in this work are modulation-doped GaAs/$Al_xGa_{1-x}As$ double quantum wells grown by molecular beam epitaxy. They consist of two 200 Å wide GaAs quantum wells separated by a thin undoped $Al_xGa_{1-x}As$ barrier layer. Although we have obtained qualitatively similar results with samples having barrier thicknesses of 175 Å and 100 Å, most of the quantitative results presented here were obtained using the latter. For this sample the barrier is pure AlAs (i.e. $x = 1$). Small differences in the sheet densities of the two wells were removed using a Schottky gate electrode on the sample top surface. So balanced, the 2D density in each quantum well was $N = 1.38 \times 10^{11}$ cm^{-2}, and the average low temperature mobility was $\mu \approx 1.7 \times 10^6$ cm^2/V s. For these measurements simple Hall bar mesas were fabricated with width $w = 40$ μm and length $l = 400$ μm.

Separate electrical contacts to the individual 2D layers were established via the "selective depletion" technique [10]. Drag measurements were performed by injecting a small drive current ($I \leq 10$ nA @ 13 Hz) down the bar in one of the 2D layers and recording the differential voltage V_D appearing along the bar in the other layer. Spurious signals arising from the capacitive coupling of the two layers were minimized by keeping the measurement frequency low and the common mode voltage of both layers small. Direct measurements [11] of the tunneling resistances in our samples leave us confident that tunneling is not influencing the drag data presented here.

At zero magnetic field the drag data obtained from the 175 Å sample is in good agreement with that obtained earlier by Gramila *et al.* [2,3]. As in this earlier data, the temperature dependence of the drag scattering rate τ_D^{-1} (calculated from the measured drag resistivity

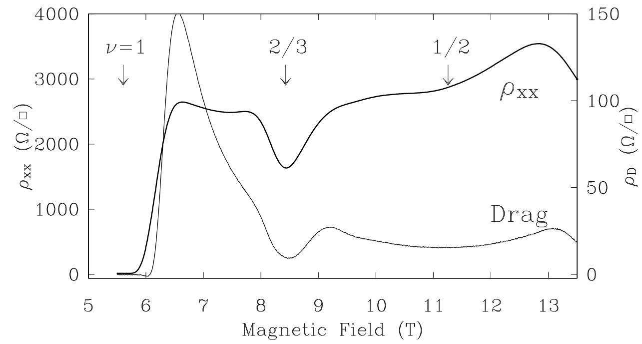

FIG. 1. Comparison of ρ_{xx} to ρ_D at $T = 0.6$ K.

$\rho_D = -(w/l)V_D/I = (m/Ne^2)\tau_D^{-1}$) exhibits an anomaly around $T = 2$K due to momentum relaxation resulting from the exchange of phonons. In the 100 Å sample, however, the zero field drag is roughly twice as large as in the 175 Å sample and the phonon peak is thus less significant. This is expected since the Coulombic part [2,12] of the drag is very sensitive to the separation between the layers while the phonon part [13] is not. At low temperatures the Coulomb drag between two ordinary Fermi liquids in zero magnetic field should vary quadratically with temperature: $\tau_D^{-1} \propto T^2$. For the 100 Å sample we find the ratio τ_D^{-1}/T^2 to be constant to better than 15% over the temperature range $2 < T < 8$ K and on average equal to $\tau_D^{-1}/T^2 \approx 4 \times 10^6$ s^{-1}K^{-2}.

On applying a magnetic field perpendicular to the 2D planes we find, in agreement with earlier work [9], that the magnitude of the drag between the layers increases dramatically. As at zero field, the *sign* of the induced drag voltage is opposite to that of the resistive voltage drop in the current-carrying layer. This is consistent with a momentum transfer mechanism which sweeps carriers along in the dragged layer in the same direction as those in the drive layer. We have also observed that the magnitude of the induced voltage is unchanged when the roles of the drive and dragged quantum wells are interchanged.

Fig. 1 compares the drag resistivity ρ_D to the ordinary longitudinal resistivity ρ_{xx} of one of the 2D layers at $T = 0.6$ K and magnetic fields $B > 5$ T. (These data, and all that follow, were obtained using the 100 Å AlAs barrier sample.) Over the field range shown the (per layer) Landau level filling factor $\nu = hN/eB < 1$. Qualitatively, the two traces are quite similar: Where ρ_{xx} exhibits a minimum due to a quantized Hall effect (e.g. $\nu = 1$ and 2/3), so does ρ_D. This is not surprising since both depend on the density of states available for scattering. If a gap develops in the energy spectrum then both electron-impurity and electron-electron scattering will be suppressed and so therefore will be ρ_{xx} and ρ_D. Note also that there is no evidence in the data of Fig. 1 for any QHE at *total* filling factor $\nu_{tot} = 1/2 + 1/2 = 1$. In the present samples the layer spacing is too large to support this intriguing QH state [1].

