Exciton condensation and perfect Coulomb drag

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Coulomb drag is a process whereby the repulsive interactions between electrons in spatially separated conductors enable a current flowing in one of the conductors to induce a voltage drop in the other²–³. If the second conductor is part of a closed circuit, a net current will flow in that circuit. The drag current is typically much smaller than the drive current owing to the heavy screening of the Coulomb interaction. There are, however, rare situations in which strong electronic correlations exist between the two conductors. For example, double quantum well systems can support exciton condensates, which consist of electrons in one well tightly bound to holes in the other⁴–⁶. ‘Perfect’ drag is therefore expected: a steady transport current of electrons driven through one quantum well should be accompanied by an equal current of holes in the other.⁷ Here we demonstrate this effect, taking care to ensure that the electron–hole pairs dominate the transport and that tunnelling of charge between the quantum wells, which can readily compromise drag measurements, is negligible. We note that, from an electrical engineering perspective, perfect Coulomb drag is analogous to an electrical transformer that functions at zero frequency.

The exciton condensate of interest here develops at high perpendicular magnetic field B⊥ where the separation d between two parallel two-dimensional electron systems (2DESs) is comparable to the magnetic length 〈r = (ℏ/eB⊥)ⁱ⁄₂〉 and the total density n = n₁ + n₂ of electrons in the bilayer matches the degeneracy eB⊥/ℏ of a single spin-resolved Landau level (ref. 6 and references therein, refs 8, 9). (We consider here only the balanced case, with n₁ = n₂; ℏ is Planck’s constant divided by 2π, e is the electronic charge.) Hence, the total Landau level filling factor is ν = 1. When d/〈r ≪ 1, an energy gap to charged excitations opens and the bilayer electron system displays a quantized Hall plateau ρ₂ν = ℏ/e². The interlayer tunnelling conductance becomes strongly enhanced near zero bias and, when equal electrical currents are driven in opposite directions through the two layers, the Hall effect vanishes at low temperature⁹–¹³. Even in the limit of zero tunnelling through the barrier separating the layers, interlayer Coulomb interactions at ν = 1 are believed to be sufficient to both open a charge gap and to spontaneously generate quantum phase coherence between electrons in opposite layers⁶–⁸,⁹. Spontaneous interlayer phase coherence allows the system ground state to be described as a Bose condensate of interlayer excitons. At low temperatures, the charged excitations of the ν = 1 system are frozen out and unable to transport current across the bulk of the two-dimensional system. In contrast, the neutral electron–hole pairs in the condensate remain abundant and free to move about the bulk. Transport of these excitons is equivalent to counter-flowing electrical currents in the two layers. Interestingly, the ν = 1 quantum Hall system is closely related to exciton–polariton condensates at zero magnetic field, for which evidence of spontaneous phase coherence has recently been reported¹⁴–¹⁶.

Evidence for exciton transport at ν = 1 was obtained from Hall effect measurements in which counter-flowing electrical currents were driven through the two layers¹¹–¹³. The observed vanishing of the Hall voltage at ν = 1 is consistent with the counter-flowing currents being carried by excitons. However, interpretation of these experiments is complicated by the conducting edge states which exist at the boundary of all quantum Hall systems. Furthermore, because the experiments were performed using simply-connected Hall bar geometries, they were incapable of proving that excitons were moving through the bulk of the 2DES. Subsequent experiments by Tiemann et al.¹⁷,¹⁸ and Finck et al.¹⁹ employed the multiply connected Corbino geometry (essentially an annulus with separated edge states on the two rims) in order to search for exciton transport across the insulating bulk. By connecting the two layers together at one rim while applying a voltage between the layers at the other rim, Finck et al. observed that relatively large, oppositely directed currents would flow across the bulk of the ν = 1 quantum Hall state¹⁹. This observation contrasts sharply with the observed inability of the bulk to support co-directed currents in the two layers. Finck et al. concluded that bulk exciton transport was responsible for their results¹⁹.

We show here that the excitonic correlations built into the ν = 1 quantum Hall state can force oppositely directed currents to flow in the two layers even when there is no electrical connection between them. For small driving currents the observed drag current is closely equal in magnitude to the drive current; that is, the drag is ‘perfect’. The role of interlayer tunnelling is investigated and shown to be irrelevant in the proper circumstances.

