Activated Transport in the Separate Layers that Form the $\nu_T = 1$ Exciton Condensate

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We observe the total filling factor $\nu_T = 1$ quantum Hall state in a bilayer two-dimensional electron system with virtually no tunneling. We find thermally activated transport in the balanced system with a monotonic increase of the activation energy with decreasing d/ℓ_B below 1.65. In the imbalanced system we find activated transport in each of the layers separately, yet the activation energies show a striking asymmetry around the balance point, implying a different excitation spectrum for the separate layers forming the condensed state.

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The Bose-Einstein condensate (BEC) is an ordered state of a many particle system with properties which no longer depend upon the many individual wave functions but rather upon a single macroscopic one. Presently known BECs include superconductors, the two Helium isotopes and rarefied atomic vapors. Excitons, consisting of a hole in the valence band bound to an electron in the conduction band in a semiconductor, have long been suspected of forming a BEC as well [1], but, initially, the short lifetimes and the intrinsic self-heating of optically generated excitons prevented condensation. More recently, optically generated indirect excitons displayed peculiar ring-shaped luminescence [2]. The low temperature fragmentation of these rings has been attributed to collective behavior [3], yet coherence among the excitons remains to be demonstrated.

Indirect excitons can be produced in spatially separated quantum wells where they have infinite lifetimes so that they can be cooled down to low temperatures. Recently, it has been shown that a BEC most likely exists in double quantum wells (DQW) where each of the two wells contains a two-dimensional electron gas (2DEG) at a half-filled Landau level in the appropriate magnetic field [4]. In this system, the excitons are formed by the pairing of empty and filled electron states in the conduction band in the two layers. Tunneling experiments [5] revealed a huge zero-bias conduction peak that is orders of magnitude larger than the one at zero magnetic field, indicating coherence between the layers. In drag experiments, where current is passed through one of the layers (''drive'' layer) and the induced voltage drop in the other (''drag'') layer is measured, the other signatures of the new state can be seen: an activation gap in the longitudinal resistance and a quantized Hall drag, which is identical to the Hall voltage of the current carrying layer [6]. As a consequence, when identical but counter-flowing currents are passed through the two layers a dramatic vanishing of both the longitudinal and the Hall resistance is observed [7]. More recently, similar phenomena have also been observed in coupled 2D hole gases [8].

The requirement for observing this novel superfluid state is the ratio of the interlayer Coulomb interactions (parameterized by the distance (d) between the 2DEGs) and the intralayer Coulomb interactions (parameterized by the magnetic length ($\ell_B \equiv \sqrt{\hbar/eB} = 1/\sqrt{2\pi n_T}$) at the half-filled Landau levels) being below a critical value of ≈ 1.8 [6,9]. Here B is the magnetic field and n_T the total electron density of the bilayer. $d/\ell_B < 1.8$ requires DQWs containing two 2DEGs with respective densities of about $3.0 \times 10^{14}\ \mathrm{m}^{-2}$ separated by barriers of 5 to 20 nm thickness. Mobilities exceeding $40\ \mathrm{m}^2/\mathrm{V\,s}$ at these densities are required to prevent electrons from becoming localized before the required magnetic field is reached.

In this Letter we reveal unexpected properties of the novel superfluid condensed exciton state. We study electric transport in the condensed phase, find a thermally activated behavior, and determine the dependence of the activation energy on the coupling parameter d/ℓ_B. Strikingly, upon producing a symmetric density imbalance at a constant total filling factor of 1 ($\nu_T = 1$), we observe a huge asymmetry of the activated transport in each of the layers showing that the measured activation energy does not reflect the condensation energy of the superfluid $\nu_T = 1$ state. Our data additionally demonstrate that care has to be taken when interpreting data measured with both layers in parallel [10,11].