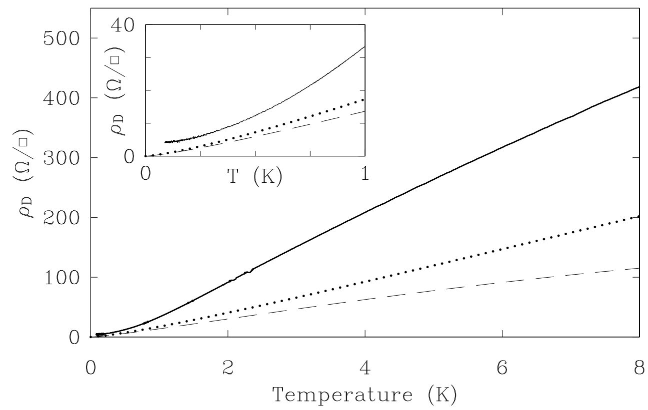

FIG. 2. Temperature dependence of ρ_D at $\nu = 1/2$ (solid line). The broken lines are calculations [16,17] of ρ_D assuming two different CF effective masses (dotted, $m^* = 12m_b$, dashed, $m^* = 4m_b$, where m_b is the GaAs band mass).

The similarity between the ordinary and drag resistivities disappears when their temperature dependences are examined. As is well known, ρ_{xx} exhibits a strong variation with temperature only in the vicinity of quantized Hall states. At non-QHE filling fractions, like $\nu = 1/2$, ρ_{xx} is only weakly dependent on temperature. Indeed, for our sample ρ_{xx} at $\nu = 1/2$ varies (increases) by only 6% when the temperature is reduced from $T = 4$ K to 0.2 K. In contrast, over the same temperature range ρ_D at this filling factor decreases by about a factor of 40.

Fig. 2 shows the temperature dependence of ρ_D at $B = 11.45$ T, corresponding to filling factor $\nu = 1/2$ in each layer. These data illustrate the huge enhancement of frictional effects on going to high field: At $B = 0$ the drag at $T = 4$ K is only $\rho_D \approx 0.1\Omega/\Box$ while at $\nu = 1/2$ it is some 2000 times larger. In addition to this the drag at high field exhibits a different temperature dependence than at $B = 0$. In particular, in neither the 100 Å nor 175 Å barrier sample does the $\nu = 1/2$ data show any evidence of a "phonon peak" in τ_D^{-1}/T^2 similar to that seen at $B = 0$. While phonon-mediated drag at high magnetic field has not been theoretically studied, it seems plausible that a such a peak might be observed when the thermal phonon wavevector matches $2k_F$ for the CF's. The absence of such a feature, plus the vast enhancement of the drag itself, suggests to us that phonons are relatively unimportant in our samples.

Recent theoretical work [14–16] has concluded that at low temperatures the Coulomb drag resistivity between two clean 2DES's, each in the $\nu = 1/2$ CF metallic state, ought to scale with temperature as $T^{4/3}$ and *not* as T^2 as expected for simple Fermi liquids. This result has been traced to the unusual wavevector and frequency dependence of the conductivity σ_{xx} of the CF liquids. In addition, Ussishkin and Stern [16] (US) have calculated the magnitude of the drag, its dependence upon density, and the leading corrections to the $T^{4/3}$ law within a model of two perturbatively coupled 2DES's. In agreement with experiment, they find the drag at high magnetic field to be far larger than at $B = 0$; they attribute this to the very slow relaxation of charge density fluctuations characteristic of the extreme quantum limit. There is not, however, good quantitative agreement between their theory and our experimental results. The two broken lines in Fig.2 show the results of the US calculation for two reasonable choices of the CF effective mass. The theory substantially underestimates the observed drag [17]. US have also argued that disorder actually reduces the drag and thus further degrades the comparison with experiment.

