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Bilayer 2D electron systems at $\nu_{tot} = 1$: phase boundary between weak and strong coupling

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Abstract

The collapse of the excitonic quantized Hall state at $\nu_{tot} = 1$ in double layer two-dimensional electron systems is studied via interlayer tunneling and Coulomb drag. We find that spontaneous interlayer phase coherence, perhaps the most important hallmark of the excitonic phase and directly detected via a strong resonant enhancement of the zero-bias tunneling conductance, collapses very rapidly above a critical layer separation. In contrast, a related anomaly in the longitudinal component of Coulomb drag at $\nu_{tot} = 1$ subsides much more slowly as the layer separation is increased beyond the critical point.

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1. Introduction

For sufficiently small separation between the layers, a bilayer 2D electron system (2DES) supports an excitonic superfluid ground state when the total electron density in the system, N_{tot}, equals the degeneracy eB/h of a single spin-resolved Landau level produced by a perpendicular magnetic field B.[1] In addition to exhibiting the quantized Hall effect (QHE) (with $\rho_{xy} = h/e^2$), this collective state is expected to possess a number of much more unusual properties. For example, early on Murphy et al. [2] showed that the quasiparticle energy gap for this $\nu_{tot} = hN_{tot}/eB = 1$ QHE state was extremely sensitive to a magnetic field component parallel to the plane of the layers. Using a ferromagnetism model, Yang et al. [3] successfully explained this effect in terms of a textural phase transition in the pseudospin magnetization of the system. Beyond this there were several outstanding theoretical predictions about the system, including the existence of a finite-temperature Kosterlitz–Thouless phase transition [3,4], a Josephson effect in interlayer tunneling [4,5], and most dramatically, superfluidity for counter-propagating currents in the two layers [3,4].

In order to experimentally search for these important properties of the excitonic phase, it is essential to establish separate electrical contacts to the individual layers in the system. Although a robust technique for doing this in weakly coupled bilayers was developed more than a decade ago [6], its extension to double-layer systems which are simultaneously strongly coupled via interlayer Coulomb interactions

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[1] For a review of bilayer 2D electron systems at high magnetic fields, see the chapters by Girvin and A.H. MacDonald and by J.P. Eisenstein in Ref. [1].

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and yet weakly coupled via tunneling, did not occur until recently. Once this technical issue was resolved, a number of very interesting experimental results were obtained. Spielman et al. [7,8] have shown that a giant and sharply resonant enhancement of the interlayer tunneling conductance appears around zero bias. This effect, which is very suggestive of the anticipated Josephson effect, is a compelling indicator of spontaneous interlayer phase coherence among the electrons in the system and may be viewed as a direct manifestation of the expected pseudospin Goldstone mode [4,9]. In addition, Kellogg et al. [10], have reported the existence of a large, and accurately quantized, Hall component of the drag resistance between the layers. This observation is a striking demonstration of the interlayer correlations in the excitonic phase, and adds strong indirect evidence for the expected counter-flow superfluidity.

This paper focusses on the conditions for the stability of the $\nu_{tot} = 1$ excitonic phase, using the probes of interlayer tunneling and Coulomb drag. In particular, we will examine and compare these phenomena in the vicinity of the phase boundary (as a function of layer separation) between the excitonic phase and the non-QHE weakly coupled phase.

2. Transport vs. tunneling

Fig. 1 compares the way in which the $\nu_{tot} = 1$ excitonic phase appears in three different kinds of measurements; ordinary longitudinal resistance R_{xx}, the Hall component of the drag resistance, $R_{xy,D}$, and the zero-bias interlayer tunneling conductance, $G(0)$. The data shown are derived from a single sample which consists of two 18 nm GaAs quantum wells separated by a 10 nm $Ga_{0.1}Al_{0.9}As$ barrier layer. In its as-grown state, each quantum well contains a 2DES with density 5.5×10^{10} cm^{-2} and a low-temperature mobility of about 1×10^{6} cm^2/V s. With these physical parameters, the ratio of the layer separation d (defined as the center-to-center quantum well spacing, 28 nm) to the magnetic length $\ell = (\hbar/eB)^{1/2}$ at $\nu_{tot} = 1$ is $d/\ell = 2.3$. This is too large for the excitonic phase to exist. To obtain the data in Fig. 1, the densities in the two layers were symmetrically reduced, via electrostatic gating, until $d/\ell \approx 1.57$, which is well below the phase boundary near $d/\ell \sim 1.8$.