Our DQWs consist of two 17 nm GaAs quantum wells separated by a superlattice of 12.4 nm total thickness made up of alternating four monolayers (ML) AlAs (1.13 nm) and 1 ML GaAs (0.28 nm). The electrons originate from

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bulk doping with Si that is placed 300 nm below and 280 nm above the wells, respectively. The two 2DEGs have intrinsic densities (n_U, n_L) of $\sim 4.0 \times 10^{14}\ \mathrm{m}^{-2}$ in both the upper and the lower layer and mobilities of $70\ \mathrm{m}^2/\mathrm{V\,s}$. Eight Ohmic contacts were made to the upper 2DEG and six to the lower 2DEG using metallic front gates [12] and buried back gates [13] for contact separation. The densities in the layers can be adjusted independently by another front gate and back gate atop and below the Hall bar that has a width of 80 μm and a length of 900 μm. Interlayer leakage is negligibly small: at 50 mK and in zero magnetic field, the interlayer resistance is several GΩ and the dI/dV shows no resonant tunneling peak within the noise level $(0.5 \times 10^{-9}\ \Omega^{-1})$. From the observed zero-bias tunneling peak at $\nu_T = 1$ (the dI/dV is about $9.0 \times 10^{-8}\ \Omega^{-1}$ with a width of 10 μV), we deduce that tunneling is at least 50 times smaller than in previous experiments [5]. Transport measurements were done in a dilution refrigerator at temperatures down to 35 mK. ac currents of 0.1–0.5 nA at 1.2 to 6 Hz were used to measure the longitudinal and Hall resistances. The independent contacts to the layers additionally allowed measurements of the drag, i.e., the voltage in the drag layer divided by the current in the drive layer. The linearity of the measurements was tested under all measurement conditions and no significant deviations were found up to $\sim$1.0 nA.

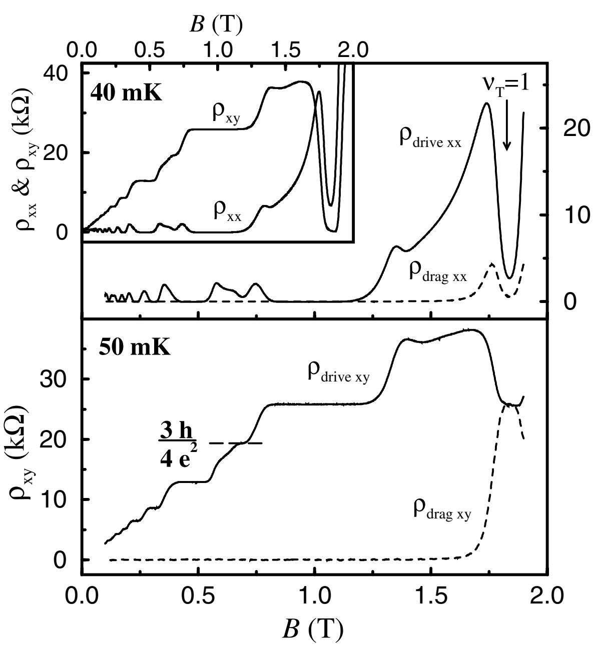

FIG. 1. (top) $\rho_{\mathrm{drive},xx}$ and $\rho_{\mathrm{drag},xx}$ and (bottom) $\rho_{\mathrm{drive},xy}$ and $\rho_{\mathrm{drag},xy}$ vs magnetic field at 50 mK and matched densities ($n_U = n_L = 2.22 \times 10^{14}\ \mathrm{m}^{-2}$ corresponding to $d/\ell_B = 1.57$). At $\nu_T = 1$ both longitudinal components tend to zero, while both Hall components tend to h/e^2. The inset plots the counterflow experiment; ρ_{xx} and ρ_{xy} both tend to zero.

Data taken with a density in each layer of $2.22 \times 10^{14}\ \mathrm{m}^{-2}$ are shown in Fig. 1 that plots longitudinal $(\rho_{\mathrm{drive},xx})$ and Hall $(\rho_{\mathrm{drive},xy})$ resistances of the layer to which the current is applied, as a function of magnetic field. At $\nu_T = 1$, $\rho_{\mathrm{drive},xx}$ shows a pronounced minimum while $\rho_{\mathrm{drive},xy}$ drops to approximately 25.8 kΩ (h/e^2). Away from $\nu_T = 1$, the traces show Shubnikov-de Haas oscillations of a single layer. At temperatures above $\sim$250 mK, the minimum in $\rho_{\mathrm{drive},xx}$ and the quantization of $\rho_{\mathrm{drive},xy}$ have disappeared. Also shown are the longitudinal drag $(\rho_{\mathrm{drag},xx})$ and the Hall drag $(\rho_{\mathrm{drag},xy})$. In the vicinity of $\nu_T = 1$ both components of the drag increase by orders of magnitude, showing that interlayer correlations become very large. Note that although a current is applied to one of the layers only, because of reciprocity the ρ_{xx} measured on this layer also contains the (non-negligible) contribution arising from the *interlayer* scattering that produces the drag. Nonetheless, the term "separate layer" is used, since the current can still be applied to either one of the layers. The approximate quantization h/e^2 in $\rho_{\mathrm{drag},xy}$ indicates the formation of the superfluid exciton condensate. This is verified by sending equal but counter-flowing currents through each of the layers simultaneously. Indeed as recently observed [7,8], both the longitudinal and the Hall voltages in the layers tend to zero at the lowest experimental temperatures (inset of Fig. 1).