Our sample consists of two parallel 2DESs confined in a GaAs/AlGaAs double quantum well structure, the details of which are given below. The bilayer 2DES is patterned into an annulus (1 mm inner diameter, 1.4 mm outer diameter) with arms extending from each rim to ohmic contacts; a schematic plan-view of the device is shown in Fig. 1a. Each ohmic contact may be connected either to both two-dimensional layers simultaneously or to either layer separately¹⁰. Electrostatic gating of the 2DESs in the annulus (but not the contact arms) allows the key parameter d/l to be tuned from 2.35 down to about 1.49 at ν = 1. In addition to the perpendicular magnetic field of 0.2–0.6 T, we have varied the value of ν = 5. When d/l < 1.5, an energy gap to charged excitations opens and the neutral exciton–polariton system displays a quantized Hall plateau ρ₂ν = ℏ/e², and the chiral exciton–polariton system displays a quantized Hall plateau ρ₂ν = ℏ/e².

Figure 1 | Corbino conductance σ²ν at ν = 1. a, ∂l/V = (V = σ²ν) at zero d.c. voltage versus 1/kT at ν = 1 with d/l = 1.5 and θ = 26°. Solid line implies an energy gap of 1.360 mK. Inset, schematic plan-view of device; see text for details. Filled dots indicate contacts to both layers; open dots show contacts to lower layer only. b, σ²ν versus applied d.c. voltage Vdc under same conditions as in a for various temperatures.
$B_1$ needed to establish $v_T = 1$, an in-plane field $B_1$ may also be applied by tilting the sample relative to the total magnetic field. This allows us to suppress the interlayer tunnelling which can otherwise pollute Coulomb drag measurements. The sample displays a robust quantum Hall effect at $v_T = 1$ for $d/l \leq 1.8$ for all tilt angles up to at least $\theta = 66^\circ$. Figure 1a illustrates the insulating character of the bulk of the two-dimensional system at $v_T = 1$ (with $d/l = 1.5$ and $\theta = 26^\circ$) in an Arrhenius plot of the Corbino conductance $\sigma_{xx}^{\|}$ for parallel transport in the two layers. A small a.c. excitation voltage ($V_{ex} \approx 18$ $\mu$V at 13 Hz) is applied between contacts (to both layers) on the inner and outer rim of the annulus. The resulting current flow $\delta I_1$ plus the rim-to-rim voltage difference $\delta V$ between two additional contacts, are recorded and used to compute $\sigma_{xx}^{\parallel} = \delta I/\delta V$. As expected, the conductance is thermally activated, $\sigma_{xx}^{\|} \propto e^{-\Delta/2T}$, and gives an energy gap $\Delta \approx 360$ mK. When a d.c. voltage $V_{dc}$ is added to the a.c. excitation voltage $V_{ex}$, the conductance $\sigma_{xx}^{\|}$ increases. This smooth ‘breakdown’ of the $v_T = 1$ quantum Hall effect, shown in Fig. 1b, has important consequences for the Coulomb drag results to which we now turn.

In a Corbino Coulomb drag measurement, a voltage $V$ is again applied between the inner and outer rims of the annulus, but only via contacts to one of the two two-dimensional layers. The other layer is either left open or is closed upon itself by connecting an external resistor between the two rims. The open-circuit case is similar to the $\sigma_{xx}^{\|}$ measurement discussed above; current will flow in the drive layer, but only in proportion to $\sigma_{xx}^{\|}$. The closed-circuit case is potentially different; if strong interlayer correlations are present, relatively large oppositely directed currents, mediated by exciton transport, might flow in the two layers.

Figure 2 shows the results of such closed-circuit drag measurements. External resistors in both the drive and drag loops allow us to monitor the currents $I_1$ and $I_2$ flowing in each. This arrangement is illustrated in Fig. 2a inset; $I_1$ and $I_2$ are defined as positive if they flow in the direction of the arrows. Whereas the drive circuit is grounded at one point, the drag circuit is left to float. Figure 2a shows the d.c. currents $I_1$ and $I_2$ flowing, at $T = 17$ mK, in response to a d.c. drive voltage $V_{dc}$, at $v_T = 1$, with $d/l = 1.49$ and $\theta = 26^\circ$. For small $V_{dc}$, $I_1$ and $I_2$ are very nearly equal and grow steadily, if somewhat super-linearly, with voltage. In the $V_{dc} \rightarrow 0$ limit, the conductances $\partial I_1/\partial V = \partial I_2/\partial V$ exceed the parallel flow Corbino conductance $\sigma_{xx}^{\parallel}$ at $v_T = 1$ by a factor of 5. At large $V_{dc}$, the currents separate, with $I_2$ continuing to grow steadily while $I_1$ begins to saturate. Figure 2b shows the magnetic field dependence (at $\theta = 26^\circ$) of the drag conductance $\partial I_2/\partial V$ at $V_{dc} = 0$ (obtained by applying a weak purely a.c. excitation voltage $V_{ex}$ across the drive circuit) at $T = 25$ mK. As expected, significant drag is found only in the vicinity of $v_T = 1$ at $B_1 = 1.87$ T.

