Negative Electron Drag and Hole-Like behavior in the Integer Quantum Hall Regime

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(October 9, 2018)

Electron drag between two two-dimensional electron gases in magnetic fields has been observed with a polarity opposite that for zero field. This negative drag requires that the electrons have a hole-like dispersion. Density dependence measurements in the integer quantum Hall regime show that drag is negative only when the upper Landau level of one layer is more than half filled while the other is less than half filled, indicating that hole-like dispersion is present in a half of each Landau level. Negative drag is argued to be a consequence of disorder.

73.40.Hm, 71.61.Ey, 73.20.Dx

The integer quantum Hall effect (IQHE) is a central element of two-dimensional electron gas (2DEG) physics, in which disorder plays a critical role. Numerous experimental techniques have explored aspects of the effect. A new approach, electron drag, has recently been applied to the study of this important topic. This approach, in which electron-electron (e-e) scattering between two parallel 2DEGs is measured, can provide information complementary to single layer measurements. In particular, it was predicted and observed that for each individual magneto-resistance peak, a double-peaked structure would exist for drag with matched density electron layers, due to an enhanced importance of screening. In this Letter, drag measurements exploring the case of unmatched densities in detail are presented, which reveal a new regime of electron drag. In this regime, the polarity of the measured drag voltage is opposite that normally found for electron layers, matching instead the polarity of an electron-hole (e-h) system. (We refer to the drag polarity of the e-e/e-h case as positive/negative).

Previous drag experiments between electron layers with matched densities find a positive drag throughout the IQHE regime. Our measurements, in which electron densities were systematically varied by application of an interlayer bias and/or an overall top gate voltage, showed both positive and negative drag.

The sample was a GaAs/AlGaAs double quantum well structure with two 200Å wells separated by a 225Å barrier, each with an electron density of \( \sim 1.6 \times 10^{11}/cm^2 \) as grown, and mobilities of \( 2.5 \times 10^6 cm^2/V s \). The striking implications of negative drag require we ensure the observed polarity is not due to well-known complications of transport in magnetic fields or other drag difficulties.

FIG. 1. Drag versus magnetic field for matched (c) and unmatched (a) layer densities at 1.15K. The longitudinal magneto-resistance (b) for the drive layer in both cases \((1.66 \times 10^{11}/cm^2)\) (solid line), the dotted line is the drag layer with a mismatched density \((1.49 \times 10^{11}/cm^2)\). A clear difference in filling factors is evident for negative drag (a).
Standard tests \( \text{[5]} \) of changing drag layer ground to test for inter-layer leakage, varying drive current to check for linearity, and interchanging drive and drag layers, all confirm the measurements validity. In addition, reversing the magnetic field yields no change in the signals, indicating that the drag is longitudinal, i.e., the Hall voltages which develop in these fields play no role.

Negative drag emerges when the densities of the electron layers are \textit{not} matched. A comparison of \( \rho_D \) for matched and unmatched densities is shown in Fig. 1. For matched densities, each layer has a magneto-resistance \( (\rho_{xx}) \) similar to the solid curve of Fig. 1b, with the corresponding drag versus field shown below. The measurements are comparable to those previously showing the double-peak structure \( \text{[2]} \). If the the drag layer density is decreased 10\%, however, with \( \rho_{xx} \) shown by the dotted line in Fig. 1b, the negative drag of Fig. 1a is obtained.

