

ENHANCEMENT OF COULOMB DRAG AWAY FROM HALF FILLED LANDAU LEVELS

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Coulomb drag between two parallel two dimensional electron gases has been measured at high magnetic fields in samples with two different layer spacings. As the layer filling factor deviates from $\nu = 1/2$, we find that the magnitude of the drag is enhanced quadratically with $\Delta\nu = \nu - 1/2$, and the curvature of the enhancement is insensitive to both the sign of $\Delta\nu$ and the spacing between the layers. Our results suggest that the enhancement is *not* due to non-perturbative interlayer correlations.

Double layer two-dimensional electron gases (2DEGs) have been of recent interest due to the rich many-body physics they exhibit. Of particular interest is the case when each of the 2DEGs is at filling factor $\nu_{tot} = 1/2 + 1/2$. If the separation between the layers is large relative to the interparticle separation, the system behaves as two individual layers, each of which is widely viewed at a composite fermion (CF) liquid. If the separation is small, a gap develops and the system forms a ferromagnetic quantum Hall state characterized by total filling factor $\nu_{tot} = 1$. The nature of this transition is a frontier topic in the field.¹

Novel transport techniques such as Coulomb drag can be utilized in double layer 2DEGs. In a Coulomb drag measurement, current flowing in one layer induces a voltage in the other whose magnitude measures the interlayer momentum relaxation rate, τ_m . At high magnetic fields τ_m in our samples is dominated by electron-electron scattering between the layers. Previous measurements of Coulomb drag at half-filling² show the drag to be typically 1000 times larger than at $B=0$. Models of weakly coupled CF layers^{3,4,5} also predict this large increase of the drag and attribute it to the increased importance of electron interactions in the lowest Landau level. In this paper we report measurements of Coulomb drag between 2DEGs where the layer filling factor is systematically varied around $\nu = 1/2$. Two samples having different layer separations have been studied. We find that the drag increases quadratically as a function of $\Delta\nu = \nu - 1/2$, where $\nu = hn/eB$, n is the density, and B is the magnetic field.

The two samples studied here are modulation doped GaAs/AlGaAs double quantum wells grown by molecular beam epitaxy. They consist of two 200 Å wide GaAs wells separated by an $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier. Sample A has a 100 Å

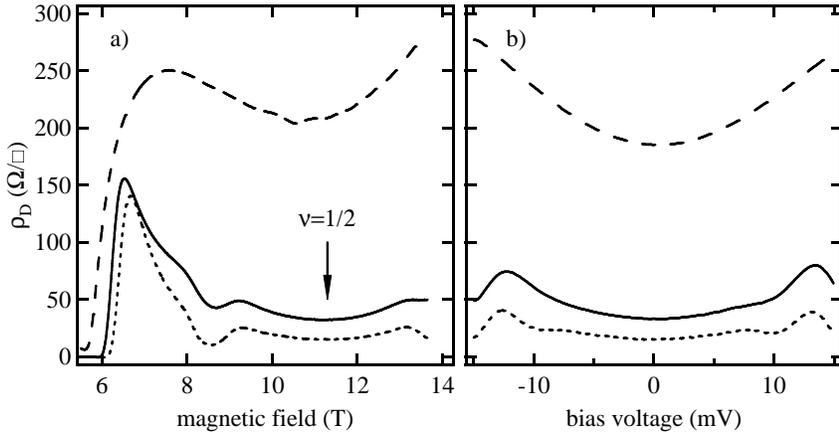


Figure 1: In (a) the magnetic field dependence of drag in sample A is shown for $T = 0.6$ K (dotted), 1.0 K (solid), and 4.0 K (dashed). In (b) an interlayer bias voltage is applied to sample A at a constant magnetic field for 0.6 K (dotted), 1.0 K (solid), and 3.5 K (dashed).

barrier with $x = 1$ and sample B has a 225 \AA barrier with $x = 0.32$. The electron densities in both samples A and B were balanced using central top and bottom gates to a nominal density of $n \approx 1.4 \times 10^{11} \text{ cm}^{-2}$. Each sample was patterned into a Hall bar ($l = 400 \mu\text{m}$, $w = 40 \mu\text{m}$) with indium ohmic contacts. Drag measurements are made by injecting a current, $I = 10 \text{ nA}$, 13 Hz in one 2DEG (drive layer) and measuring resulting voltage, V_D , induced in the other (drag layer).

Fig. 1a shows the drag resistivity, $\rho_D = -(w/l)V_D/I$, of sample A for $\nu \leq 1$ at several temperatures. The sign of the drag voltage is opposite that of the resistive voltage drop in the drive layer. This sign is consistent with electrons in the drag layer building up a voltage to oppose the momentum transfer of the electrons from the drive layer. At $B = 5.7 \text{ T}$, each layer is in the integer quantum Hall state $\nu = 1$. Owing to the large energy gaps in each layer at this filling, the drag $\rho_D \rightarrow 0$. At $T = 0.6 \text{ K}$, the same effect is evident as the fractional quantum Hall effect (FQHE) $\nu = 2/3$ develops at $B = 8.55 \text{ T}$. Around $\nu = 1/2$ in each layer, the 2DEGs remain compressible, and ρ_D forms a shallow minimum. As the temperature is lowered, the magnitude of the drag decreases, although the minimum around $\nu = 1/2$ persists.

