Double layer two-dimensional electron systems: Probing the transition from weak to strong coupling with Coulomb drag

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Frictional drag measurements revealing anomalously large dissipation at the transition between the weakly- and strongly-coupled regimes of a bilayer two-dimensional electron system at total Landau level filling factor $\nu_T = 1$ are reported. This result suggests the existence of fluctuations, either static or dynamic, near the phase boundary separating the quantized Hall state at small layer separations from the compressible state at larger separations. Interestingly, the anomalies in drag seem to persist to larger layer separations than does interlayer phase coherence as detected in tunneling.

At high magnetic fields two-dimensional electron systems (2DES) exhibit a variety of collective states. For example, if the perpendicular magnetic field is adjusted so that the density of electrons N_s equals one-half the degeneracy eB/h of the lowest spin resolved Landau level (i.e. at filling factor $\nu = N_s h/eB = 1/2$), the resulting strongly correlated electron system can be successfully modeled as a metallic liquid of composite fermions[1]. The system crudely resembles a conventional 2DES in zero magnetic field. No quantized Hall effect is seen. Remarkably, the system possesses a well-defined Fermi surface and quasiparticles which move in semiclassical cyclotron orbits whose diameters diverge as $\nu \to 1/2$.

Now consider a system consisting of two parallel 2DESs, each at $\nu = 1/2$, separated by a barrier layer. Obviously, if the separation d between the two 2DESs is large, they are uncoupled and the net system behaves much the same as a single layer. In contrast, if d is very small (less than the average separation between electrons in each layer) the ground state of the bilayer system is qualitatively different. In this strongly-coupled limit interlayer Coulomb interactions engender a novel broken symmetry, spontaneous interlayer phase coherence, in which all electrons are coherently spread between both layers, even in the hypothetical limit of zero interlayer tunneling[2]. This bizarre state, which is best characterized by the *total* filling factor $\nu_T = 1$, may be viewed in a number of equivalent ways, including as an itinerant pseudospin ferromagnet or a Bose condensate of interlayer excitons. Experimentally, the system has been found to display numerous striking properties, including the quantized Hall effect (at $R_{xy} = h/e^2$)[3], a pseudospin textural phase transition[4, 5], Josephson-like interlayer tunneling[6], and, most relevant here, quantized Hall drag[7]. Additional properties, including counterflow superfluidity, are anticipated[8].

The nature of the transition between the strongly-coupled ferromagnetic or excitonic phase at small d and the weakly-coupled composite fermion liquids at large d is very poorly understood. As d increases from zero (at zero temperature) the ferromagnetic phase suffers increasingly severe quantum fluctuations which eventually destroy the (algebraic) pseudomagnetic order at a critical layer separation. Although there exists numerical evidence suggesting that this quantum phase transition may be weakly first order[9], current experiments suggest a continuous transition.

Beyond the nature of the demise of the ferromagnetic phase as d increases, remains the question of the ground state of the system above the critical separation. Before reverting to independent composite fermion liquids at very large d, there is the possibility of additional interlayer correlated phases at intermediate separations. Candidate states include bilayer Wigner crystals[10], paired composite fermion liquids[11], and various other exotic phases which may share some but not all of the properties of the ferromagnetic phase (e.g. interlayer phase coherence but no quantized Hall effect, etc.)[12, 13]. In this paper we report interlayer friction measurements ("Coulomb drag") which shed light on the transition between the strongly- and weakly-coupled regimes at $\nu_T = 1$. In particular, we observe a large enhancement of the longitudinal component of the drag near the transition. Although rapidly attenuated, this enhancement persists to surprisingly large layer separations.

Drag measurements are performed by driving a current I, typically 1nA at 5Hz, through one of the two layers of a double layer 2DES while monitoring the voltage V_D which appears in the other, electrically isolated, layer. At zero magnetic field the drag resistance $R_D = V_D/I$ provides a unique measure of the interlayer momentum relaxation rate. For closely-spaced layers and low temperatures this rate is dominated by simple Coulomb scattering and hence the moniker Coulomb drag.