The existence of negative drag, the same polarity as the the e-h system \( \text{[14]} \), has implications for the nature of the states in the IQHE regime. It would appear to suggest holes have a role in the process, but this is clearly inconsistent with the sign of the Hall voltage. Instead, negative drag with two electron layers requires interlayer scattering induce a drift of drag layer electrons in a direction \textit{opposite} the drive layer drift velocity, contrary to expectations of classical momentum conservation. Such expectations, however, are complicated by the presence of a magnetic field, \( B \). In the Landau gauge, in particular, where states are infinite strips along the current direction \( y \), it is the canonical momentum \( \hbar k_y \) which is conserved during scattering, and not the classical momentum or velocity. To obtain a negative drag signal, a scattering event which transfers \( \Delta k_y \) from one layer to the other must result in a change in velocity, \( dE/dk_y \), in the \textit{same} direction in both layers. Negative drag thus places a strong constraint on the electron dispersion; \( d^2E/dk_y^2 \) must have different signs in the two layers.

The dispersion relation required for negative drag should not exist for 2-D electrons in magnetic fields in the absence of disorder. For a system with hard-wall confinement, the \( E-k_y \) dispersion for a single LL has been shown \( \text{[12]} \) to be flat when the electron center of mass is near the middle of the sample, with \( E \) increasing as the electron comes within a cyclotron radius of the sample edge. Although electrons on both sides of the sample have opposite velocities, the change in velocity with \( k_y \), \( d^2E/dk_y^2 \), is always positive or zero. The absence of a ‘hole-like’ dispersion (i.e. \( d^2E/dk_y^2 < 0 \) in this system implies that negative drag is a disorder-related effect.

It is widely recognized that disorder broadening of Landau levels is an important element of the IQHE. A significant complication introduced by disorder, though, is that \( k_y \) is no longer strictly a good quantum number, as disorder lacks translational symmetry. It still remains possible to consider properties of the dispersion relation. In particular, the use of periodic boundary conditions, as in the numerical studies of Ref. \( \text{[14]} \), preserve the Bloch momentum along \( y \) as a conserved quantity. (In such cases, only the change in \( k_y \) is physically meaningful). Qualitative information about the dispersion relation deduced from our measurements is valid if we consider the lack of true translational symmetry in a similar manner.

Ascertaining the conditions required for negative drag is clearly important. A rough correspondence in \( B \) between the transition from positive to negative drag (Fig. 1a) and the onset of significant differences in the Schubnikov-de Haas oscillations (Fig. 1b), suggests that relative LL filling plays a role. To test this, \( \rho_D \) was measured at fixed \( B \) and drive layer density while varying the drag layer density, or equivalently its filling factor \( \nu \). Odd integer \( \nu \) corresponds to two half filled LL’s, as spin is not resolved. As shown in Fig. 2a, with a drive layer LL more than half filled \( (\nu = 7.39) \), \( \rho_D \) shows alternating positive and negative peaks. Drag is positive when the highest drag layer LL is more than half filled; negative drag appears only when that LL is less than half filled, irrespective of the overall LL index. Changing \( B \) so the upper drive layer LL is less than half filled \( (\nu = 8.47) \), (Fig. 2b) reverses the polarity of drag versus drag layer \( \nu \).

The symmetry in this behavior clearly establishes a negative drag criteria: the deviation from half filling must be opposite in the two layers. The observation that the drag polarity is nearly periodic in the drag layer \( \nu \) shows further that the sign of \( d^2E/dk_y^2 \) is directly related to the position of the electron states within each LL, with hole-like dispersion existing for each Landau level.

The drag temperature dependence provides further information about the dispersion. While the density dependence measurements require a different dispersion for states above or below half-filling, it provides little infor-

![FIG. 2. Drag versus drag layer filling factor(density).](image-url)
The reduced oscillations in 1.53K, 1.87K, and 2.18K are shown. Inset: A Dingle plot of layers are 1.66 and 1.49 × ∼ show its disappearance above 1.8 K. All states in the LL should be accessible, h/τo, of 1.7K. All states in the LL should be accessible and thus participate in scattering once the temperature is of this order. The observation that negative drag disappears at roughly 1.8K thus provides support for a bulk state source for the hole-like dispersion.