A second measurement which yields enhanced drag away from half-filling occurs when the densities of the layers are intentionally unbalanced at fixed magnetic field. Starting at $\nu = 1/2$ with density n_0 in each layer, a dc bias

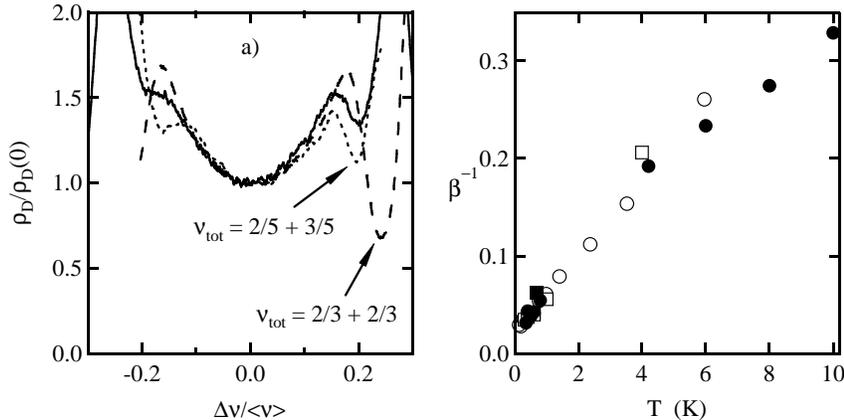


Figure 2: (a) Scaled drag resistivity as filling factor departs from $\nu = 1/2$ at $T=0.6$ K for sample A field sweep (dashed), sample A interlayer bias (solid) and sample B interlayer bias (dotted). (b) Summary of curvature at different temperatures for sample A field sweep (open square), sample A interlayer bias (open circle), sample B field sweep (solid square), and sample B interlayer bias (solid circle).

voltage, V_{bias} is applied between the layers. The bias voltage transfers charge between layers, increasing the density of one layer to $n_0 + \Delta n/2$ and decreasing it in the other to $n_0 - \Delta n/2$ (Δn is the density difference). The change in density at a fixed field causes a corresponding change in the filling factor that we define by $\Delta\nu = \nu - 1/2$. The results for sample A are shown in Fig. 1b at $T=0.6$ K, 1.0 K and 3.5 K. At $V_{bias} = 0$, both layers are at $\nu = 1/2$. For small V_{bias} , ρ_D increases quadratically with a curvature that depends on temperature. The minimum in ρ_D in the $T = 0.6$ K data (dotted line) at $V_{bias} = 10$ mV is due to the development of the FQHE at $\nu_{tot} = 2/5 + 3/5$. This feature allows calibration between V_{bias} and $\Delta\nu$. A similar increase in ρ_D as a function of V_{bias} was found in sample B.

In order to compare the enhancement of the drag away from half-filling for the two situations described above, we plot the normalized drag resistivity, $\rho_D/\rho_D(\Delta\nu = 0)$, as a function of the relative change in filling factor, $\Delta\nu/\langle\nu\rangle$, where $\Delta\nu = \nu - 1/2$ and $\langle\nu\rangle = (\nu_1 + \nu_2)/2$ (the subscripts indicate the layer index). When V_{bias} is applied, $\Delta\nu_1 = -\Delta\nu_2$, and $\langle\nu\rangle = 1/2$ is constant with V_{bias} . When the field is changed, $\Delta\nu_1 = \Delta\nu_2$, and $\langle\nu\rangle = hn/B$ changes with the field. Results for $T = 0.6$ K are shown in Fig. 2a for interlayer bias in sample A (solid line), magnetic field for sample A (dashed) and interlayer bias for sample

B (dotted). For small $\Delta\nu$, the relative drag signal increases quadratically for a with the same curvature for all three sets of data. At larger $\Delta\nu$, features related to the FQHE are observed at $\Delta\nu/\langle\nu\rangle = 0.2$ ($\nu_{tot} = 2/5 + 3/5$) in the interlayer bias traces (solid and dotted lines) and at $\Delta\nu/\langle\nu\rangle = 0.25$ ($\nu_{tot} = 2/3 + 2/3$) for the field sweep (dashed line).

Defining the curvature by $\rho_D/\rho_D(0) = \beta(\Delta\nu/\langle\nu\rangle)^2 + 1$, in Fig. 2b we show the temperature dependence of β^{-1} . The open symbols are results for sample A (squares for field sweeps and circles for interlayer bias) and the closed symbols for sample B. Extrapolating to $T = 0$, β^{-1} appears to have a finite intercept. We note that β follows the same curve in all cases. Comparing the two different measurements on the same sample, it may not be surprising that the enhancement of the drag should not depend on whether the field is changed or an interlayer bias is applied, especially for small changes in $\Delta\nu$. On the other hand, comparing the curvatures of sample A to sample B which have different layer separations, the data also fall on the same curve. The enhancement of the drag does not depend on the spacing between the 2D layers. From this independence, we conclude that the enhancement in drag is due to the response of a single layer, and *not* due to interlayer correlations.

In conclusion, measurements of Coulomb drag near half filling show a quadratic increase in the drag as a function of $\Delta\nu$. The increase in the drag signal for a given sample does not depend on whether the density is changed or whether the magnetic field is changed, and is symmetric around $\nu = 1/2$. In addition, the curvature does not depend on the spacing between the layers. This suggests that the enhanced drag signal is due to the response of the individual layers.

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References

1. For recent reviews, see *Perspectives in the Quantum Hall Effects*, edited by S. Das Sarma and A. Pinczuk (Wiley, New York, 1997).
2. M. P. Lilly, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Letters **80**, 1714 (1998).
3. Y. B. Kim and A. J. Millis, preprint cond-mat/9611125.
4. I. Ussishkin and A. Stern, Phys. Rev. B **56**, 4013 (1997); Physica E **1**, 176 (1997).
5. S. Sakhi, Phys. Rev. B **56**, 4098 (1997).