The samples used in the present experiments consist of two 18nm GaAs quantum wells separated by a 10nm barrier layer of $Al_{0.9}Ga_{0.1}As$. Each quantum well contains a 2DES which, in the sample's as-grown state, has a density of about $N_s \approx 5.3\times10^{10}\text{cm}^{-2}$ and a low-temperature mobility of $\mu \approx 10^6\text{cm}^2/\text{Vs}$. Data from three samples, A,

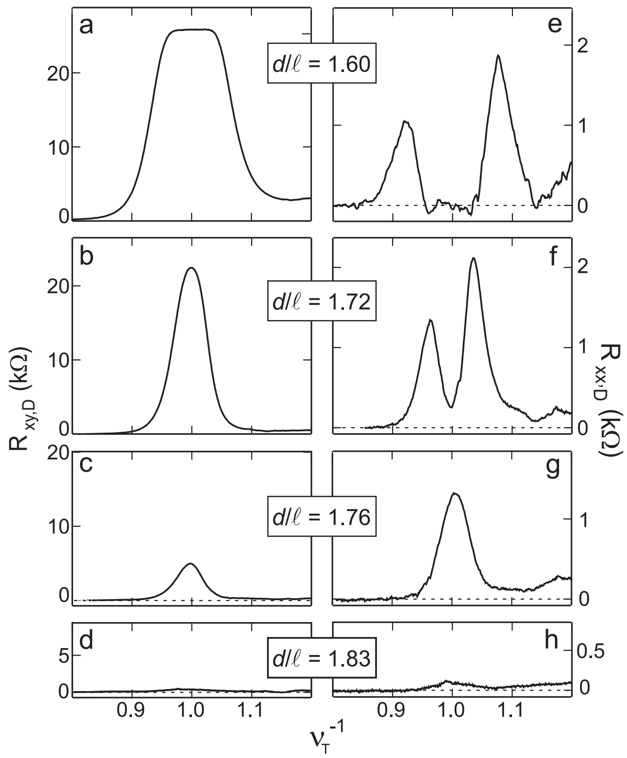

FIG. 1: Coulomb drag resistances in sample A at $T = 30$mK, in the vicinity of $\nu_T = 1$. Left column: Hall drag $R_{xy,D}$; right column: longitudinal drag $R_{xx,D}$. Each row corresponds to a different 2D density in the bilayer sample, and thus a different effective layer separation d/ℓ at $\nu_T = 1$.

B, and C, are reported here. Samples A and B consist of square mesas, 250μm on a side, with four arms extending outward to remote ohmic contacts. Sample C is bar-shaped, $40 \times 400\mu$m, and has five arms and ohmic contacts. These contacts are connected to one or the other 2DES using a selective depletion scheme[14]. The densities of the individual 2DESs in the central mesa region are controlled with electrostatic gates deposited on the top and backside of the samples. A detailed study of the Coulomb drag in these samples at zero magnetic field has been reported elsewhere[15].

Figure 1 shows representative Coulomb drag data from sample A in the vicinity of $\nu_T = 1$ at $T = 30$mK. Each row corresponds to a different effective layer separation d/ℓ, with $d = 28$nm the center-to-center quantum well separation and $\ell = (\hbar/eB)^{1/2}$ the magnetic length at $\nu_T = 1$. This key ratio governs the relative importance of inter- and intra-layer Coulomb interactions in the bilayer system, and can be varied *in situ* by symmetrically changing the electron densities in the individual quantum wells. The data in Fig. 1 is therefore plotted versus the inverse total filling factor ${\nu_T}^{-1}$, instead of magnetic field, to aid in comparing the different densities. The right-hand panels display the longitudinal drag resistance $R_{xx,D}$ (i.e. drag voltage parallel to the current flow in the drive layer) while the left-hand panels present the transverse, or Hall, drag resistance $R_{xy,D}$.

The top two panels (a and e) of Fig. 1 show Hall and longitudinal drag data at $d/\ell = 1.60$. At this effective layer separation the system is well within the strongly-coupled bilayer quantum Hall effect phase and, as reported previously[7], at $\nu_T = 1$ the Hall drag exhibits a plateau accurately quantized at $R_{xy,D} = h/e^2$ while the longitudinal drag $R_{xx,D}$ is essentially zero. While it is not surprising that $R_{xx,D}$ is zero in the quantized Hall state (the gap to charged excitations suppressing dissipation at low temperatures), the quantization of Hall drag is a dramatic consequence of the physics of the strong coupling regime and supports, albeit indirectly, the existence of counterflow superfluidity[8].

