Interaction and disorder in bilayer counterflow transport at filling factor one

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We study high mobility, interacting GaAs bilayer hole systems exhibiting counterflow superfluid transport at total filling factor \( \nu = 1 \). As the density of the two layers is reduced, making the bilayer more interacting, the counterflow Hall resistivity \( (\rho_{xy}) \) decreases at a given temperature, while the counterflow longitudinal resistivity \( (\rho_{xx}) \), which is much larger than \( \rho_{xy} \), hardly depends on density. On the other hand, a small imbalance in the layer densities can result in significant changes in \( \rho_{xx} \) at \( \nu = 1 \), while \( \rho_{xy} \) remains vanishingly small. Our data suggest that the finite \( \rho_{xx} \) at \( \nu = 1 \) is a result of mobile vortices in the superfluid created by the ubiquitous disorder in this system.

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Interacting bilayer systems of two-dimensional carriers in the limit of zero tunnelling can exhibit superfluidity in a peculiar "counterflow" transport configuration, where currents of equal magnitude are passed in opposite directions in the two layers. This phenomenon occurs when the bilayer is subject to a perpendicular magnetic field \( (B) \) so that the total Landau level filling factor, \( \nu \), is 1 (layer filling factor 1/2) and the inter-layer interaction is sufficiently strong to stabilize a quantum Hall state (QHS). The physics of this QHS can be understood by pairing the particles in the lowest Landau level of one layer with the vacancies in the other layer, hence forming neutral objects (excitons) which condense at the lowest temperatures. A similar superfluid was predicted to occur in a closely spaced electron-hole bilayer at \( B = 0 \). Key experimental evidence for the particle-vacancy pair formation at \( \nu = 1 \), and the ensuing condensation, has been provided so far by two types of experiments. Inter-layer tunnelling measurements have shown a much enhanced tunnelling conductivity in the \( \nu = 1 \) QHS, a behavior reminiscent of a Josephson junction’s. Most recently, counterflow transport measurements have revealed that both the longitudinal \( (\rho_{xx}) \) and Hall \( (\rho_{xy}) \) resistivities vanish in the \( \nu = 1 \) QHS in the limit of zero temperature \( (T \rightarrow 0) \). The vanishing of \( \rho_{xx} \) is especially important since it directly demonstrates that the counterflow current is carried by neutral particles, that is, particle-vacancy pairs which have zero electrical charge and therefore experience no Lorentz force.

An outstanding puzzle is what causes the dissipation in the currently available samples and why experimentally there is no finite critical temperature below which the counterflow dissipation vanishes as the theory predicts. Here we study the counterflow transport in strongly interacting, high mobility GaAs hole bilayers as a function of total density \( (p) \) as well as layer density imbalance. Our data show that, at a given temperature, the \( \nu = 1 \) QHS counterflow \( \rho_{xy} \) decreases when \( p \) is reduced to increase the inter-layer interaction. But the counterflow \( \rho_{xx} \), which is always much larger than \( \rho_{xy} \), barely depends on density. Furthermore, small changes in the layer densities can substantially change the counterflow \( \rho_{xx} \), while \( \rho_{xy} \) remains vanishingly small. The vanishing \( \rho_{xy} \) at low temperatures demonstrates that inter-layer interaction is responsible for the particle-vacancy pairing. The counterflow dissipation, signaled by the finite \( \rho_{xx} \) at finite temperature, has been attributed to the existence of disorder-induced mobile vortices which move across the superfluid current, much like in superfluid helium. Our observed dependences of counterflow \( \rho_{xx} \) on total density and layer density imbalance are consistent with this picture.

Our sample is a Si-modulation-doped GaAs double-layer hole system grown on a GaAs (311)A substrate. It consists of two, 15nm wide, GaAs quantum wells separated by an 8nm wide AlAs barrier. The top and bottom barriers are Al\(_{0.2}\)Ga\(_{0.8}\)As layers. We used a Hall bar geometry of 100\(\mu\)m width, aligned along the [011] crystal direction. The Hall bar mesa has two current leads at each end, and three leads for measuring the longitudinal and Hall voltages across the bar. Diffused InZn Ohmic contacts are placed at the end of each lead. We use a combination of front and back gates to selectively deplete one of the layers near each contact, in order to realize independent contacts to each layer. As grown, the densities were \( p_T = 3.1 \times 10^{10} \) cm\(^{-2} \) and \( p_B = 3.8 \times 10^{10} \) cm\(^{-2} \) for the top and bottom layers, respectively. The mobility along [011] at these densities is approximately 32 m\(^2\)/Vs. Top and bottom gates were added on the active area to control the layer densities. The measurements were performed down to \( T = 30 \) mK, and using low-current (0.5nA-1nA), low-frequency lock-in techniques.

