Observation of Quantized Hall Drag in a Strongly Correlated Bilayer Electron System

M. Kellogg,[1] I. B. Spielman,[1] J. P. Eisenstein,[1] L. N. Pfeiffer,[2] and K. W. West[2]

[1]*California Institute of Technology, Pasadena, California 91125*

[2]*Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974*

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The frictional drag between parallel two-dimensional electron systems has been measured in a regime of strong interlayer correlations. When the bilayer system enters the excitonic quantized Hall state at total Landau level filling factor $\nu_T = 1$, the longitudinal component of the drag vanishes but a strong Hall component develops. The Hall drag resistance is observed to be accurately quantized at h/e^2.

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The repulsive interactions between electrons in double layer two-dimensional electron systems (2DES) can lead to the condensation, at high magnetic field, of a remarkable quantum fluid [1]. The correlations present in this fluid include the binding of electrons in one layer to holes in the other. The holes, which in this case are in the conduction band of the host semiconductor crystal, exist when the individual 2DES partially fill the discrete Landau energy levels produced by a magnetic field applied perpendicular to the 2D planes. From this perspective, the system may be viewed as a Bose condensate of interlayer excitons [2,3]. This collective state exhibits the quantized Hall effect [4–6] (with Hall resistance $R_{xy} = h/e^2$) and has recently been found to display Josephson-like interlayer tunneling characteristics [7]. Here we report the observation of yet another intriguing property of this system: the exact quantization of the frictional drag which one 2DES exerts upon the other. This frictional drag, whose signature is a voltage buildup in one layer in response to a current flowing in the other, depends directly on the interlayer correlations present in the system.

The excitonic condensate point of view is not unique. The strongly correlated bilayer system may be described in several mathematically equivalent ways, including as an easy-plane ferromagnet or a condensate of composite bosons. In all cases, however, the essential physical attribute of the system is interlayer phase coherence [1,8,9]: Each electron in the ground state is in a specific quantum state which is a linear combination of the individual layer eigenstates, $|\uparrow\rangle$ and $|\downarrow\rangle$. There is complete uncertainty as to which layer any electron (or hole) is in. If tunneling between the layers is strong, this phase coherence is easy to understand: Individual electrons have lowest energy when they occupy the symmetric double well state $|\uparrow\rangle + |\downarrow\rangle$. On the other hand, when tunneling is weak (or even absent) Coulomb interactions can spontaneously produce interlayer phase coherence, provided that the distance separating the two 2DES is less than a critical value, and the total number of electrons in both layers equals the number of degenerate states in the lowest Landau level. In the weak tunneling limit appropriate here, interlayer phase coherence implies the possibility of superfluid (i.e., dissipationless) flow of the excitonic condensate [8–12]. However, unlike Cooper pairs in a superconductor, interlayer excitons are charge neutral and, thus, their uniform flow corresponds to equal but opposite electrical currents in the two 2DES layers. The data presented here provide indirect evidence for the existence of such superfluid counterflows.

The samples used in these experiments are GaAs/AlGaAs heterostructures grown by molecular beam epitaxy (MBE). Two 18 nm GaAs quantum wells are separated by a 9.9 nm $Al_{0.9}Ga_{0.1}As$ barrier layer. This double quantum well (DQW) is symmetrically doped via Si layers placed in the $Al_{0.3}Ga_{0.7}As$ cladding layers outside the DQW. The as-grown density of each 2DES is $N_1 = N_2 = 5.3 \times 10^{10}$ cm^{-2}, and their low temperature mobility is about 7.5×10^5 cm^2/V s. The densities can be independently varied using metal gate electrodes deposited on the sample top surface and back side, but for simplicity we shall discuss only the balanced ($N_1 = N_2$) case here. Standard photolithography was used to pattern a square mesa 250 μm on a side onto the sample. Ohmic contacts were placed at the ends of arms extending outward from this mesa. A selective depletion scheme [13] allows these contacts to be connected *in situ* to either 2DES separately, to both in parallel, or to be disconnected entirely. At zero magnetic field, the interlayer tunneling resistance of these samples exceeds 30 MΩ. Data from two, identically patterned, samples cut from the same parent MBE wafer are presented here.