Predictions have also been made for how the drag should vary when the densities of both layers are changed symmetrically (adjusting B to maintain $\nu = 1/2$) and asymmetrically where, at fixed B, the density of one layer is increased and the other equally decreased [16]. For the symmetric case theory gives $\rho_D \propto N^{-4/3}$ at low temperatures. We find a significantly stronger dependence. By combining a negative voltage ($V_{TG} = -0.4$ V) on the top gate covering the drag mesa with a small dc bias voltage ($V_i = 15$ mV) applied *between* the two 2D layers, we were able to reduce the density of each layer from 1.38 to 1.08×10^{11} cm^{-2}. This produced a roughly 70% increase in the drag whereas the change in $N^{-4/3}$ is only 39%. For small *asymmetric* density changes US find a quadratically increasing drag: $\Delta\rho_D/\rho_D = \beta(\Delta N/\langle N\rangle)^2$ with ΔN the total density difference between the layers, $\langle N\rangle$ the average single layer density, and $\beta = 7/48$. To produce such asymmetric density changes requires only the voltage V_i applied between the layers. Fig. 3 shows the results, at two representative temperatures, of such experiments at $B = 11.45$ T where at $V_i = 0$ each 2D layer is at filling factor $\nu = 1/2$. The data have been normalized by the value observed with $V_i = 0$. The $T = 0.6$ K trace shows well-defined features [18] around $V_i \approx \pm 10$ mV that can be associated unambiguously with one layer being driven into the $\nu = 2/5$ fractional QH state while the other goes into the $\nu = 3/5$ state. These features provide a simple calibration of the density shift $\Delta N/\langle N\rangle$ vs. V_i. Qualitatively, the data support the theoretical prediction of a quadratic increase of the drag with ΔN. It is clear however, that the observed strength of the effect is much larger than the theoretical prediction (the dashed line in the figure). For the $T = 0.6$ K data a least squares parabolic fit gives $\beta \approx 6$, some 40 times greater than the theoretical value. We find β to increase as the temperature is reduced; from $T = 0.2$ to 6 K our results are well fit by $\beta^{-1} \approx 0.08 + 0.16$ T.

Turning again to the temperature dependence of the drag at $\nu = 1/2$, we note that while at all tempera-

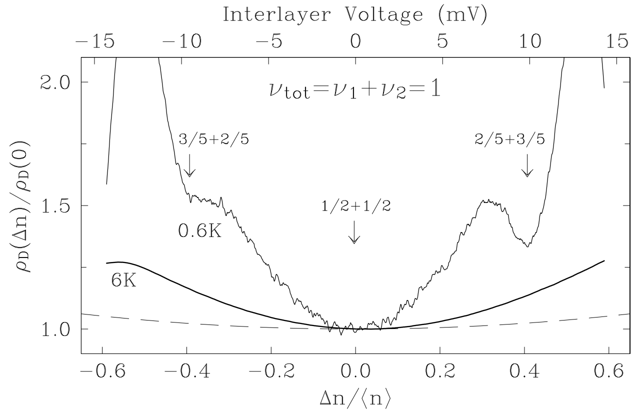

FIG. 3. Normalized dependence of drag on shifts of charge density from one 2D layer to the other at $B = 11.45$ T. Total Landau filling factor remains at $\nu_{tot} = \nu_1 + \nu_2 = 1$. Dashed line is theoretical prediction [16].

tures our data exhibit a sub-quadratic variation with T, they do not provide compelling evidence for the predicted $T^{4/3}$ dependence. This is not surprising since it is known [15,16] that corrections to this power law occur at both high and, owing to the disorder in the sample, at low temperatures. More importantly, our data exhibit unexpected behavior in the low temperature limit. As the inset to Fig. 2 reveals, the drag appears to *remain finite* as $T \to 0$. This peculiar result, which is at odds with the conventional picture of drag as resulting from inelastic scattering events for which the phase space vanishes at $T = 0$, led us to re-examine our measurement scheme in search of spurious effects. In particular, the possibility of capacitive and resistive leakage effects was carefully considered. No dependence on the measurement frequency or the precise grounding configuration of either 2D layer was found in the in-phase resistive drag signal. Capacitive coupling was likely responsible for the *quadrature* signal which was generally present, but its small magnitude and linear frequency dependence made it easy to discriminate against. Finally, although a non-zero drag in the $T \to 0$ limit was observed over a range of filling factor around $\nu = 1/2$, it was *not* a ubiquitous feature of our results. Very much smaller low temperature drag resistances were observed at $B = 0$, inside QH states, and, interestingly, at and around $\nu = 3/2$. These observations suggest that simple circuital coupling effects are not responsible for the residual drag effect.

If the 2D electrons are heated out of equilibrium with the system thermometer then an apparently non-zero drag at $T = 0$ would result. To examine this possibility we studied the dependence of the drag resistance on excitation current. Above about 0.5 K no non-linear effects were found at any magnetic field. Below this temperature non-linearities do appear, but in a way that is

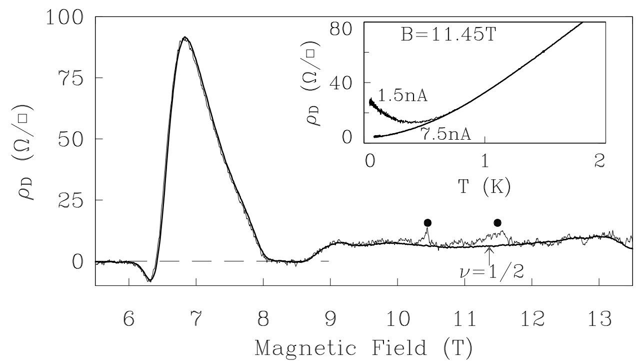

FIG. 4. Drag resistivity at $T = 0.3$ K at $I = 7.5$ nA (smooth curve) and 1.5 nA (noisy curve). Although the two curves are indistinguishable below $B = 9.5$ T, the dots indicate fields around which the drag is significantly non-linear. Inset: Drag temperature dependence at $B = 11.45$ T for $I = 7.5$ and 1.5 nA.