The second source considered involves edge states. The presence of disorder can permit edge states of lower LL’s to mix with bulk states of a higher LL. States with energies well below the bulk state LL will be little influenced, but as the energy approaches that of the bulk states, the resultant mixed states will acquire greater bulk-like character. Above half filling, the transition is from bulk to edge-like character. The inset of Fig. 4a compares a schematic of the resultant energy level diagram (top) to the case in the absence of disorder (bottom). Such mixing has been explored in numerical investigations [12–13], our simple diagram is drawn from that work. The theoretical work addresses a key question regarding the dispersion: how ķy varies within these states. It increases as the curves are traversed in a clockwise fashion, as shown by arrows in the figure. The mixing of bulk and edge states thus provides a mechanism for hole-like dispersion below half filling (i.e. for these states, dE/dky ≤ 0), while states above half filling retain an electron-like dispersion.

Energy differences between electron and hole-like states for this source would likely be comparable to that deter-
mined in Fig. 3, though questions concerning the relatively small number of edge states, whose influence must dominate drag measurements, must be considered.

A potential test for the influence of edge states arises through severe reduction of their number. Measurements made at 10.1, 6.23, and 4.76 Tesla, and 1.2K are shown in Fig. 4a, b, and c, respectively. In Fig. 4a, the drive layer density is fixed so $\nu = 0.8$, with the drag layer $\nu$ varied between 0.4 and 0.8. Above $\nu \sim 0.5$, i.e. with both layers’ LL’s more than half filled, drag is positive, as expected. Reducing the drag layer $\nu$ below 0.5, so the layers have opposing deviations from half filling, which would yield negative drag at low fields, results instead in a positive signal. This measurement remains entirely in the lowest LL, so no edge states from lower LL’s exist. Similar behavior is observed in the next LL, where only a single edge state is present. In Fig. 4b, with a drive layer $\nu = 1.3$, drag remains positive irrespective of the deviation from half filling, with a clear zero near $\nu = 1$. Remaining within the second LL continues to generate only positive drag; in Fig. 4c, the drive layer $\nu$ is 1.7 with the drag layer ranging from 1.2 to 1.7. The observation that negative drag disappears at this temperature as the number of edge states is greatly reduced appears to support the involvement of edge states in negative drag in negative drag. While the behavior is inconsistent with the simple picture previously considered for a bulk state source, as LL widths have been measured in Ref. 8 to increase like $B^{0.5}$ at high fields, it remains possible that other influences of high magnetic fields, such as the enhanced importance of intra-layer e-e interactions, could instead cause the observed disappearance of negative drag.

Although a full understanding of the effect remains elusive, the observation of hole-like behavior for electrons in magnetic fields has revealed, we believe, direct new information about the nature of the states in the IQHE regime. Because its observation depends critically on the density difference between electron layers, it is unlikely the information is accessible in single layer transport measurements. The quantitative results presented here are suitable for comparison to calculation, and may help further illuminate the important role of disorder in the IQHE. Negative drag may also be important for analysis of the double peaked structure seen in Ref. 3 (also Fig. 1c) in drag at matched densities, argued to result from a competition between an increasing DOS and enhanced screening. The degree to which the existence of both positive and negative drag scattering processes contributes to this effect will require further investigation.

In summary, negative drag has been observed for 2DEG’s with mismatched densities in the IQHE regime. The polarity observed is opposite that for zero field, and the same as for the electron-hole double layer system. The sign the drag polarity exhibits nearly periodic behavior as the filling factor of one layer is varied, supporting a criteria for negative drag: if the upper Landau level of one layer is more than half filled, that of the other must be less than half filled. The existence of the hole-like dispersion relation required for negative drag, $d^2E/dk_y^2 < 0$, is argued to result from disorder.

We appreciate discussions with A. H. MacDonald and N. Bonesteel, and the contributions of J. P. Eisenstein to both this work and the drag technique. Support from NSF grant DMR-9503080, the Sloan Foundation, and the Research Corp. is gratefully acknowledged.

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