Mesoscopic Fluctuations of Coulomb Drag of Composite Fermions

A. S. Price\textsuperscript{1}, A. K. Savchenko\textsuperscript{1}, D. A. Ritchie\textsuperscript{2}
\textsuperscript{1}School of Physics, University of Exeter, Exeter EX4 4QL, UK
\textsuperscript{2}Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

We present the first experimental study of mesoscopic fluctuations of Coulomb drag in a system with two layers of composite fermions, which are seen when either the magnetic field or carrier concentration are varied. These fluctuations cause an alternating sign of the average drag. We study these fluctuations at different temperatures to establish the dominant dephasing mechanism of composite fermions.

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Coulomb drag is a powerful technique for measuring directly the strength of electron-electron (e-e) interaction. Coulomb drag studies are performed on two closely spaced but electrically isolated layers, where a current is driven through one of the layers (active layer) and the voltage drop is measured along the other (passive) layer. The origin of this voltage is a momentum transfer between the charge carriers in the two layers via e-e interaction. Coulomb drag is well studied theoretically in single layer systems, and arises from the interference between electrons in each layer. Unlike the conductance of single layer systems, and arise from the interference of each layer can be independently controlled by gate voltage over the range of \( n = 0.4 - 2.0 \times 10^{11} \text{cm}^{-2} \), with a corresponding change in the mobility from 1.2 – 6.7 \( \times 10^5 \text{cm}^2\text{V}^{-1}\text{s}^{-1} \). The GaAs quantum wells are 200 Å in thickness, and are separated by an Al\textsubscript{0.33}Ga\textsubscript{0.67}As layer of thickness 300 Å. Each layer has a Hall-bar geometry, 60 μm in width and with a distance between the voltage probes of 60 μm. The measurement circuit of the drag voltage \( V_2 \) is shown in Fig. \textbf{1A}. The drag resistance \( R_D \) is found from the ratio of the drag voltage to the current \( I_1 \) passed through the active layer, \( R_D = -V_2/I_1 \).

The samples studied in this work are AlGaAs-GaAs double-layer structures \[ \text{[21]}, \] where the carrier concentration of each layer can be independently controlled by gate voltage over the range of \( n = 0.4 - 2.0 \times 10^{11} \text{cm}^{-2} \), with a corresponding change in the mobility from 1.2 – 6.7 \( \times 10^5 \text{cm}^2\text{V}^{-1}\text{s}^{-1} \). The GaAs quantum wells are 200 Å in thickness, and are separated by an Al\textsubscript{0.33}Ga\textsubscript{0.67}As layer of thickness 300 Å. Each layer has a Hall-bar geometry, 60 μm in width and with a distance between the voltage probes of 60 μm. The measurement circuit of the drag voltage \( V_2 \) is shown in Fig. \textbf{1A}. The drag resistance \( R_D \) is found from the ratio of the drag voltage to the current \( I_1 \) passed through the active layer, \( R_D = -V_2/I_1 \).

The drag resistance as a function of magnetic field, \( \rho_D(B) \), is shown in Fig. \textbf{1I} for various temperatures in the vicinity of \( \nu = 1/2 \). A cross-section of the curves is taken at a fixed B-field, indicated by the dotted vertical line, and is plotted in Fig. \textbf{1B}. The solid line is a plot, without adjustable parameters, of the expected value of the drag resistance of composite fermions \[ \text{[10]} \] in a macroscopic sample:

\[ \rho_D = 0.825(h/e^2)(T/T_0)^{4/3}. \] (1)

Here \( T_0 \approx \pi e^2 n d/\epsilon = 330 \text{K} \), \( \epsilon \) is the dielectric constant, \( n \) is the carrier concentration, and \( d = 500 \text{Å} \) is the spacing between layers. One can see that at high temperatures, \( T > 1 \text{K} \), the drag resistance is in good agreement with Eq. \textbf{11} and its \( T \)-dependence is similar to that seen in \textbf{1I}, where the average drag of composite-fermions was measured. However, as \( T \) is decreased the temperature dependence changes: as \( T \) decreases \( \rho_D \) can either decrease or increase as in Fig. \textbf{1B}, depending on the carrier concentration. This non-monotonic \( T \)-dependence can be accounted for by the competition between the average drag and mesoscopic effects. The average drag dominates at high temperatures and decreases with decreas-
ing temperature, whilst the amplitude of the mesoscopic fluctuations of $\rho_D$ increase with decreasing temperature, and dominate at low temperatures.