On moving away from $\nu_T = 1$, the Hall drag rapidly diminishes while the longitudinal drag displays two strong maxima. The sign of the Hall drag voltage is the same as that of the conventional Hall voltage in the current-carrying layer. In contrast, the sign of the longitudinal drag voltage is the *opposite* of the conventional longitudinal voltage drop in the current-carrying layer. Indeed, for all the data reported here the sign of $R_{xx,D}$ is the same as that encountered at zero magnetic field where the drag voltage reflects the electric field needed to counteract the frictional force due to the current flow in the drive layer.

The remaining panels of Fig. 1 show how Coulomb drag changes as d/ℓ increases and the strongly-coupled bilayer quantized Hall phase collapses. Panels b, c, and d show that the Hall drag plateau becomes a rapidly subsiding local maximum as the d/ℓ increases. More interestingly, panels f, g, and h reveal that the longitudinal drag first evolves from a broad zero into a local minimum between tall peaks. By $d/\ell = 1.76$ these peaks have merged to form a single peak. Further increases of d/ℓ steadily reduce the magnitude of this peak in $R_{xx,D}$.

Figure 2 displays both drag resistances precisely at $\nu_T = 1$ as functions of d/ℓ. These data were obtained from sample B at $T = 50$mK. As the figure indicates, the Hall drag resistance $R_{xy,D}$ undergoes a rapid yet smooth transition from very small values above $d/\ell \approx 1.8$ to the very large value of $h/e^2 = 25.8$kΩ for d/ℓ below about 1.65. At the same time, the longitudinal drag $R_{xx,D}$ exhibits a strong and rather symmetric peak in the transition region. At $T = 50$mK this peak is centered at $d/\ell \approx 1.73$ and has a half-width of about $\Delta(d/\ell) = 0.035$. The height of the peak, about 1.8kΩ, represents an impressively large drag resistance. This value is in fact roughly comparable to the conventional longitudinal resistance R_{xx} of the bilayer system under the same conditions (the deep minimum in R_{xx} characteristic of the $\nu_T = 1$ QHE developing only at lower values of d/ℓ). Both the d/ℓ location and the height of this peak in $R_{xx,D}$ vary slightly from one sample to the next, but its existence and qualitative behavior is quite robust.

The width and location of the peak in $R_{xx,D}$ at $\nu_T = 1$

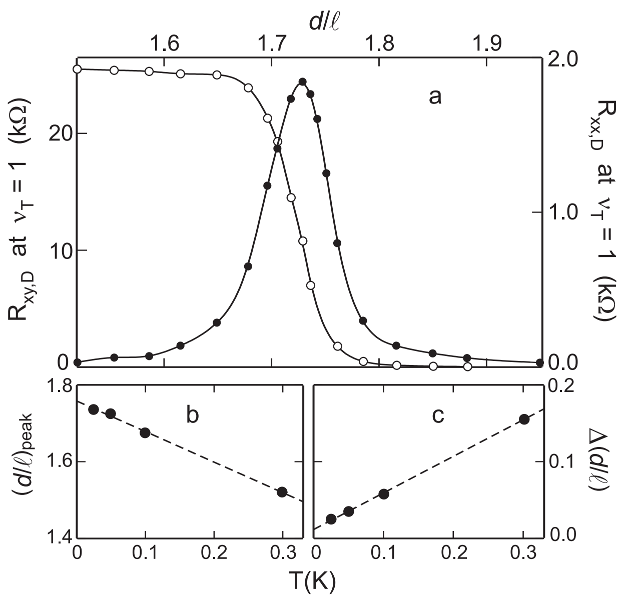

FIG. 2: a) Hall (open dots) and longitudinal (closed dots) drag at $\nu_T = 1$ and $T = 50$mK *vs.* d/ℓ in sample B. b) and c) Temperature dependence of location and half-width of peak in $R_{xx,D}$ at $\nu_T = 1$. Lines are guides to the eye.

