Exciton condensate at a total filling factor of 1 in Corbino 2D electron bilayers

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Magneto-transport and drag measurements on a quasi-Corbino 2D electron bilayer at the systems total filling factor 1 (νT = 1) reveal a drag voltage that is equal in magnitude to the drive voltage as soon as the two layers begin to form the expected νT = 1 exciton condensate. The identity of both voltages remains present even at elevated temperatures of 0.25 K. The conductance of the drive layer vanishes only in the limit of strong coupling between the two layers and at T → 0 K which suggests the presence of an excitonic circular current.

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When two closely spaced two-dimensional electron systems (electron bilayer) are exposed to a perpendicular magnetic field B so that each layer has a filling factor close to 1/2 and the relative distance between interlayer electrons, parameterized by the ratio d/lB (d: layer separation, lB = √ℏ/eB = 1/√2πνT: magnetic length with νT as the total density), is sufficiently small, a new quantum Hall (QH) state characterized by the total filling factor ν = 1 QH effect. Due to the absence of sample edges the single layer current flow shows nearly no trace of the edge channels [6, 7]. However, in the case of the νT = 1 and its associated superfluid transport mode, it cannot be ruled out from the Hall bar data that a dissipationless quasi-particle current at the sample edges is responsible for the observed effects [5].

In this paper, we report on interlayer drag measurements on a quasi-Corbino electron bilayer with independent contacts to both layers. An ideal Corbino structure allows direct measurement of the conductivity σxx in contrast to the common Hall bar geometry where the resistivities are measured. We observe that at νT = 1 a voltage develops in the drag layer that equals in sign and magnitude the voltage across the drive layer. We find that the identity of the drag and drive voltages is maintained up to high temperatures or large d/lB where the single layer current flow shows nearly no trace of the νT = 1 QH effect. Due to the absence of sample edges connecting source and drain contacts in a ring, the current is driven selectively through the bulk of the ψ = 1 system. At low temperatures, drive and drag voltage remain identical and the drive current nearly vanishes. The Corbino experiments thus open a new venue to explore the bulk property of the νT = 1 system.

Our two-dimensional (2D) electron bilayer is confined in two 19-nm GaAs quantum wells, separated by a 9.9 nm superlattice barrier composed of alternating layers of AlAs (1.70 nm) and GaAs (0.28 nm). Each quantum well has an intrinsic electron density of about 4.3 × 10^14 m^-2 and a low-temperature mobility of 67 (45) m^2/Vs for the upper (lower) quantum well (measured on a Hall bar fabricated from the same wafer). Since the ideal Corbino geometry is not compatible with the selective-depletion technique [3, 10] for independently contacting each layer, we instead employ a quasi-Corbino geometry with four contact arms attached to each ring as depicted in Fig. 1. The back gates were patterned ex situ from a Si-doped GaAs epitaxial layer before growing an insulating GaAs/AlGaAs superlattice and the bilayer on top. Elec-
trical isolation between the two layers is achieved by applying appropriate negative voltages to the buried back gates and metallic front gates crossing the contact arms. One set of contacts can then be used to pass a current and another one to measure the voltage across the ring. The densities in each layer can be adjusted independently by using another set of front and back gates (not shown) covering the active region of the Corbino ring including the ring edges.

Below we present data from two samples from the same wafer which show essentially the same behavior. Sample A consists of a quasi-Corbino ring with an outer diameter of \( d_O = 600 \mu \text{m} \) and a ring width of \( w = 140 \mu \text{m} \), while sample B is characterized by \( d_O = 780 \mu \text{m} \) and \( w = 230 \mu \text{m} \). For all samples interlayer tunneling is small; the interlayer resistance (at zero magnetic field and 0.25 K) is of the order \( 10^7 - 10^9 \Omega \). Transport measurements were performed by using a standard lock-in technique with the sample mounted at the cold finger of a dilution refrigerator or a \(^3\text{He} \) system. For all measurements the electron densities in the two layers were adjusted to be equal. A small excitation voltage \( V_{\text{exc}} \) (60-65 \( \mu \text{V} \), 3-5 Hz \[19\]) was applied radially across one layer (the drive layer) through an isolation transformer and the induced current through this layer was measured with a small resistance connected in series. We would like to stress that the total current has a radial and an azimuthal part. These two parts oscillate anti-cyclically as a function of the magnetic field, i.e. in a QH state the radial fraction is zero while the azimuthal (circular) part is maximal. Hence, the (radial) voltage dropping over the drive layer changes in response to the radial current as well. For that reason, the voltage across the drive layer was monitored using a separate pair of contacts in a quasi four-terminal geometry together with the induced voltage in the drag layer. This excludes also the effects of the finite resistances of the ohmic contacts and the contact arms. The measurements were reproducible upon interchanging contacts and upon interchanging drive and drag layer.

