Activated Transport in the individual 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 tunnelling. We find thermally activated transport in the balanced system with a monotonic increase of the activation energy with decreasing $d/\ell_B$ 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. This implies that the gap to charge-excitations in the individual layers is substantially different for positive and negative imbalance.

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The Bose-Einstein condensate (BEC) is an ordered state of a many particle system with properties which do 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 vapours. Excitons, consisting of a hole in the valance band bound to an electron in the conduction band in a semiconductor, have long been suspected to form a BEC as well [1], but initially the short life times and the intrinsic self-heating of optically generated excitons prevented condensation. More recently, however, optically generated indirect excitons displayed features arising from collective behaviour [2, 3, 4, 5].

Indirect excitons can be produced in spatially separated quantum wells where they have infinite life times and long mean free paths and where they can be cooled down to lowest possible 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 [6]. In this system, the excitons are formed by the pairing of empty and filled electron states in the conduction band in the two 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 signatures of the new state can be seen: an activation gap in the longitudinal resistance and a quantised Hall drag which is identical to the Hall voltage of the current carrying layer [7]. As a consequence, when identical but counter-flowing currents are passed through the two layers then a dramatic vanishing of both the longitudinal and the Hall resistance is observed [8]. 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 (parameterised by the distance ($d$) between the 2DEGs) and the intra-layer Coulomb interactions (parameterised by the magnetic length ($\ell_B = \sqrt{\hbar/eB} = 1/\sqrt{2\pi n_T}$) at the half-filled Landau levels) being below a critical value of about 1.8 [9, 10]. 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 $3 \times 10^{14}$ $\text{m}^{-2}$ separated by barriers of 5 to 20 $\text{nm}$ thickness. Mobilities exceeding 40 $\text{m}^2/\text{Vs}$ at these densities are required in order to prevent electrons from becoming localised 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 behaviour, and determine the dependence of the activation energy on the coupling parameter $d/\ell_B$. Strikingly, upon producing a symmetric density imbalance at a constant total filling factor 1 ($\nu_T=1$), we observe a huge asymmetry of the activated transport in each of the individual layers. This implies that the measured activation energy is not connected with the condensation energy of superfluid $\nu_T=1$ state. Instead it reflects the gap to charge-excitations of the individual layers which turns out to be substantially different for positive and negative imbalances. Our data additionally demonstrate that measuring both layers in parallel easily leads to erroneous conclusions [10].

Our DQWs consist of two 17 $\text{nm}$ GaAs quantum wells separated by a superlattice of 12.4 $\text{nm}$ total thickness made up of alternating 4 monolayers (ML) AlAs (1.13 nm) and 1 ML GaAs (0.28 nm). The electrons originate from bulk doping with Si that is placed 300 nm below and 280 nm above the wells, respectively. The two 2DEGs have intrinsic densities ($n_{\uparrow\uparrow}, n_{\downarrow\downarrow}$) of $4 \times 10^{14}$ $\text{m}^{-2}$ in both the upper and the lower layer and mobilities of 70 $\text{m}^2/\text{Vs}$. Eight Ohmic contacts were made to the upper 2DEG and six to the lower 2DEG using metallic frontgates [11] and buried backgates [12] for contact separation. The densities in the layers can be adjusted
independently by another front- and backgate 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 tunnelling peak within the noise level (0.5 × 10^{-9} Ω^{-1}).

Data taken with a density in each layer of 2.22 × 10^{14} m^{-2} are shown in Fig. 1 that plots longitudinal (ρ_{drive,xx}) and Hall (ρ_{drive,xy}) resistances of the layer to which the current is applied, as a function of magnetic field. At ν_T=1, ρ_{drive,xx} shows a pronounced minimum while ρ_{drive,xy} drops to approximately 25.8 kΩ (h/e^2). Away from ν_T=1, the traces show Shubnikov-de Haas oscillations of a single layer. At temperatures above ~ 250 mK, the minimum in ρ_{drive,xx} and the quantisation of ρ_{drive,xy} have disappeared. Also shown are the longitudinal drag (ρ_{drag,xx}) and the Hall drag (ρ_{drag,xy}). The approximate quantisation to h/e^2 in ρ_{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 [3], both the longitudinal and the Hall voltages in the layers tend to zero at the lowest experimental temperatures (inset Fig. 1).