At high magnetic field B, the degeneracy eB/h of the lowest spin-split Landau level exceeds the electron density $N_{1,2}$ in either layer. If, however, the *total* Landau level filling fraction $\nu_T = h(N_1 + N_2)/eB$ equals unity, then the net bilayer system will display the quantized Hall effect (QHE) if the layer separation d is small enough or the tunneling is strong enough. The latter case is relatively uninteresting since the origin of the energy gap which engenders the QHE is then merely the single-particle tunnel splitting Δ_{SAS} between the lowest symmetric and antisymmetric combinations of individual layer eigenstates. Since the estimated Δ_{SAS} in the present sample is only ~0.1 mK, far smaller than both the measurement temperature ($T \sim 50$ mK) and the mean

Coulomb energy ($E_C \sim 50$ mK), this mechanism can be safely ignored. On the other hand, at $\nu_T = 1$ the excitonic condensate and its associated QHE can develop even in the total absence of tunneling if the layers are close enough together [1]. The center-to-center quantum well separation $d = 27.9$ nm of the present sample is too large for this to occur at the as-grown densities of the 2DES. However, since the physics is governed by the ratio of d to the average separation between electrons within each layer, the transition to the excitonic phase can be driven by reducing the densities $N_{1,2}$. At fixed filling fraction, the mean electron spacing is simply proportional to the magnetic length $\ell = (\hbar/eB)^{1/2} = (\nu_T/2\pi N_T)^{1/2}$. Via gating, we are able to reduce the key ratio d/ℓ at $\nu_T = 1$ from about 2.3 down to below 1.6. Consistent with earlier observations [7], the $\nu_T = 1$ bilayer QHE first appears around $d/\ell = 1.83$. By $d/\ell = 1.6$ it is well developed: A deep minimum is observed in the longitudinal resistance R_{xx} and a clear plateau is evident in the Hall resistance at $R_{xy} = h/e^2$. In this situation, the QHE is due almost exclusively to electron-electron interactions.

Frictional drag measurements [14–16] are performed by driving current through one 2DES while monitoring the voltage which appears in the other, electrically isolated, 2DES. The drag voltage is a direct measure of the inter-layer momentum relaxation rate [14,17]. In the present sample, with its small layer separation and low electron density, the dominant relaxation mechanism at low temperatures is direct electron-electron Coulomb scattering. A careful study, to be reported elsewhere, of the zero magnetic field drag in these samples reveals the expected near-quadratic temperature dependence. For reference, at $N_1 = N_2 = 5.3 \times 10^{10}$ cm^{-2}, the measured drag resistivity is $\rho_D \approx (0.4\ \Omega/\square \cdot \mathrm{K}^2)T^2$ for $T < 4$K.

Figure 1 shows the main results of this study. The densities have been reduced by symmetric gating to $N_1 = N_2 = 2.6 \times 10^{10}$ cm^{-2}, making $d/\ell = 1.6$ at $\nu_T = 1$. The four traces shown correspond to the magnetic field dependence of various voltage measurements made on the system; these are converted to resistances by dividing by the excitation current I, typically 2 nA at 5 Hz. The insets to the figure depict the various measurement configurations. Trace A shows the conventional longitudinal resistance R_{xx} of the sample, measured with the current flowing in parallel through both layers. The deep minimum near $B = 2.15$ T reflects the strong $\nu_T = 1$ bilayer QHE present at this density. Although omitted from the figure, a well-developed plateau is also observed in the conventional Hall resistance of the sample at $R_{xy} = h/e^2$.