We now turn to the temperature dependence of the longitudinal resistance at $\nu_T = 1$. The inset of Fig. 2 plots $\rho_{\mathrm{drive},xx}$ of the lower layer vs the inverse temperature for a series of different d/ℓ_B values, obtained by adjusting both

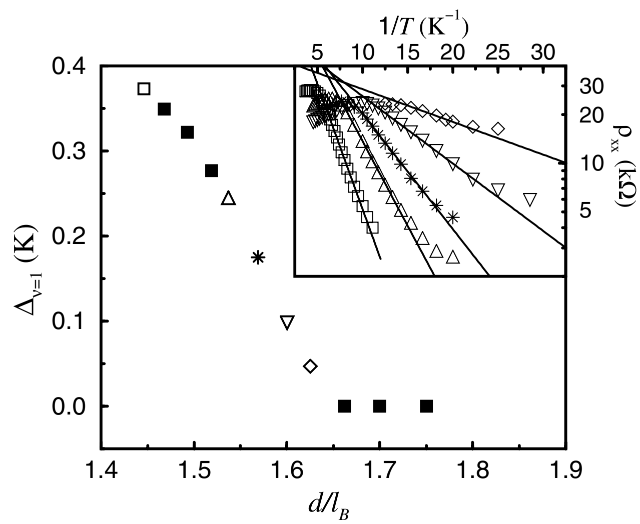

FIG. 2. Activation energies of the $\nu_T = 1$ state obtained from $\rho_{\mathrm{drive},xx}$ with balanced layer densities for various d/ℓ_B. The inset shows Arrhenius plots of some of the data with corresponding symbols in the main panel; lines are fits to $\rho_{xx} \propto \exp(-\Delta_{\nu=1}/k_B T)$.

the front gate and back gate. In all cases one can distinguish between three different temperature regimes: at higher temperatures the resistance is only weakly temperature dependent as expected for filling factor 1/2 for a single layer. With decreasing temperature there is an exponential decrease of the resistance which, in the end, levels off into saturation around ~50 mK. At present it is not clear if this is an intrinsic phenomenon or caused by insufficient cooling of the 2D system below 50 mK. From the intermediate exponential range we deduce activation energies ($\Delta_{\nu=1}$), which are plotted in the main panel of Fig. 2; the symbols in the inset correspond to the symbols in the main panel. Also included are zeroes corresponding to measurements that did not display a minimum at $\nu_T = 1$ at the lowest temperature.

The activation energy shows a monotonous increase with decreasing d/ℓ_B below a certain $d/\ell_{B,\text{crit}}$, which is 1.65 for our sample. This $d/\ell_{B,\text{crit}}$ is significantly smaller than the value of ~1.83 reported previously [6,9] and it could possibly be due to our slightly lower mobility or our much smaller interlayer tunneling. The increase of $\Delta_{\nu=1}$ below $d/\ell_{B,\text{crit}}$ reminds of the behavior at a phase transition, for example, that of a gap in a superconductor. It is, however, not clear what type of excitations are contributing to the measured $\Delta_{\nu=1}$. In particular, it is not clear if $\Delta_{\nu=1}$ reflects the thermodynamic condensation energy of the excitonic state. In order to gain insight into this question, we conducted temperature dependent resistance measurements on the separate layers that were symmetrically density imbalanced. If $\Delta_{\nu=1}$ reflects a thermodynamical property of the exciton condensate, then for a fixed imbalance the $\Delta_{\nu=1}$ measured in both the upper and lower layer should be the same. Surprisingly however, we find that they are very different.