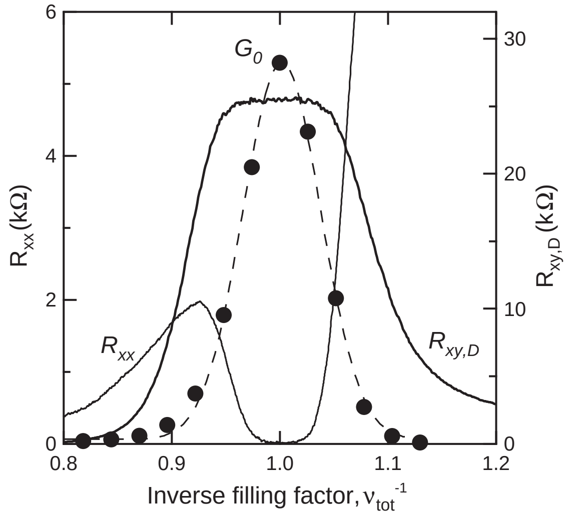

Fig. 1. Comparison of conventional longitudinal resistance (R_{xx}, light solid trace), Hall drag resistance ($R_{xy,D}$, dark solid trace) and zero-bias tunneling conductance ($G(0)$, solid dots) versus inverse total filling factor ν_{tot}^{-1} at $T = 50$ mK in a strongly coupled bilayer 2D ES. For these data the effective layer separation $d/\ell \approx 1.57$ and the excitonic $\nu_{tot} = 1$ bilayer quantum Hall state is well developed. (The peak value of $G(0)$ is about $1.4 \times 10^{-6}\Omega^{-1}$.)

The data shown in Fig. 1 reveal a deep minimum in the conventional longitudinal resistance R_{xx} centered at $\nu_{tot} = 1$, clearly signaling the presence of the QHE energy gap. As emphasized elsewhere, the $\nu_{tot} = 1$ QHE in this sample is overwhelmingly dominated by Coulomb interactions, with the mean inter-electron Coulomb energy in the system exceeding the estimated single-particle tunnel splitting Δ_{SAS} by nearly *six orders of magnitude*. Fig. 1 also demonstrates that the recently discovered phenomena of enhanced interlayer tunneling and quantized Hall drag are also centered at $\nu_{tot} = 1$. The fairly wide plateau in the Hall drag resistance shows, not surprisingly, that this new transport probe is affected by the same localization physics that the conventional resistivity is. Interestingly, however, the Hall drag remains large well outside the plateau region. This suggests that the strong interlayer correlations which produce the excitonic phase persist even in the presence of a large population of delocalized quasiparticles. In contrast, the interlayer tunneling conductance does not develop a plateau around $\nu_{tot} = 1$. Although localized quasiparticles almost certainly contribute to the magnitude of $G(0)$, there is

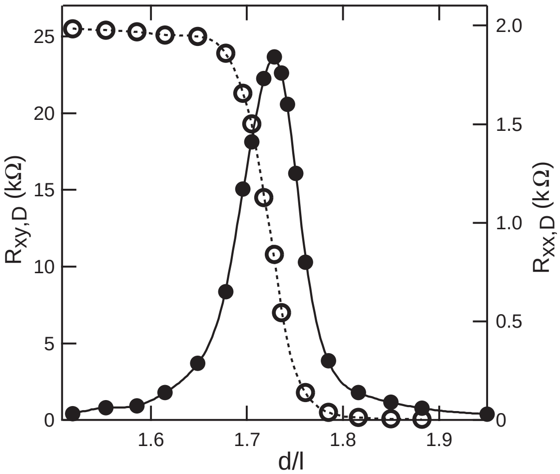

Fig. 2. Hall (open dots) and longitudinal (solid dots) drag resistances at $\nu_{tot} = 1$ and $T = 50$ mK vs. d/ℓ in the vicinity of the strong to weak-coupling transition.

no anticipation of any mechanism, analogous to the QHE, whereby $G(0)$ would be independent of small changes in their population.