We start by showing data at lowest temperatures. Fig. 2 presents data at \( T_{\text{bath}} = 15 \text{ mK} \) on sample B. The (integer) filling factors \( \nu \leq 2 \) and \( \nu_T = 1 \) (\( d/l_B=1.62 \)) are labeled. Bottom panel: Measured current in the drive layer. The inset plots the temperature dependence of the radial conductance \( G \); the line is a fit using \( G \propto \text{exp}(-E_{\text{gap}}/T) \).
the existence of an azimuthal (i.e. circling) current in the drive layer, in analogy to the ordinary QH states. Owing to the excitonic coupling it would trigger an azimuthal current of the same magnitude in the drag layer, leading to identical voltages across both layers. However, we neither know the nature of this excitonic current nor where it flows. It could be homogeneously distributed throughout the bulk or rather concentrated at the sample edges. Nevertheless, the well-established model of electron-hole pairing around v_T = 1 implies that such a transport mode in Corbino bilayers might be possible. Supported is that notion by the fact that the ohmic contacts of the drag layer in our geometry are located at the opposite side of the ring, i.e. approximately 1 mm away from the ohmic contacts of the drive layer. In previous drag experiments using a standard Hall bar geometry, identical Hall voltages in the drag and drive layers were also considered to be signaling the underlying excitonic superfluidity.

The origin of identical voltages could equivalently be attributed to the special nature of the excitonic state. Since an excitonic (quasi-particle) wave function would have to exist across the barrier, quasi-particle transfer between the layers would become possible as soon as the system reaches a total filling factor of 1. While standard tunneling spectroscopy experiments performed on very similar electron bilayer samples indeed indicate that tunneling becomes resonantly enhanced in the vicinity of v_T = 1, identical voltages could only be explained if the interlayer resistance became insignificantly small compared to the bulk resistance. This, however, is inconsistent with tunneling experiments on common electron bilayer samples, showing resistances within the MΩ range instead.

Fig. 3 plots data taken at a temperature of T = 0.25 K on sample A. The densities in both layers are still equal but reduced to a total electron density of approximately 4.2 × 10^{14} m^{-2}. Now v_T = 1 occurs at B\text{=}1.76 T which corresponds to d/l_B = 1.49. At 0.25 K the minimum in the current has almost entirely disappeared (bottom panel). Nonetheless, there is still a sizeable peak in the drive voltage at v_T = 1 (solid line in the top panel). Surprisingly, the voltage over the drag layer (dash-dot line) also displays a peak with the same amplitude. This striking observation of a nearly doubled dissipation in the drive layer accompanied by an identical drag voltage can be interpreted as evidence that both layers are in a state of commencing interlayer correlation. A previous report on drag experiments on Hall bar bilayers has shown that identical voltages, i.e. the quantization of the Hall resistance to \( \hbar/e^2 \), are only observable at lowest temperatures and low d/l_B ratios when the v_T = 1 QH state is fully developed. While this is in direct contrast to our data and might indicate a geometry-dependence, the resilience of the v_T = 1 QH state to increasing temperatures yet is a behavior reminiscent of results obtained on bilayer 2-dimensional hole gas samples in counterflow configuration. We cannot offer any explanation for these similarities, however, it might simply be owing to the reported interlayer leakage or the larger effective mass of the holes.

We find that the ratio of both voltages remains \( 1 \) until d/l_B approaches a critical limit. We have traced the drag and drive voltages for a number of different (but matched) total densities at 0.25 K. The results are summarized in Fig. 4 which plots drag and drive voltage at v_T=1 versus d/l_B. At 0.25 K, the identity of both drag and drive voltages can be tracked up to a d/l_B ratio of about 1.65 where the v_T = 1 QH state is collapsing owing to thermal fluctuations. For d/l_B > 1.65 small peaks of different amplitude can be observed as illustrated in the inset.

At some finite temperature, the collapse of the excitonic condensate at v_T = 1 in the bilayer can be observed. For sample B and temperatures below 0.25 K, the conductance G\text{=}I/V is well described by thermal activation, i.e. G ∝ \exp(-E_{gap}/T), with an activation energy gap of approximately 0.5 K as shown in the inset of Fig 2. The magnitude of the extracted energy gap is in good agreement with earlier reports on comparable double quantum
field sweep for the last pair of points at filling factor 1 diverge. The inset shows the corresponding B_d/l dependence of the longitudinal resistance in Hall bars.

Well structures [2, 15, 16, 17], where the activation energy was extracted from measurements of the temperature dependence of the longitudinal resistance in Hall bars. In a theoretical Letter, Stern and Halperin [18] suggested that the electron bilayer system at high d/l_B ratios is composed of puddles of strong interlayer correlation incorporated in the compressible fluids of the individual layers. Their model, albeit addressing specifically Hall bar geometries, appears to be connected with our observations as well. As long as these puddles are small in number and/or unrelated, a sizeable current could flow through the bulk between source and drain contacts. As d/l_B is decreased their number and/or size will increase until they eventually percolate, while the current through the bulk slowly diminishes. The smooth transition we observe in Corbino samples from a compressible to a nearly fully incompressible state upon decreasing the temperature and/or the parameter d/l_B appears to signify such a percolation.

In conclusion, we have conducted interlayer drag experiments on quasi-Corbino electron bilayers. At the lowest temperature and strong coupling, the ratio of drag and drive voltages is 1 while the conductance in the drive layer vanishes. These data imply a circular potential distribution along the sample edges owing to a circling (azimuthal) excitonic current in both layers. At elevated temperatures, the identity of both voltages is still present.

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