In our counterflow measurements, two leads contacting opposite layers at one end of the Hall bar are used to drive a current in and out of the sample, while the leads at the other end are shorted so that the same current, but in opposite directions, flows in both layers. We define the resistances in the counterflow configuration as the corresponding voltage drops along or across the Hall bar measured in one single layer, the bottom layer in our case, divided by the current flowing in each layer.

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The longitudinal resistivity $\rho_{xx}$ is the measured longitudinal resistance divided by two, the number of squares between the voltage probes in our sample, while the Hall resistivity $\rho_{xy}$ is simply the Hall resistance. These resistivities revert to those of a single layer when the coupling between the two layers is negligible. In our counterflow measurements a small fraction of the current injected in one layer leaks unintentionally into the opposite layer. The leakage current at $\nu = 1$ is about 1% of the total current at 30mK and increases with $T$ to 15% at 700mK; this behavior suggests that the leakage is determined by factors (e.g. defects in the AlAs barrier) other than the enhanced inter-layer tunnelling at $\nu = 1$ [5]. The leakage translates in a slightly lower counterflow current, resulting in a small error in $\rho_{xx}$ and $\rho_{xy}$. We emphasize that none of our conclusions are affected by such errors.

The phase-space of the $\nu = 1$ QHS is parametrized by the ratio $d/l_B$, of the mean inter-layer spacing ($d$) and the magnetic length ($l_B = \sqrt{\hbar/eB}$) at $\nu = 1$. This parameter quantifies the ratio between the intra- and inter-layer interaction: when $d/l_B \gg 1$ the latter is negligible and the physics of the bilayer is essentially that of two independent layers, while for $d/l_B \approx 1$ the inter-layer interaction is sufficiently strong to give rise to collective bilayer phenomena such as the $\nu = 1$ QHS [12]. Exploring this desired regime of small values of $d/l_B$ poses experimental challenges. Small $d$ and/or large $l_B$, hence low densities, are needed to reduce $d/l_B$. Reducing $d$, however, increases the single particle inter-layer tunnelling, which impedes the fabrication of independent contacts and also can reduce the bilayer physics to that of a single layer. From this perspective, GaAs holes are desirable for exploring interacting bilayer phenomena: owing to their relatively large effective mass, the inter-layer barrier thickness can be reduced without substantially increasing the tunnelling, hence placing the hole bilayers in a very strong interacting regime with small tunnelling [13]. Indeed the data presented here correspond to the smallest $d/l_B$ at $\nu = 1$ yet reported for samples with independent contacts, also evinced by the fully developed $\nu = 1$ and vanishingly small counterflow $\rho_{xy}$ at relatively high temperatures.

In Fig. 1 we present the counterflow $\rho_{xx}$ and $\rho_{xy}$ data when the two layers have equal densities (balanced). The different $d/l_B$ indicated in the figure (1.24 to 1.42) correspond to different $p$ (4.5 to 6.1 $\times 10^{10}$ cm$^{-2}$). Data of Fig. 1(a,b) show $\rho_{xx}$ and $\rho_{xy}$ vs $1/\nu$, measured at $T = 600$ mK, illustrating that $\rho_{xx} \gg \rho_{xy}$ at this temperature for all values of $d/l_B$ explored here. The data of Fig. 1(b) further reveal that $\rho_{xy}$ at $\nu = 1$ decreases when $d/l_B$ is reduced. For example, as shown in Fig. 1(b), at $T = 600$ mK $\rho_{xy}$ at $\nu = 1$ drops by more than a factor of 4 when $d/l_B$ is reduced from 1.42 to 1.24. This observation demonstrates that the inter-layer interaction is responsible for the particle-vacancy pairing, signaled by the vanishing counterflow $\rho_{xy}$ [14]. Remarkably, the same change in $d/l_B$ induces a much smaller change ($\approx 30\%$) in counterflow $\rho_{xx}$ at $\nu = 1$, as shown in Fig. 1(a).

Figure 1(c) summarizes the counterflow $\rho_{xx}$ and $\rho_{xy}$ data at $\nu = 1$ vs $T^{-1}$, for various values of $d/l_B$. These data further demonstrate that, in contrast to $\rho_{xx}$, the counterflow $\rho_{xy}$ is much less dependent on $d/l_B$ at any temperature. Fitting an exponential dependence $\rho_{xy} \propto \exp(-\Delta_H/2T)$ to the data of Fig. 1(c) yields a Hall energy gap $\Delta_H$ which increases from 6.8K to 9.2K, as $d/l_B$ is reduced from 1.42 to 1.24. The gap extracted by fitting $\rho_{xx} \propto \exp(-\Delta/2T)$ to the $\rho_{xx}$ data is $\Delta \approx 2K$, almost independent of $d/l_B$. This finding is very revealing: unlike the pairing, which becomes stronger when the bilayer is made more interacting (smaller $d/l_B$), the dissipation is barely dependent on the inter-layer interaction in our sample. We will discuss this observation in our closing paragraph.