3. Drag near the phase boundary

When the effective layer spacing d/ℓ at $\nu_{tot} = 1$ is increased (by symmetrically increasing the electron density in the quantum wells) beyond a critical value, the signatures of the excitonic bilayer QHE state shown in Fig. 1 disappear. Fig. 2 shows this effect for the case of Coulomb drag, where both $R_{xy,D}$ and $R_{xx,D}$ at $\nu_{tot} = 1$ and $T = 50$ mK are plotted vs. d/ℓ. The rapid collapse of the Hall drag $R_{xy,D}$ near $d/\ell \approx 1.73$ suggests that this is the location of the phase boundary between the strongly coupled excitonic QHE state and some weakly coupled phase. Interestingly, the longitudinal drag $R_{xx,D}$ exhibits a strong maximum at the transition [11].

Earlier measurements [12] done at large layer separation ($d/\ell \sim 4$, well outside the excitonic QHE phase) revealed quite small longitudinal drag resistivities (of order tens of Ω at $T = 50$ mK) at $\nu_{tot} = 1$. Very small longitudinal drag values were also obviously expected deep inside the excitonic phase at small d/ℓ owing to the QHE energy gap for charged excitations. That $R_{xx,D}$ would rise to kΩ values in between these two limits came as a surprise.

It is apparent from Fig. 2 that the transition region has a significant width. Indeed, the half-width of the peak in $R_{xx,D}$ at $T = 50$ mK shown in Fig. 2 is $\Delta(d/\ell) \approx 0.04$. Both the position and width of the peak vary with temperature: As $T \to 0$ the peak position extrapolates toward $d/\ell = 1.76$ and the half-width falls to about $\Delta(d/\ell) \approx 0.02$. These data suggest that in the transition region, the 2D system may be fluctuating between the excitonic QHE phase and the non-QHE phase. This may reflect dynamic critical point fluctuations or, as Stern and Halperin (SH) suggest, static phase fluctuations due to inhomogeneities in the 2D electron density [13]. In their picture, as d/ℓ is reduced toward the critical point, droplets of the excitonic phase appear in a background of a weakly coupled fluid. SH assume that the droplets are superfluids for counter-propagating currents in the two layers and conventional quantum Hall conductors for parallel currents. This assumption implies that Hall drag is quantized in the droplet regions. In contrast, the background fluid is taken to be a conventional non-QHE bilayer system with small conventional and longitudinal drag resistivities and no Hall drag. Neglecting the small longitudinal resistivities of both fluids, SH arrive at a semi-circle law for the drag resistivity components (in units of h/e^2) of the composite system:

$$\left(\rho_{xy,D} - \tfrac{1}{2}\right)^2 + (\rho_{xx,D})^2 = \tfrac{1}{4}. \quad (1)$$

In order to compare this formula [2] to the data in Fig. 2, we first convert the longitudinal drag resistance $R_{xx,D}$ into resistivity $\rho_{xx,D}$ by assuming a classical current distribution in the square sample. The open dots in Fig. 3 display the combination $\xi_0 \equiv \left(\rho_{xy,D} - \tfrac{1}{2}\right)^2 + (\rho_{xx,D})^2$ vs. d/ℓ as the transition region is traversed. Not surprisingly ξ_0 approaches $\tfrac{1}{4}$ both well above and well below the transition region: $\rho_{xy,D}$ is zero or 1 in these regions, respectively, while $\rho_{xx,D}$ is small in both. In the transition region itself, where $R_{xx,D}$ is large and $R_{xy,D} \sim h/2e^2$, ξ_0 falls well short of $\tfrac{1}{4}$, demonstrating that Eq. (1) is not obeyed. Stern and Halperin emphasize, however, that Eq. (1) is only valid in the limit of zero conventional longitudinal resistivity of

[2] Here we use a definition of $\rho_{xy,D}$ which is opposite in sign to that of Stern and Halperin [13].