Traces B and C illustrate our most important results. For these data, the excitation current was driven through only one 2DES while voltages in the non-current-carrying 2DES were recorded. Trace B represents "Hall drag," a voltage drop which appears transverse to the current flowing in the other layer. At low magnetic field, the Hall

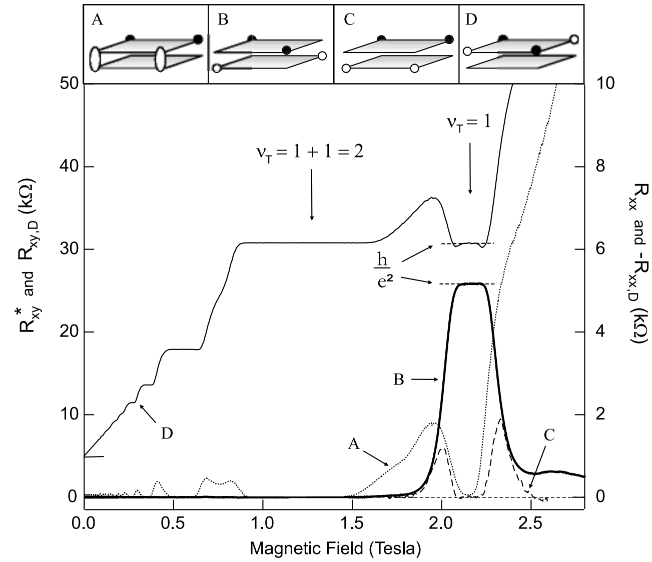

FIG. 1. Conventional and Coulomb drag resistances of a low density double layer 2DES. Trace A: Conventional longitudinal resistance R_{xx} measured with current in both layers. Trace B: Hall drag resistance $R_{xy,D}$. Trace C: Longitudinal drag resistance $R_{xx,D}$; sign reversed for clarity. Trace D: Hall resistance R^*_{xy} of the single current-carrying layer (displaced vertically by 5 kΩ for clarity). Trace B reveals the quantization of Hall drag in the $\nu_T = 1$ excitonic QHE. Insets schematically illustrate the measurement configurations: Current is injected and withdrawn at the open dots; voltage differences between the solid dots are recorded. Traces A, B, and D obtained at $T = 20$ mK; trace C at 50 mK. Layer densities: $N_1 = N_2 = 2.6 \times 10^{10}$ cm^{-2}, giving $d/\ell = 1.6$ at $\nu_T = 1$.

drag resistance $R_{xy,D}$ is undetectably small, but around $B = 2$ T it rises up and forms a flat plateau. This plateau is centered at the location of the $\nu_T = 1$ QHE state. At still higher fields $R_{xy,D}$ falls off again to much smaller values. On the plateau, we have found that $R_{xy,D}$ equals the quantum of resistance $h/e^2 = 25\,813\ \Omega$ to within about five parts in 10^4. We emphasize that the same quantization of Hall drag is observed when the roles (drive vs drag) of two layers are interchanged and that the sign of the Hall drag is the same as that of the conventional Hall effect in the current-carrying layer.

Along with this plateau in the Hall drag, trace C demonstrates that the longitudinal drag resistance $R_{xx,D}$ (i.e., the drag voltage drop which is parallel to the current in the drive layer) simultaneously exhibits a deep minimum. Note, however, that the longitudinal drag voltage is opposite in sign to the longitudinal resistive voltage drop in the current-carrying layer. This sign difference (which has been removed for clarity from Fig. 1) is commonplace in drag studies [14,16] on weakly correlated bilayer electron systems where it merely reflects the force balance resulting from the constraint that no current flow in the drag layer. In any case, it is apparent from Fig. 1 that the two components of Coulomb drag display the $\nu_T = 1$ quantized Hall effect just as conventional resistivity measurements do, in spite of the fact that the drag voltages exist in the layer in which there is no current.

Finally, for trace D the current again flows through only one layer, but now the Hall voltage across that same layer is recorded. At low magnetic fields this Hall resistance, denoted by R_{xy}^*, reflects *single-layer* physics: The slope of the initial linear rise of R_{xy}^* with field is determined by the density of the current-carrying layer ($N_{1,2} = N_T/2$), and the subsequent QHE plateaus at intermediate fields correspond to integer values of the individual filling factors $\nu_{1,2}$. The last such single-layer QHE plateau, at $R_{xy}^* = h/e^2$, is centered at $B = 1.1$ T and corresponds to $\nu_1 = \nu_2 = 1$, i.e., $\nu_T = 2$. At still higher fields, R_{xy}^* begins to deviate from h/e^2 but then remarkably returns to form a *second plateau* at h/e^2 around $B = 2.15$ T, exactly where the Hall drag plateau exists and the bilayer system is in the $\nu_T = 1$ QHE state.