In view of the large counterflow $\rho_{xx}$ and $\rho_{xy}$ anisotropy at $\nu = 1$, it is useful to examine the role of the mobility anisotropy in our sample. Our measurements show

![FIG. 1: (a) $\rho_{xx}$ and (b) $\rho_{xy}$ counterflow resistivities vs $1/\nu$ for different values of $d/l_B$, corresponding to different total bilayer densities. (c) Counterflow $\rho_{xx}$ (hollow symbols) and $\rho_{xy}$ (filled symbols) at $\nu = 1$ vs $T^{-1}$ for different $d/l_B$. The data of all panels were taken when the two layers have equal densities. Inset in (b) illustrates the geometry for counterflow measurements.]}
that the Hall drag remains close to the quantized value of $h/e^2$ as $T$ is increased, and hardly depends on the crystal direction along which the current flows. The close quantization of the Hall drag at higher $T$ is consistent with a small counterflow $\rho_{xy}$ and suggests that the counterflow $\rho_{xy}$ does not depend on the crystal direction. On the other hand, our bilayer measurements on samples without independent contacts (parallel flow) show that $\rho_{xx}$ at $\nu = 1$ is about 2.5 times larger for current oriented along the low mobility direction, and exhibits activated $T$ dependence with an energy gap that is independent of the current direction. These findings suggest that, while $\rho_{xx}$ along the low mobility direction, and exhibits activated dependence with an energy gap that is independent of the current direction. These findings suggest that, while $\rho_{xx}$ at $\nu = 1$ may be partially enhanced by the mobility anisotropy in our samples, the latter is not the main factor behind the observed counterflow anisotropy and the strong pairing.

Two noteworthy aspects of Fig. 1 data are (1) the large difference between the counterflow $\rho_{xx}$ and $\rho_{xy}$, and (2) the absence of a finite temperature below which the counterflow transport is dissipationless. These can both be understood by considering the motion of unpaired, mobile vortices in the superfluid flow. Vortices in a superfluid are subject to a Magnus force, perpendicular to the direction of the superfluid current, which causes them to move across the superflow. The unpaired vortex motion results in phase slip and implicitly, dissipation, hence the finite values of $\rho_{xx}$ while $\rho_{xy}$ remains close to 0. In the case of the $\nu = 1$ QHS counterflow superfluid the picture is slightly complicated because the vortices possess electrical charge and dipole moment, but the conclusions of the above argument remain valid. Theoretical studies have further shown that the source of unpaired vortices in the $\nu = 1$ superfluid is disorder. The experimentally observed absence of a critical temperature below which the superfluid is dissipationless suggests that mobile vortices are present at any finite $T$ in our sample. As the temperature is lowered the vortices become pinned by disorder, form a vortex glass, and lead to dissipationless flow only in the $T = 0$ limit. We emphasize, however, that a quantitative understanding of the role of disorder, vortex formation, and pinning in $\nu = 1$ counterflow superfluid is currently lacking.

It is instructive to compare our data with similar counterflow measurements reported for GaAs electron bilayer systems. In Ref. the $T$ dependence of $\rho_{xx}$ and $\rho_{xy}$ at $d/B = 1.48$ was measured in the range of 30-500mK and, in contrast to our GaAs hole data, little difference was reported between counterflow $\rho_{xx}$ and $\rho_{xy}$ in this $T$ range. On the other hand, in Ref. the counterflow $\rho_{xy}$ is reported to be much smaller than $\rho_{xx}$ at 40mK for a bilayer electron system with a relatively large $d/B = 1.57$, qualitatively consistent with our hole data. While we cannot explain these similarities and differences, we mention three distinguishing factors of holes, besides their mobility anisotropy. First, the larger cyclotron effective mass of GaAs holes vs electrons causes more Landau level mixing; whether this leads to a stronger pairing is not clear. Second, there is less inter-layer tunnelling in the hole system. Third, it is possible that the holes are more fully spin polarized at $\nu = 1$ thereby increasing the strength of the $\nu = 1$ QHS.