unexpected and not consistent with simple heating. Fig. 4 compares the drag resistivity observed at $T = 0.3$ K using $I = 7.5$ nA and 1.5 nA excitation currents. Over most of the field range shown, these two currents yielded essentially identical results. This is true even at fields where the drag exhibits a specially large temperature dependence, e.g. the flanks of the $\nu = 1$ and $2/3$ QH minima. Surprisingly though, non-linearities *are* evident in the general vicinity of $\nu = 1/2$. At $B = 11.5$ T, for example, the drag is significantly larger at $I = 1.5$ nA than it is at 7.5 nA. This is just the opposite of what a simple heating model would imply. As the temperature is reduced these non-linearities become stronger and more widespread. At very low currents ($I < 0.5$ nA) a linear regime seems to reappear but the poor signal-to-noise ratio at these currents leaves this conclusion tentative. The inset to Fig. 4 shows the temperature dependence of the drag at 11.45 T measured at 7.5 and 1.5 nA. It is clear that these non-linearities can become quite large and, remarkably, that the drag at small current can grow dramatically as the temperature is reduced. We emphasize that these non-linear effects do not appear to be specific to the $\nu = 1/2$ state but have so far been found throughout the range $0.6 > \nu > 0.4$. While stable with time (for at least several days) it is possible to alter their precise "magneto-fingerprint" by making large changes in the experimental parameters (e.g. gate voltages, magnetic field, temperature, etc.) Finally, we have even observed non-linearities in which the small current drag is not only larger in magnitude but is *of opposite sign* to that found using higher currents.

In this paper we have reported Coulomb drag measurements on double layer 2D electron systems in the extreme quantum limit, focussing especially on filling factor $\nu = 1/2$. For $T \gtrsim 0.5$ K our results, while in qualitative agreement with recent theoretical models of weakly coupled composite fermion liquids, point to significantly stronger interlayer couplings than such models include. We have also observed that the Coulomb drag does not always appear to vanish in the limit $T \to 0$ and that in the vicinity of the half-filled configuration remarkable non-linear effects can appear. These effects, which recall charge density wave depinning, are not understood. It is interesting to speculate on whether they point to the existence, perhaps only in isolated regions of the sample, of an unexpected bilayer ground state [19].

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[1] For general reviews of the bilayer quantum Hall effect and the composite fermion theory of the $\nu = 1/2$ state, see *Perspectives in Quantum Hall Effects*, edited by S. Das Sarma and A. Pinczuk (Wiley, New York, 1997).

[2] T. J. Gramila *et al.*, Phys. Rev. Lett. **66**, 1216 (1991); for the electron-hole case see U. Sivan, P. M. Solomon, and H. Shtrikman, Phys. Rev. Lett. **68**, 1196 (1992).

[3] T. J. Gramila *et al.*, Phys. Rev. B **47**, 12957 (1993).

[4] K. Flensberg and B. Y.-K. Hu, Phys. Rev. Lett. **73**, 3572 (1994); Phys. Rev. B **52**, 14796 (1995).

[5] J. P. Eisenstein, unpublished.

[6] N. Hill *et al.*, Phys. Rev. Lett. **78**, 2204 (1997).

[7] H. Noh *et al.*, to be published.

[8] M. C. Bønsager, K. Flensberg, B. Y.-K. Hu, and A.-P. Jauho, Phys. Rev. Lett. **77**, 1366 (1996).

[9] H. Rubel *et al.*, Phys. Rev. Lett. **78**, 1763 (1997).

[10] J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Appl. Phys. Lett. **57**, 2324 (1990).

[11] See, for example, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **69**, 3804 (1992).

[12] A. P. Jauho and H. Smith, Phys. Rev. B **47**, 4420 (1993).

[13] M. C. Bønsager, K. Flensberg, B. Y.-K. Hu, and A. H. MacDonald, preprint cond-mat/9707111

[14] Y. B. Kim and A. J. Millis, preprint cond-mat/9611125.

[15] S. Sakhi, Phys. Rev. B **56**, 4098 (1997).

[16] I. Ussishkin and A. Stern, Phys. Rev. B **56**, 4013 (1997); Physica E, in press.

[17] To evaluate the theory we have taken the layer separation to be 300 Å, the center-to-center distance between the quantum wells.

[18] The different strength of these two features is likely due to different levels of disorder in the two layers.

[19] For a recent suggestion see N. E. Bonesteel, I. A. McDonald, and C. Nayak, Phys. Rev. Lett. **77**, 3009 (1996).