Below we study the transport in each of the layers separately at imbalanced electron densities, yet at a constant total electron density. The front gates and back gates were adjusted to have a total density of $2n = 4.44 \times 10^{14}$ m^{-2} equally distributed between the layers, corresponding to $d/\ell_B = 1.57$ (star symbol in Fig. 2). Then an interlayer bias was added that produces a symmetric imbalance between the two layers, i.e., one layer had $n + \Delta n$, while the other had $n - \Delta n$. Next, $\rho_{\text{drive},xx}$ and $\rho_{\text{drag},xx}$ were measured as a function of temperature. Then the drag and drive layer were interchanged and the procedure was repeated. We have done measurements for several imbalances ($\equiv [n_L - n_U]/n_T$) between -0.1 and $+0.1$. To check for consistency, for two of the measurement points, the front gates and back gates were fine-tuned to exactly produce the symmetric density imbalance and no interlayer bias was used. In these cases, identical results were obtained.

Throughout the range of density imbalances studied, the low temperature Hall drag remained approximately quantized, indicating that at the lowest temperature nearly all electrons remain paired to holes in the opposite layer. The temperature dependence of both longitudinal resistance and longitudinal drag however, changed significantly. Typical data are shown in Fig. 3 that plots the lower layer $\rho_{\text{drive},xx}$ vs inverse temperature for various density imbalances indicated in the right part of the figure. Strikingly, upon increasing the imbalance from negative to positive values (i.e., increasing the lower layer density while simultaneously decreasing the upper layer density), the activation energy measured in the lower layer, increases. Furthermore, when interchanging the role of the two layers and sending a current in the upper layer, we find that the upper layer ρ_{xx} at a given imbalance resembles very closely the lower layer ρ_{xx} for minus that imbalance. As a consequence, the activation energy determined from the upper layer ρ_{xx} decreases with increasing imbalance (i.e., it increases with increasing the upper layer density).

This asymmetry of the activation energies of the separate layers with imbalance is summarized in Fig. 4. It indicates that the measured activation energies do not reflect the condensation energy of the excitonic state nor the binding energy of the excitons, both of which should be independent of whether it is measured in the upper or in the lower layer. Instead, it implies that the activation energy reflects a gap to charge excitations in the *separate* layers that form the bilayer and that the excitation spectrum of a layer is substantially different for positive and negative imbalance. The asymmetry further tells us that upon increasing the density of one layer, while keeping the total density constant, it costs more energy to produce such excitations.

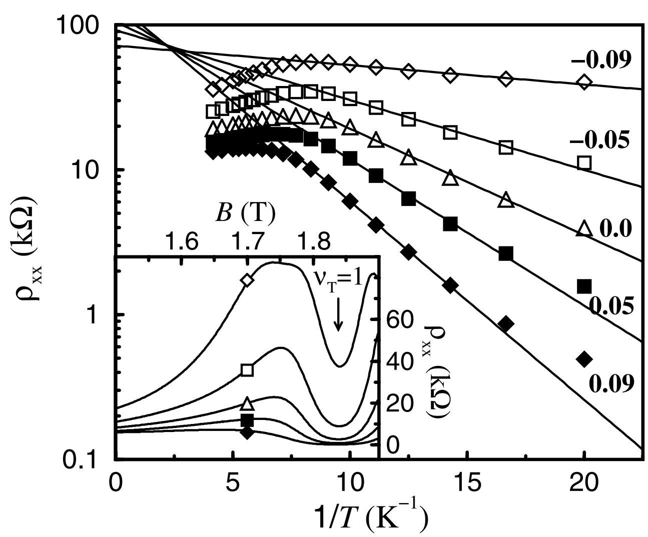

FIG. 3. Arrhenius plot of the lower layer $\rho_{\text{drive},xx}$ for five different imbalances ($\equiv [n_L - n_U]/n_T$) indicated in the right of the figure. The inset plots the lower layer $\rho_{\text{drive},xx}$ at 50 mK vs magnetic field for these five imbalances. The total electron density is fixed at 4.44×10^{14} m^{-2}, corresponding to $d/\ell_B = 1.57$.