It is interesting to examine the counterflow $\rho_{xy}$ data at $\nu = 1$ on a linear scale and down to the lowest $T$, as shown in Fig. 2. For all $d/B$, the counterflow $\rho_{xy}$ remains small up to a certain temperature at which it starts to increase relatively sharply. As apparent from Fig. 2, this onset increases as $d/B$ is reduced. In Fig. 2 inset we show an empirical scaling of the $\rho_{xy}$ data at different values of $d/B$. When the counterflow $\rho_{xy}$ is plotted vs $T \cdot B_{c=1}$, where $B_{c=1}$ is the magnetic field at $\nu = 1$, the data points collapse onto a single curve. Although the decrease of $\rho_{xy}$ with decreasing $d/B$ and the resulting stronger pairing is expected, the origin of such simple scaling is unclear. When extrapolated to large values of $d/B$ the scaling shown of Fig. 2 must break down, since it does not predict a critical $d/B$ for the disappearance of the $\nu = 1$ QHS. Experimentally such critical $d/B$ exists and in GaAs hole bilayers with negligible tunnelling is between 1.6 and 1.9.

We now turn to a study of counterflow transport at $\nu = 1$ as a function of layer density imbalance. Using the top and bottom gates on the active area, we keep $p$ constant while transferring charge from one layer to another. We define the layer density imbalance as $\Delta p = (p_B - p_T)/2$, and measure the counterflow resistivities of the bottom layer. Depending on the sign of $\Delta p$, the latter is either the majority density layer ($\Delta p > 0$), or the minority layer ($\Delta p < 0$). In Fig. 3(a,b) we show examples of counterflow $\rho_{xx}$ and $\rho_{xy}$ vs $B$ traces, measured at $T = 345$mK for different values of $\Delta p$, at constant $p = 5.45 \times 10^{10}$ cm$^{-2}$ corresponding to $d/B = 1.35$. The data of Fig. 3(a) clearly demonstrate that $\rho_{xx}$ at $\nu = 1$ and therefore the dissipation, can be greatly changed by a small layer density imbalance: a $\Delta p/p$ of $\approx 5\%$ changes the counterflow $\rho_{xx}$ by more than one order of magnitude.

A similar dependence of individual layer $\rho_{xx}$ with density imbalance was recently reported in GaAs electron bilay-
ers\cite{16}. More importantly, Fig. 3(b) further reveal that the counterflow \( \rho_{xy} \) at \( \nu = 1 \) remains vanishingly small at this \( T \) for all values of \( \Delta p \). The data of Fig. 3(a,b) illustrate that the dissipation in counterflow transport at \( \nu = 1 \) dramatically changes when the layers are imbalanced while the particle-vacancy pairing remains strong, as evinced by the vanishing counterflow \( \rho_{xy} \) at \( \nu = 1 \). In Fig. 3(c) we summarize our counterflow \( \rho_{xx} \) and \( \rho_{xy} \) vs \( T^{-1} \) at different values of \( \Delta p \), taken at different values of \( \Delta p \) and at constant \( p = 5.45 \times 10^{10} \text{ cm}^{-2} \). The data substantiate the findings of Fig. 3(a,b), namely that the counterflow \( \rho_{xx} \) is very sensitive to layer density imbalance, while the counterflow \( \rho_{xy} \) is not.

Why does a rather small change in layer density distribution so dramatically change the counterflow \( \rho_{xx} \) at \( \nu = 1 \), while \( \rho_{xy} \) remains vanishingly small? It is unlikely that this behavior results from the small changes in the intra-layer interaction energies of the two layers. Disorder, on the other hand, can be the culprit. When \( \Delta p < 0 \), the (bottom) layer, which we probe, has a smaller density than in the balanced case and is thus more prone to disorder since, e.g., the screening of the ionized impurity potential is less effective. It is therefore not surprising that its \( \rho_{xx} \) at \( \nu = 1 \) is larger than in the balanced case. The converse is true when \( \Delta p > 0 \). The data of Fig. 3 also provide a natural clue for understanding the results of Fig. 1. Lowering the density and therefore \( d/l_B \) in the balanced case has two consequences which influence \( \rho_{xx} \) in opposite directions. First, it strengthens the inter-layer interaction and leads to a lowering of \( \rho_{xy} \), as observed. Theoretically, we would also expect a reduction in \( \rho_{xx} \) with decreasing \( d/l_B \). But a second consequence of lowering the density is to enhance the effective disorder in the bilayer system and thus increase \( \rho_{xx} \). We believe these two, compensating effects are responsible for \( \rho_{xx} \) in Fig. 1 being essentially independent of \( d/l_B \) while \( \rho_{xy} \) significantly decreases with decreasing \( d/l_B \). The combination of the data of Figs. 1 and 3 therefore suggests that the sample disorder, and the ensuing mobile vortices\cite{3,4,15}, are the likely culprits for the finite counterflow dissipation in our samples.

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