In Fig. 1C it is seen that at high temperatures the drag resistance does not contain visible fluctuations, but at lower temperatures fluctuations appear and below $T \sim 200$ mK the fluctuations dominate the drag resistivity.

Note that the magnitude of these fluctuations is greatly enhanced, by a factor of $\sim 1000$, in comparison to those seen in weak $B$-fields [1], where fluctuations were of the order of 20 mΩ.

The close values of $\Delta n$, found from $\rho_D(n)$ and $\rho_D(B)$ is an important result that is expected from the flux attachment of 2Φ0 to each electron [22] and is a proof that the charge carriers in our system are composite fermions.

Mesoscopic fluctuations depend on both change in the Fermi energy and magnetic field. Composite fermions experience a reduced effective magnetic field that is dependent upon the external magnetic field and the density of carriers: $B^* = B - 2\Phi_0 n$. Consequently, mesoscopic fluctuations for composite fermions observed when varying the carrier density result not only from the change in the Fermi energy $\Delta E_F$, but also from the change in the effective $B$-field, $\Delta B^*(n) = 2\Phi_0 \Delta n$ [20].

ructations due to the first mechanism occur over a scale of $\Delta n_c = (h/\tau B) G = g_{cf}/L^2_\phi$, where $G$ is the density of states of composite fermions, and $g_{cf}$ is their dimensionless conductance. The second mechanism results in fluctuations on a scale of $\Delta B^* = 2\Phi_0 \Delta n / L^2_\phi$. Thus, comparing the order of magnitudes of the two scales we find that fluctuations due to changes in $E_F$ occur over a scale which is $g_{cf}$ times larger than fluctuations due to the change in $B^*(n)$, so that $\Delta n_c = (\partial B^*/\partial n) \Delta B^* = 1/2L^2_\phi$.

The effect of varying the external $B$-field is the same for composite fermions as it is for conventional electrons in weak $B$-fields: the correlation magnetic field $\Delta B_c$ corresponds to one magnetic flux quantum through a coherent area $L^2_\phi$. This results in the relationship between the correlation magnetic field and correlation concentration near $\nu = 1/2$: $B_c/n_c = 2\Phi_0$. (This relation has been seen in the case of a single-layer system in which conductance fluctuations were measured near $\nu = 1/2$ [23].)

In [20] the variance of the drag fluctuations in the “diffusive” regime of drag (where the mean free path is much shorter than the distance between the layers, $l \ll d$) is predicted to be

$$\langle \rho_D^2 \rangle \approx \frac{\hbar^2}{e^2} \frac{1}{{g_{cf}^3}(kd)^2} \left( \frac{L^2_{\phi}}{L} \right)^2,$$

where $\kappa$ is the inverse Thomas-Fermi screening length, $L^2_{\phi}$ is the coherence length of composite fermions, and $L$ is the size of the square sample. Near $\nu = 1/2$ the effective magnetic field $B^*$ is small and $g_{cf}$ is simply related to the inverse of the longitudinal resistance: $g_{cf} = (h/e^2)(R_{xx})^{-1} = 4.4$. This results in a composite fermion mean free path of $l_{cf} = g_{cf}/k_F = 46$ nm, where $k_F = \sqrt{2\pi n}$. Thus, whilst the normal-electron properties infer that the Coulomb drag in our structures is “ballistic”, with $l/d = 200$, the properties of composite fermions suggest that the drag will be much more diffusive in nature, with $l/d = 0.92$.

The calculation of the expected variance in Eq. 4 depends on the knowledge of the dephasing length of the
on dephasing in composite fermion systems where, in the
presence of long-range interactions, $L_\phi$ is expected to be
well described by $e-e$ scattering in the limit of low tem-
peratures, $T \ll 100/g_{cf}^2 e_f$, which for our system (with a
low conductance of composite fermions) applies already
below 35 K.