The assumption that no current flows in the layer in which drag voltages are measured is always a key issue in drag experiments. It requires particularly careful scrutiny at $\nu_T = 1$ since a huge increase in the interlayer tunneling conductance has been observed [7] to occur when d/ℓ is reduced below $\sim$1.83 and the excitonic condensate develops. Several facts, however, leave us confident that tunneling is not a serious problem. First, the tunneling enhancement is sharply resonant around zero interlayer voltage. At low temperatures, the width of the tunnel resonance in the present samples is less than 10 μV [18]. In contrast, we find the Hall drag plateau unaffected by intentionally imposed interlayer voltages of up to $\pm$500 μV. Second, a small additional magnetic field ($B_\parallel \sim 0.7$ T) applied parallel to the 2D layers has been demonstrated [18] to suppress the $\nu_T = 1$ tunneling conductance by more than an order of magnitude. We find that the same in-plane field has no effect on the quantized Hall drag plateau. Finally, direct tunneling experiments on the present samples have shown that the *maximum* tunnel current that can flow between the layers at $\nu_T = 1$ is around 10 pA, independent of interlayer voltage up to several mV. Since our drag measurements are performed with excitation currents of $\sim$1 nA, a reasonable worst-case estimate of the maximum current flowing in the "wrong" layer is 1% of the total.

The data in Fig. 1 demonstrate that the same Hall voltage appears across both layers at $\nu_T = 1$, in spite of the fact that current flows only in one of them. This voltage is precisely the same as that which appears across both layers when the current is driven in parallel through both layers. Thus, the same voltages appear across both layers irrespective of how the total current I is divided between them. This remarkable fact is a direct manifestation of interlayer phase coherence.

Figure 2 shows that the phenomena of quantized Hall drag and the anomalous second h/e^2 plateau in R_{xy}^* both disappear when the effective layer separation d/ℓ is increased beyond about 1.83. To facilitate their comparison, the data in Fig. 2 are plotted versus inverse total filling factor ν_T^{-1}, not magnetic field. Not surprisingly, at large d/ℓ very little Hall drag is present, and the Hall resistance R_{xy}^* of the current-carrying layer remains close to the classical Hall line in the field range around $\nu_T = 1$. Although not shown in the figure, the minimum in the longitudinal drag $R_{xx,D}$ at $\nu_T = 1$ is also absent at large d/ℓ. To within experimental uncertainty, the collapse of quantized Hall drag occurs simultaneously with the vanishing of the conventional QHE and the system's Josephson-like tunneling characteristics.

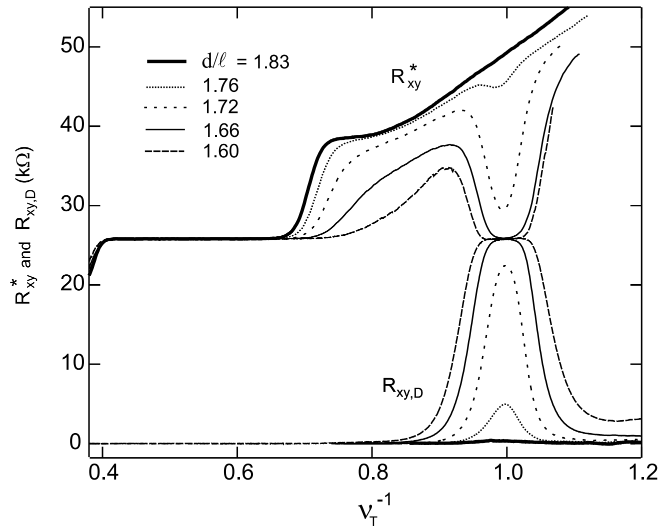

FIG. 2. Collapse of $\nu_T = 1$ Hall drag quantization and second h/e^2 plateau in R_{xy}^* at large d/ℓ. Layer densities $N_1 = N_2 =$ 2.6, 2.8, 3.0, 3.2, and 3.4 $\times 10^{10}$ cm^{-2}, giving $d/\ell = 1.6$, 1.66, 1.72, 1.76, and 1.83, respectively, at $\nu_T = 1$. Measurement temperature $T = 30$ mK.