Because the currents $I_1$ and $I_2$ are detected outside the bilayer 2DES, it is not obvious that the drive current is truly passing through the top two-dimensional layer and the drag current through the bottom two-dimensional layer. Instead, interlayer tunnelling could allow the current to shunt from the top to the bottom layer near the outer rim of the device, pass through the external drive layer loop, and then tunnel back from the bottom to the top layer near the inner rim. If this is the case, the current $I_2$ need not be due to Coulomb drag, as recognized in the prior Corbino transport measurements of Tiemann et al. To eliminate this possibility, we intentionally suppress interlayer tunnelling by tilting our sample relative to the applied magnetic field.

Figure 3 shows d.c. tunnelling current–voltage characteristics at $v_T = 1$ and $d/l = 1.49$, for $\theta = 0$ and $26^\circ$. These data were obtained at $T = 20$ mK by applying an external d.c. voltage $V_{dc}$ between contacts to the ‘upper’ and ‘lower’ 2DES layer on the outer rim of the annulus and recording both the resultant tunnelling current $I$ and the interlayer voltage $V_{int}$, between the two remaining outside rim contacts. Figure 3a shows the tunnelling currents plotted versus $V_{int}$, while Fig. 3b plots the currents versus $V_{dc}$: the two figures therefore contrast the ‘four-terminal’ and ‘two-terminal’ tunnelling current–voltage characteristics of the bilayer system. The four-terminal $I$–$V_{int}$ characteristic at $\theta = 0$ clearly shows the Josephson-like near-discontinuity at $V_{int} = 0$ reported previously. In contrast, the two-terminal $I$–$V_{dc}$ characteristic shows the tunnelling current initially rising smoothly with $V_{dc}$. This difference is due almost entirely to the extrinsic series resistances presented by the arms leading into the annulus. Indeed, comparison of the two- and four-terminal tunnelling data allows us to accurately estimate the series resistances and their nonlinearity with voltage; these estimates are important in the analysis of the Coulomb
drag data. Note that for \( \theta = 0 \) the maximum tunnelling currents are comparable to the currents \( I_1 \) and \( I_2 \) observed in the drag measurement and shown in Fig. 2a.

Most importantly, Fig. 3a and b reveal the expected\(^1\) suppression of the tunnelling current resulting from tilting the sample. At \( \theta = 26^\circ \) the zero bias anomaly so prominent at \( \theta = 0 \) in the four-terminal \( I-V \) characteristic is essentially obliterated. Even relatively at the high applied voltage of \( |V_{dc}| = 300 \mu \text{V} \) the tunnel current is only ~0.1 nA. The two- and four-terminal characteristics at \( \theta = 26^\circ \) are very similar, because the tunnelling resistance at this tilt angle is much larger than the extrinsic series resistances.

Comparing the tunnelling data in Fig. 3 with the Coulomb drag data in Fig. 2a demonstrates that tunnelling is not an important contributor to the drag current \( I_2 \) at \( \theta = 26^\circ \). Ignoring, for the moment, the different excitation means in the two cases (interlayer versus intralayer biasing), it is clear that the tunnelling conductance near \( I_2 \) observed in the drag measurement is very similar, because the tunnelling resistance at this tilt angle is much larger than the extrinsic series resistances.

The above discussion enables us to conclude that the drive and drag currents shown in Fig. 2b do indeed flow across the bulk of the top and bottom two-dimensional layers in the annulus, and in opposite directions. For small drive voltages, \( I_1 \approx I_2 \) and thus the drag is essentially perfect. In this nearly pure counter-flow regime, the drag process is dominated by neutral exciton transport.

Figure 4a and b shows how the drag ratio \( I_2/I_1 \) depends on temperature \( T \) and effective layer separation \( d/I \), respectively. For small drive voltages \( V_{dc} \), the drag ratio is close to unity \( (I_2/I_1 \approx 0.97) \) only at the lowest \( T \) and \( d/I \), where the \( v_F \approx 1 \) quantum Hall state is strongest. Increasing either parameter reduces the drag ratio at small \( V_{dc} \). In all cases, the drag ratio also falls with increasing drive voltage. We believe that these deviations from perfect drag are due primarily to the finite Corbino conductance \( \sigma_{xx}^{sl} \), which allows parallel charge transport across the bulk to occur along the neutral exciton transport.