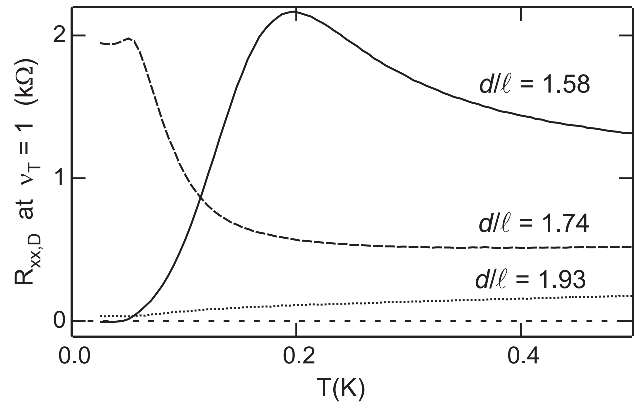

FIG. 3: Temperature dependence of longitudinal drag resistance at $\nu_T = 1$ in sample B at three different d/ℓ values.

depend upon temperature. Figure 2b reveals that the peak moves to lower d/ℓ as T increases. This dependence, which is roughly linear in T, extrapolates to about $d/\ell = 1.76$ as $T \to 0$. At the same time, Fig. 2c shows that the peak half-width, $\Delta(d/\ell)$, increases substantially as the temperature is increased to 300mK. Interestingly, over the range 25mK $< T <$ 300mK the height of the peak in $R_{xx,D}$ at $\nu_T = 1$ varies by only about 15%.

Figure 3 displays the temperature dependence of $R_{xx,D}$ at $\nu_T = 1$ at three different values of d/ℓ. For $d/\ell = 1.58$, which is well within the bilayer QHE, $R_{xx,D}$ rises as the temperature is reduced from $T = 0.5$K to about 0.2K but then drops precipitously as T is further reduced. In this low temperature regime $R_{xx,D}$ is thermally activated[7], i.e. $R_{xx,D} \sim e^{-E_A/T}$, with $E_A \approx 0.4K$. This dependence is expected within the gapped QHE phase and, indeed, the conventional resistivity R_{xx} shows the same activation energy[7]. At $d/\ell = 1.93$, which is in the non-QHE compressible phase, $R_{xx,D}$ is much smaller in magnitude and falls monotonically as T is reduced. This temperature dependence is reminiscent of that seen at $B = 0$ in the present samples[15] and at $\nu_T = 1$ in much more widely-spaced ($d/\ell \approx 3.9$) double layer 2D electron systems[16]. Roughly speaking, this behavior reflects the characteristic reduction of the phase space for inelastic Coulomb scattering events as the temperature falls. A quantitative model for Coulomb drag at $\nu_T = 1$ and large d/ℓ has been developed by Ussishkin and Stern[17].

At $d/\ell = 1.74$, i.e. in the middle of the transition region, the temperature dependence of $R_{xx,D}$ at $\nu_T = 1$ is markedly different than at both larger and smaller d/ℓ. After remaining roughly constant on cooling from $T = 0.5$K to about 0.2K, the drag rises rapidly as the temperature falls further. Below about $T = 50$mK $R_{xx,D}$ apparently saturates.

The data described above show that Coulomb drag is a sensitive indicator of the transition between the weakly and strongly-coupled regimes of a bilayer 2DES at $\nu_T = 1$. This is especially clear from the behavior of the Hall drag resistance $R_{xy,D}$ shown in Fig. 2. Although non-zero Hall drag can in principle result from density (or energy) dependent scattering rates in a 2D system[18, 19], the development of a large, and ultimately quantized, $R_{xy,D}$ is generally believed to require non-perturbative interlayer correlations. Indeed, the qualitative behavior of $R_{xy,D}$ shown in Fig. 2 was anticipated[20, 21, 22, 23, 24].

In contrast, the strong peak in the $\nu_T = 1$ longitudinal drag resistance $R_{xx,D}$ which develops in the middle of the Hall drag transition comes as a surprise. It seems reasonable to interpret the d/ℓ value at the center of this peak as the critical one separating the strongly-coupled $\nu_T = 1$ QHE phase from the weakly-coupled non-QHE phase. Within the ferromagnetism picture of the QHE phase, at zero temperature this critical point marks the destruction of the ordered state by quantum fluctuations of the pseudospin moment. The shifting of the peak to lower d/ℓ as the temperature rises (cf. Fig. 2b) is consistent with thermal fluctuations further destablizing the ordered state. The non-zero width of the peak in $R_{xx,D}$ *vs.* d/ℓ suggests an inhomogeneous situation in which the 2D electron system fluctuates between the QHE and non-QHE phases. Stern and Halperin (SH)[25] have suggested that these fluctuations are static and result from mesoscopic spatial inhomogeneities of the 2D electron density. On the other hand, dynamic critical fluctuations in an otherwise homogeneous system could also be involved.