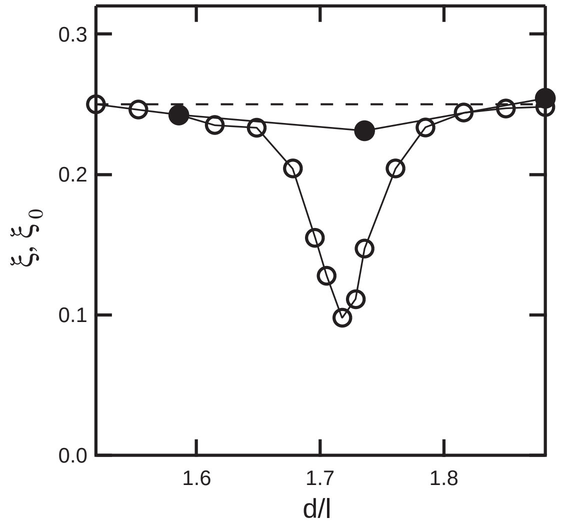

Fig. 3. Comparison between experiment and semi-circle laws of Stern and Halperin [13] at $T = 50$ mK. Open dots ignore correction due to conventional resistivity, solid dots include it to first order. See text for definition of the parameters ξ_0 and ξ.

the sample. SH offer a modified version of Eq. (1), valid to first order in the conventional resistivity, $\rho_{xx,\mathrm{S}}$, for equal currents in the two layers:

$$\left(\rho_{xy,\mathrm{D}} - \tfrac{1}{2}\right)^2 + \left(\rho_{xx,\mathrm{D}} + \tfrac{1}{2}\,\rho_{xx,\mathrm{S}}\right)^2 = \tfrac{1}{4}. \tag{2}$$

The solid dots in Fig. 3 represent the combination $\xi \equiv \left(\rho_{xy,\mathrm{D}} - \frac{1}{2}\right)^2 + \left(\rho_{xx,\mathrm{D}} + \frac{1}{2}\,\rho_{xx,\mathrm{S}}\right)^2$, evaluated at the three d/ℓ values for which sufficient data was available. Most importantly, the data point near $d/\ell \approx 1.74$ suggest that Eq. (2) is in much better agreement with experiment than Eq. (1). Clearly, more data are required to fairly assess the significance of this agreement.

We do not, however, believe that dynamic fluctuations can be ruled out on the basis of agreement with the semicircle law. Indeed, Simon et al. [14] have recently proposed a different view of the strong- to weak-coupling transition at $\nu_{\mathrm{tot}} = 1$. In their picture, which they support with detailed numerical exact diagonalization calculations, two interpenetrating fluids are present near the phase boundary. One fluid has the composite bosonic character of the $\nu_{\mathrm{tot}} = 1$ exciton condensate while the other has the composite fermionic character expected for two widely separate 2D layers, each at $\nu = \frac{1}{2}$. A smooth shifting of weight from one fluid to the other occurs as the phase boundary is traversed. Remarkably, the drag resistivity components in this spatially homogeneous two-fluid system still obey the semicirle laws given above.

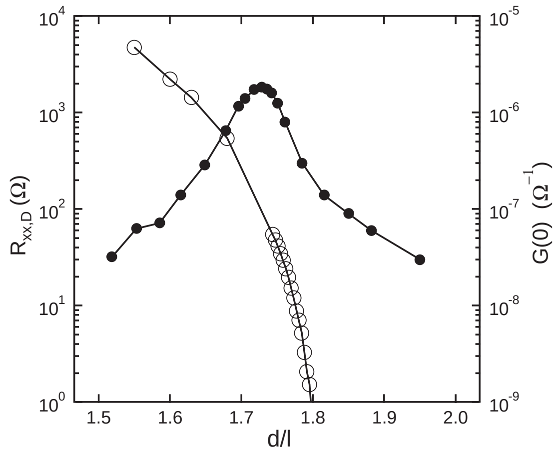

Fig. 4. Comparison of longitudinal drag resistance $R_{xx,\mathrm{D}}$ (solid dots) and zero-bias tunneling conductance $G(0)$ (open dots) at $T = 50$ mK in vicinity of phase boundary. Note that logarithmic vertical scale is the same for both parameters.