Assuming \( \sigma_{xx}^{sl} = 0 \) and dissipationless exciton transport, it is predicted\(^2\) that \( I_1 = I_2 = V/(R_1 + R_2) \), where \( R_1 \) and \( R_2 \) are the net resistances in series with the Corbino annulus in the drive and drag circuits, respectively. These include the external circuit resistors \( R_{ext} \), the resistances \( R_{int} \) of the 2DES arms leading into the annulus, and quantum Hall 'contact' resistances \( R \) of order \( h/e^2 \). Generalizing this model to include non-zero \( \sigma_{xx}^{sl} \), we find, assuming linear response, the drag current reduces to \( I_2 = V/(R_1 + R_2 + R R_{xx}^{sl}) \) and the drag ratio to \( I_2/I_1 = 1/(1 + R R_{xx}^{sl}) \). Using the tunnelling data in Fig. 3a to estimate \( R_1 \) and \( R_2 \) and the measured \( \sigma_{xx}^{sl} \) data in Fig. 1a, we can estimate the expected drag ratio \( I_2/I_1 \) near zero bias. These estimates, shown in Fig. 4a, compare quite favourably with the observed drag ratios at \( T = 17, 35 \) and 50 mK. At higher \( V_{dc} \), the nonlinearity of \( \sigma_{xx}^{sl} \) (shown in Fig. 1b) and the series resistances \( R_1 \) and \( R_2 \) must also be taken into account. The dashed lines in Fig. 2b display the results of one such calculation of the drive and drag currents. The qualitative agreement with the experimental results is strong evidence that the enhanced Corbino conductance \( \sigma_{xx}^{sl} \) at elevated temperatures and drive voltages is the dominant source of deviations from perfect Coulomb drag at \( v_F \approx 1 \).

The assumption that exciton transport across the bulk of the 2DES is dissipationless can be questioned in real, disordered samples such as ours\(^26,27\). A phenomenological excitonic 'resistance' \( R \) can be introduced whereby \( R (I_1 + I_2) \) equals the difference \( \Delta \Phi_{int} \) between the interlayer voltages on the two rims of the annulus (a spatially uniform interlayer voltage would produce no dissipation). In the \( \sigma_{xx}^{sl} = 0 \) limit, this new resistance leaves the drag perfect, but reduces the currents to \( I_1 = I_2 = V/(R_1 + R_2 + R) \). The relatively large magnitude of \( R + 2 R \) (never less than \( 2h/e^2 \)) limits the ability of the present Coulomb drag experiments to detect small values of \( R \). Future multi-terminal measurements should be able to set stringent limits on any dissipation occurring in the exciton channel.

METHODS SUMMARY

The present sample consists of two 18-nm GaAs quantum wells separated by a 10-nm GaAs/AlAs barrier. The centre-to-centre layer separation is therefore \( d = 28 \) nm. This double well structure is flanked by thick GaAs/AlAs cladding layers. Si doping sheets within the cladding layers populate the lowest subband of each quantum well with a 2DES of nominal density \( 5.5 \times 10^{10} \) cm\(^{-2} \) and low mobility of \( 1 \times 10^5 \) cm\(^2\) V\(^{-1}\) s\(^{-1} \). Standard photo-lithographic techniques are used to pattern the bilayer 2DES into the geometry depicted in Fig. 1. Diffused AuNiGe ohmic contacts are positioned at the ends of arms extending away from both rims of the annulus. Electrostatic gates cross these arms (both on the top and on the thinned back side of the sample) in order to use a selective depletion scheme which allows the contacts to communicate with the 2DES in the annulus either via both layers in parallel or either layer separately\(^28\). Additional gates control the two-dimensional layer densities in the annulus itself. The sample is mounted on a Ag platform in good thermal contact with the mixing chamber of a \( ^3 \)He–\( ^4 \)He dilution refrigerator. The electrical transport measurements reported here employ standard d.c. and/or low frequency a.c. techniques. The d.c. drive and drag currents \( I_1 \) and \( I_2 \) can be determined either by exciting the drive circuit with a purely d.c. voltage, or by numerical integration of the ac currents (shown in Fig. 1b) and the series resistances \( R_1 \) and \( R_2 \) must also be taken into account.

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