In the SH picture, as d/ℓ is reduced toward the critical value puddles of the strongly-coupled QHE phase appear within a background of weakly-coupled non-QHE

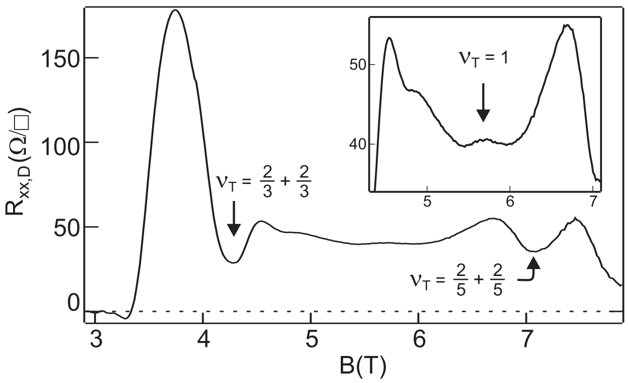

FIG. 4: Longitudinal drag in sample C at $T = 300$mK. Expanded view in the inset reveals a small enhancement near $\nu_T = 1$ where $d/\ell = 2.6$.

fluid. As d/ℓ is reduced further, these puddles eventually percolate. Via an analysis which assumes the puddles are (as expected) counterflow superfluids while the background fluid is a conventional double layer 2D conductor with a large Hall resistance but little Coulomb drag, SH conclude that the macroscopically averaged longitudinal drag resistivity $\rho_{xx,D}$ of the composite system can become very large just before the puddles percolate. In this situation, SH predict that $\rho_{xx,D}$ grows as the temperature falls, eventually saturating near $h/2e^2 \approx 13$kΩ. Figure 3 demonstrates that such a qualitative temperature dependence is observed. Although $R_{xx,D}$ near the midpoint of the transition region reaches only ≈ 1.9kΩ as $T \to 0$, classical geometric effects[26] associated with our square sample geometry suggest that the experimental longitudinal drag *resistivity* may be as much as a factor of $\pi/ln2$ larger than $R_{xx,D}$, or about 8.6kΩ. Further experiments may reveal whether, as SH suggest, the remaining discrepancy is due to the finite conventional (i.e. parallel transport) resistivity of the sample at $\nu_T = 1$.

We turn finally to the behavior of Coulomb drag at larger layer separations. Prior experiments[16], at $d/\ell \approx 3.9$, showed no evidence of any anomaly in $R_{xx,D}$ at *total* Landau level filling $\nu_T = 1$. As Fig. 2 shows, the enhancement of $R_{xx,D}$ at $\nu_T = 1$ in the present samples subsides rapidly as d/ℓ increases. Surprisingly, however, it remains observable out to $d/\ell \approx 2.6$. At these large d/ℓ the enhancement appears as a small bump on top of a background arising from drag scattering processes between weakly-coupled 2D layers - see Fig. 4. The bump at $\nu_T = 1$ is a genuine bilayer effect: It remains present even when small antisymmetric density imbalances are imposed on the double layer system. By contrast, the other features (e.g. the minima at $\nu_T = 2/3 + 2/3$ and 2/5+2/5) seen in Fig. 4 split in two, thus proving that they are fundamentally single layer effects.

The existence of enhanced longitudinal drag at $\nu_T = 1$ at such large d/ℓ is not understood. In principle, there may be local regions in our samples in which d/ℓ has been reduced by atomic steps in the various heterointerfaces. However, the needed reduction is $\sim 30\%$, or about 8nm, and this seems implausibly large[27]. We emphasize that no analogous anomaly is seen in the zero bias interlayer tunneling conductance. The enhanced tunneling, which heralds the onset of interlayer phase coherence[6], is either absent or unobservably small for $d/\ell \geq 1.85$. This discrepancy raises the possibility that the enhanced $\nu_T = 1$ drag at larger d/ℓ may not require interlayer phase coherence.

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in $R_{xx,D}$ *vs.* d/ℓ seen in Fig. 2c.