We now turn to the temperature dependence of the longitudinal resistance at ν_T=1. The inset of Fig. 2 plots ρ_{drive,xx} of the lower layer vs. the inverse temperature for a series of different d/ℓ_B values, obtained by adjusting both the front- and backgate. 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 electronic system below 50 mK. From the intermediate exponential range we deduce activation energies (∆ν=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 ν_T=1 at the lowest temperature.

The activation energy shows a monotonous increase with decreasing d/ℓ_B below a certain d/ℓ_B,crit which is 1.65 for our sample. This d/ℓ_B,crit is significantly smaller than the value of ~1.83 reported previously [4] and it
Below we study the transport in each of the layers separately at imbalanced electron densities, yet at a constant total electron density. The front- and backgates were adjusted to have a total density of $2n = 4.44 \times 10^{14}$ m$^{-2}$ equally distributed between the layers, corresponding to $d/\ell_B=1.57$ (symbol in Fig.2). Then 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 $\rho_{\text{drag,xx}}$ where 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 ($\pm |n_L-n_U|/n_T$) between $-0.1$ and $+0.1$. To check for consistency, for two of the measurement points, the front- and backgates 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 Hall drag remained approximately quantised at the lowest temperature, yet the temperature dependence of both longitudinal resistance and longitudinal drag 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), the activation energy decreases with increasing imbalance (i.e. it increases with increasing the upper layer density). This asymmetry of the activation energies of the individual layers with imbalance is summarised in Fig.4 for the $\nu_T = 1$ state vs. layer 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.
Fig. 3. It proves that the measured activation energies are not directly connected with the condensation energy of the total system that should be the same, regardless of which layer has the lower density and which the higher density. Instead, it implies that the activation energy reflects the gap to charge-excitations in the individual layers and that the excitation spectrum in the individual layers is substantially different for positive and negative imbalance.

Our non-symmetric behaviour of the activation energies around the balanced density point seems to contrast sharply to previous measurements in hole bilayers.\cite{10, 17} that found a symmetric behaviour around balanced densities. Both of those experiments however, measured the two layers in parallel (i.e. no separate contacts to the individual layers existed). We note that the resistances of the individual layers in the slightly imbalanced system are extremely different. It is thus 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 behaviour is observed.

The very different resistances of the individual layers of the slightly imbalanced $\nu_T=1$ state also shed new light on the observed disappearance \cite{10} of the insulating phase for filling factors slightly larger than 1 with imbalances. In particular, it strongly questions its interpretation in terms of a pinned bilayer Wigner crystal.\cite{10}. The inset of Fig. 4 plots $\rho_{xx}$ of the lower layer at 50 mK vs. magnetic field for the imbalances indicated in the main figure with corresponding symbols. It now becomes evident that 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, almost all current flows in the upper, less resistive layer and the acclaimed bilayer Wigner crystal seems to disappear. Our data show however, that the insulating phase actually survives in the lower-density layer. We further note that this insulating behaviour 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 $d/d_B$ 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 2DHGs \cite{17}, and very recently also in coupled 2DEGs \cite{18}. Under such circumstances, we observe a minimum in $\rho_{xx}$ at $\nu_T=1$ with thermally activated behaviour only in the higher-density layer, while $\rho_{xx}$ of the lower-density layer shows no trace of the correlated state at all.

Summarising, we have determined activation energies for transport in the balanced $\nu_T=1$ state over a wide range of the coupling parameter $d/d_B$ 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 individual layers was observed. In each layer, this activation energy increases approximately linearly with increasing the density of the respective layer. This proves that the measured activation energies are not connected with the condensation energy of the total system. Instead it implies that they reflect the gap to charge excitations in the individual layers building up the $\nu_T=1$ exciton condensate and that the excitation spectrum of the individual layers is rather different for positive and negative density imbalance.

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