Using these values of $L_\phi^{cf}$ we calculate the expected
variance of the drag resistivity fluctuations using Eq. 2,
which is plotted as the dashed line in the inset to Fig. 3
multiplied by 20 for the sake of comparison. We see that
the magnitude of the fluctuations is underestimated when
calculated using Eq. 4 and the temperature dependence
is poorly described at higher temperatures. However,
this discrepancy between the experiment and the pre-
dictions of the diffusive drag theory in [20] is less than
that previously seen for the case of Coulomb drag of nor-
amal electrons [14], where fluctuations were four orders of
magnitude larger in amplitude than that expected theo-
retically. This can be accounted for by our system being
closer to the diffusive limit, $l/d < 1$.

The found value of $L_\phi$ is seen to deviate at low tem-
peratures from that expected from $e-e$ scattering, Fig. 3.
It is possible that this effect is related to a non-linearity
of the drag fluctuations that we have observed at low
temperatures. The fluctuations of the drag at $\nu = 1/2$
are found to be strongly nonlinear, unlike in the case of
weak magnetic fields, where both the average drag res-
istance and the fluctuations of the drag resistance were

The measured $L_\phi^{cf}$ (found from the correlation concen-
tration $\Delta n_{cf} = 1/2L_\phi^{cf}$) is shown as a function of $T$
in Fig. 3. If one uses the expression for $L_\phi$ that comes
from fluctuations of the gauge field then one obtains the
correct temperature dependence, but the values are an
order of magnitude too big compared with experiment.
Our result is in agreement with the predictions of [24]

The resulting dephasing length is

$$L_\phi \approx \sqrt{2\pi e^2 d/k_B T \alpha},$$

in contrast to the usual expression for the dephasing
length of $L_\phi^{cf} = \alpha \sqrt{Dh g_{cf}/k_B T \ln g_{cf},}$ which comes from
dephasing by $e-e$ scattering at low temperatures [25].

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Our result is in agreement with the predictions of [24]
seen to be independent of the active-layer current \cite{14}. The drag resistivity as a function of $\nu$ measured using different currents is shown in Fig. 4A. The amplitude of the fluctuations increases by four times in decreasing the current from 1 nA to 0.1 nA. The nonlinearity of the fluctuations is stronger at higher currents, as demonstrated in Fig. 4C, where the variance of the fluctuations is plotted as a function of current. This nonlinearity is not simply due to Joule heating, as the single-layer resistance is seen to be independent of driving current below 1 nA (Fig. 4A). (Strong nonlinearity of the Coulomb drag of composite fermions was also seen in previous measurements of the average drag resistance \cite{11}.) The origin of this nonlinearity deserves further investigation in the future. All of the measurements we present in this paper were performed using a 0.1 nA driving current, where the nonlinearity is weak (Fig. 4B).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4}
\caption{Panel A: Drag resistivity as a function of filling factor measured with different active-layer currents: $I = 0.1$ nA, 0.3 nA, and 1 nA. Panel B: variance of the drag resistance fluctuations as a function of driving current; $T = 50$ mK, $n = 1.45 \times 10^{13} \text{ cm}^{-2}$. Panel C: single-layer resistivity as a function of filling factor measured at the same three currents, at $T = 50$ mK, and $n = 0.57 \times 10^{11} \text{ cm}^{-2}$.}
\end{figure}

To summarize, we have seen reproducible fluctuations of the Coulomb drag between composite fermions when varying carrier concentration in the two layers and magnetic field. There is a large enhancement in the size of fluctuations relative to that seen in drag between normal electrons, as was predicted theoretically. At low temperatures the magnitude of the fluctuations exceeds the average drag, such that the sign of the drag changes randomly with varying $n$ and $B$. The decoherence length found from the quasiperiod of the drag fluctuations is close to that described by $e$-$e$ scattering. The magnitude of the drag fluctuations is found to exceed that expected from the theory developed for the diffusive regime, though to a lesser extent than that seen in the case of drag fluctuations between normal electrons due to the shorter mean free path of composite fermions.

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