4. Tunneling vs. drag near the phase boundary

Fig. 4 compares, on a semi-logarithmic plot, the longitudinal drag $R_{xx,\mathrm{D}}$ and zero-bias tunneling conductance $G(0)$ at $\nu_{\mathrm{tot}} = 1$ and $T = 50$ mK in the vicinity of the phase boundary between the strong- and weak-coupling phases. The figure shows that the enhanced zero-bias tunneling conductance characteristic of the phase coherent excitonic state collapses very rapidly as the effective layer separation is increased beyond about $d/\ell \approx 1.75$. In contrast, the longitudinal drag resistance falls much more slowly. At $d/\ell = 1.9$, $G(0)$ has fallen more than 4 orders of magnitude from its highest observed value and is below the noise floor of the measurement. The longitudinal drag resistance, on the other hand, has fallen less than 2 orders of magnitude from its peak value and remains easily observable. More significantly, the fractional rate of collapse (e.g. $\mathrm{d}(\log(G(0))/\mathrm{d}(\log(d/\ell)))$ of the two effects at large d/ℓ is quite different.

The reason for the different rates at which the drag and tunneling signatures of the excitonic $\nu_{\mathrm{tot}} = 1$ phase collapse at large layer separation is not known. If the excitonic phase breaks up into a collection of puddles whose net area decreases rapidly as d/ℓ increases, the simplest model would suggest that both drag and tunneling would subside at comparable rates. On the other hand, the specificity of either probe to a particular electronic ground state is also unknown. With tunneling, the general assumption is that a strong and highly resonant enhancement of the zero-bias conductance is a strong indicator of spontaneous interlayer phase coherence [15–17]. By this measure, the data in Fig. 4 suggest that interlayer phase coherence disappears above $d/\ell \approx 1.8$ in this sample.

The quantization of Hall drag has been attributed to non-perturbative interlayer correlations, and specific predictions have been made for its value in different bilayer QHE states, including the present $\nu_{tot} = 1$ case [18–21]. However, when the Hall drag is merely non-zero, and possibly small, its significance is much less clear. [3] The situation is similarly uncertain for the longitudinal component of the drag resistance. Prior measurements [12] have shown a measurable longitudinal drag at $\nu_{tot} = 1$ and is observable even for very widely spaced layers ($d/\ell \approx 4$) where there is very little chance that any remnants of the excitonic phase survive. In those early measurements the longitudinal drag was non-zero and smoothly varying with filling factor. There was no evidence of an anomaly specific to $\nu_{tot} = 1$.

Using the present sample we have found that an anomaly specific to $\nu_{tot} = 1$ persists out to about $d/\ell \approx 2.6$. Fig. 5 shows the longitudinal drag vs. magnetic field at $T = 300$ mK at this large effective layer separation. Most of the features present in the figure, e.g. the fractional quantum Hall minima near $\nu_{tot} = \frac{2}{3} + \frac{2}{3}$ and $\frac{2}{5} + \frac{2}{5}$, and the smooth and slowly varying drag resistance between these filling factors, are very similar to those seen at much larger d/ℓ. Careful inspection, however, of the region around $B \approx 5.7$ T, which corresponds to $\nu_{tot} = 1$, shows a localized maximum. This maximum, which is not present at higher d/ℓ, grows continuously in magnitude relative to the background as the layer separation is decreased, and appears to smoothly extrapolate to the much larger longitudinal drag seen near the phase boundary. [4] The maximum is clearly a bilayer effect: It does not split into two peaks when a small density imbalance is imposed between the two layers. Such a splitting, which does occur in the minima at $\nu_{tot} = \frac{2}{3} + \frac{2}{3}$ and $\nu_{tot} = \frac{2}{5} + \frac{2}{5}$, would imply that the maximum is due to the coincidence of two independent $\nu = \frac{1}{2}$ single-layer features instead of a single $\nu_{tot} = 1$ effect.