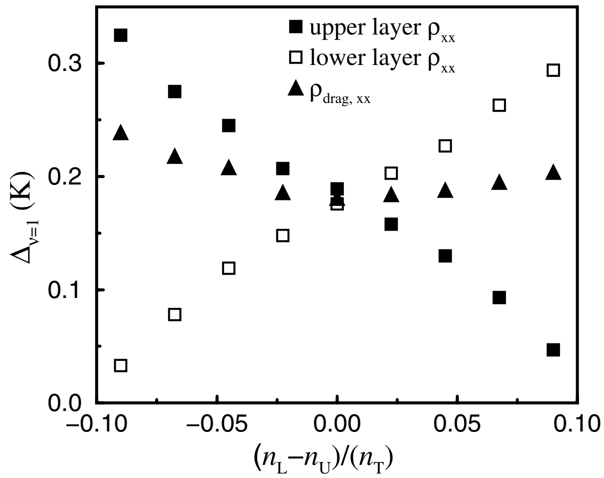

FIG. 4. Activation energies of the $\nu_T = 1$ state vs density imbalance. (□) and (■) correspond to the activation energy determined from the longitudinal resistance in the lower and upper layer, respectively. (▲) denotes the activation energy obtained from the longitudinal drag.

The nonsymmetric behavior of the activation energies around the balanced density point seems to contrast previous measurements in hole bilayers [10,11] that found a symmetric behavior around balanced densities. Both of those experiments however, measured the two layers *in parallel* (i.e., no separate contacts to the separate layers existed). We note that the resistances of the layers in the slightly imbalanced system are very different. It now becomes evident that in the imbalanced case, most of the current flows in the higher-density, less resistive layer and that mainly the properties of this layer are probed. Indeed, when we measure both layers in parallel, but also when we study the activated longitudinal drag that probes the coupled system (▲ symbols in Fig. 4), a more symmetric behavior is observed.

The very different resistances of the layers of the slightly imbalanced $\nu_T = 1$ state also shed new light on the observed disappearance [10] of the insulating phase for filling factors slightly larger than 1 with imbalance. In particular, it questions its interpretation in terms of a commensurate *bilayer* Wigner crystal [10]. The inset of Fig. 3 plots ρ_{xx} of the lower layer at 50 mK vs magnetic field for the imbalances indicated in the main figure with corresponding symbols. Upon decreasing the lower layer density (traces marked with □ and ◇ symbols) the insulating phase in the lower layer becomes much stronger, while simultaneously the upper layer gets a higher density and its insulating phase disappears (traces closely resemble those marked with ■ and ◆ symbols). Consequently when measuring the layers in parallel, most current flows in the upper, less resistive layer and the acclaimed bilayer Wigner crystal [10] seems to disappear. Our data show however, that the insulating phase actually survives in the lower-density layer. We further note that this insulating behavior in the lower-density layer is not simply due to its somewhat reduced mobility, since reducing the total density such that both layers have this lower density results in a much weaker insulating phase than that observed in the lower-density layer in the imbalanced case.

Finally we note that for d/ℓ_B slightly higher than the critical value (where no $\nu_T = 1$ state can be observed for matched densities), a density imbalance can induce the $\nu_T = 1$ state. A similar observation was made previously in coupled two-dimensional hole gases [11], and very recently also in coupled 2DEGs [14]. Under such circumstances, we observe a minimum in ρ_{xx} at $\nu_T = 1$ with thermally activated behavior only in the higher-density layer, while ρ_{xx} of the lower-density layer shows no trace of the correlated state at all.

Summarizing, we have determined activation energies for transport in the balanced $\nu_T = 1$ state over a wide range of the coupling parameter d/ℓ_B and find a monotonous increase with increasing coupling below 1.65. In the symmetrically imbalanced $\nu_T = 1$ state an asymmetry in the activation energies of the longitudinal resistances of the separate layers was observed. In each layer, this activation energy increases approximately linearly with increasing the density of the respective layer. This indicates that the measured activation energies do not reflect the condensation energy of the total system. Instead it seems likely that the origin of the different gaps is that two different activation processes exist in the two layers building up the $\nu_T = 1$ exciton condensate and that the excitation spectrum of the separate layers is rather different for positive and negative density imbalance.

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