Figure 3 displays the temperature dependence of these phenomena, again at $d/\ell = 1.6$. Three data sets

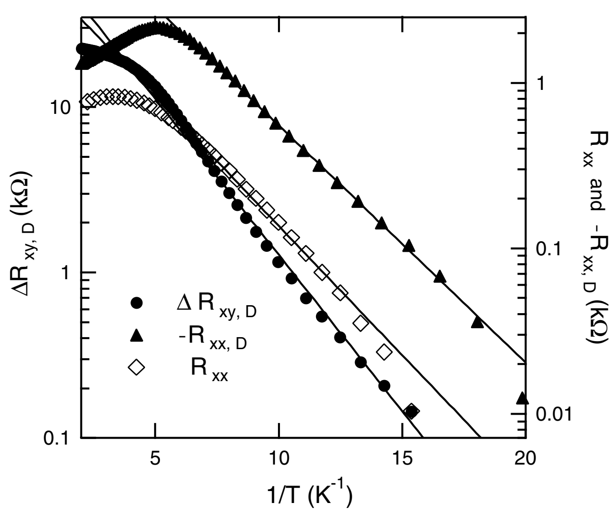

FIG. 3. Temperature dependences of conventional longitudinal resistance R_{xx}, longitudinal drag resistance $R_{xx,D}$, and deviation $\Delta R_{xy,D}$ of the Hall drag from h/e^2 at $\nu_T = 1$ and $d/\ell = 1.6$. The sign of $R_{xx,D}$ has been reversed for clarity. The lines are guides to the eye.

are shown: the conventional longitudinal resistance R_{xx} (measured with current flowing in parallel through both layers), the longitudinal drag resistance $R_{xx,D}$, and the deviation $\Delta R_{xy,D}$ of the Hall drag from its quantized value of h/e^2. As the figure shows, each of these quantities is approximately thermally activated [i.e., is proportional to $\exp(-E_A/T)$] at low temperatures. As the near parallel slopes suggest, the activation energies are all comparable: $E_A \approx 0.4$ K.

The existence of quantized Hall drag is remarkable. At the simplest level, one expects it should not exist. For two uncorrelated 2D layers, the usual argument is that, since no current flows in the drag layer, there can be no Lorentz force on its carriers. Without the Lorentz force, there ought not be any voltage buildup transverse to the current in the drive layer. This argument, however, is specious, even without interlayer correlations. Hu [19], and later von Oppen *et al.* [20], showed that Hall drag voltages can exist provided there is an energy (or density) dependence to the carrier momentum relaxation rate. More relevant here, however, are the several theoretical predictions of large and *quantized* Hall drag voltages that result from strong interlayer correlations [9,21–25]. For example, Yang [23] has recently shown that quantized Hall drag at $\nu_T = 1$ follows from the assumption of the specific many-body ground state wave function [26] (the so-called 111 state) generally believed to capture the essential physics of spontaneous interlayer phase coherence and exciton condensation.

Interlayer phase coherence implies that electrons are spread equally between both layers. A nonequilibrium current injected into one layer thus divides equally into both layers, and the resulting Hall voltages in the two layers are the same. On the other hand, this current division obviously violates the basic boundary conditions of a drag measurement. According to theory [27], the resolution of this paradox lies in the superfluid properties of the excitonic condensate itself. In addition to the transport current flowing equally through both layers, a superflow of excitons develops. Since such a superflow corresponds to counterflowing electrical currents in each layer, it produces no Hall field and allows for the net current in one layer to be zero while in the other layer it is finite. Only if the net currents in the two layers are equal is there no such superflow. From this perspective, our experimental results offer the first, albeit indirect, evidence for excitonic superfluidity at ν_T=1.

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