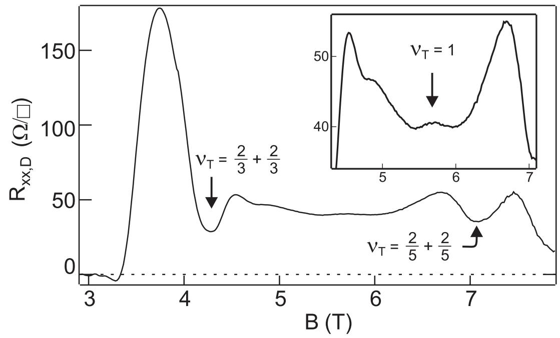

Fig. 5. Longitudinal Coulomb drag vs. magnetic field at $T = 300$ mK. Expanded view in the inset reveals a small peak at $\nu_{tot} = 1$. For these data $d/\ell = 2.6$ at $\nu_{tot} = 1$.

The smooth evolution of the longitudinal drag maximum at $\nu_{tot} = 1$ from a very weak feature at $d/\ell \approx 2.6$ to a very strong effect near the phase boundary (see footnote 4) suggests a common origin. Assuming that a true zero temperature quantum phase transition does indeed separate the strongly coupled excitonic phase from some weakly coupled phase, then the data in Fig. 4 point to a critical point around $(d/\ell)_c \sim 1.75$. If this is so, it is hard to understand how remnants of the excitonic phase could persist, at $T = 0$, out to $d/\ell = 2.6$. Inhomogeneities in the electron density, which surely exist at the few percent level, might broaden a drag maximum at $\nu_{tot} = 1$ but cannot explain its existence at such high *average* density. Variations in the thicknesses of the quantum wells and the barrier between them might be responsible, but it seems extremely unlikely that they could be severe enough to account for the magnitude of the effect.

Two interesting, if highly speculative, possibilities should be mentioned. First, noting that the data in

[3] Non-zero Hall drag can result, in principle, from energy dependent scattering rates. See [22].

[4] Note that the data in Fig. 5 were obtained at $T = 300$ mK while those in Fig. 2 were recorded at $T = 50$ mK. At 300 mK the peak in $R_{xx,D}$ vs. d/ℓ occurs near $d/\ell \approx 1.52$.

Fig. 5 were obtained at $T = 300$ mK, it seems possible that the $\nu_{tot} = 1$ drag maxima found for $d/\ell > 1.8$ are finite temperature effects and do not imply the presence of the excitonic phase in the $T \to 0$ limit. For $T > 0$ the free energy of the excitonic phase might be lower than that of the weakly coupled phase which is the actual zero temperature ground state. Experiments on the evolution of the $\nu_{tot} = 1$ drag maxima at large d/ℓ at temperatures below 300 mK should shed light on this possibility and are currently in progress.

A second possibility is that additional strongly coupled bilayer phases exist at intermediate layer separations between the excitonic QHE phase at small d/ℓ and the weakly coupled composite fermion liquids at high d/ℓ. Many possibilities exist, including BCS-like paired composite fermion states [23,24], bilayer Wigner crystals [25] and various other phases which may share some but not all of the properties of the excitonic phase (e.g. interlayer phase coherence but no quantized Hall effect, etc.) [26,27]. Whether such states would result in a drag anomaly like the one shown in Fig. 5 remains to be seen.

5. Conclusion

Recent tunneling and Coulomb drag studies of bilayer 2D electron systems at $\nu_{tot} = 1$ have provided very strong evidence that the ground state of the system at small layer separation is a novel quantum liquid with spontaneous interlayer phase coherence. These same measurements also offer indirect evidence that the system supports excitonic superfluidity, i.e. dissipationless flow of counter-propagating currents in the two layers. This paper has dealt largely with the way in which this example of an excitonic Bose condensate collapses as the effective layer separation d/ℓ is increased. Our findings suggest that interlayer phase coherence, as reflected in the zero-bias interlayer tunneling conductance, disappears rapidly above $d/\ell \approx 1.75$. In contrast, longitudinal Coulomb drag shows an anomaly at $\nu_{tot} = 1$ which persists to much larger layer separation. The origin of this difference remains unknown.

Acknowledgements

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