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Giant fluctuations of Coulomb drag

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Abstract

We have observed reproducible fluctuations of the Coulomb drag resistivity, originating from coherent scattering of electrons in two layers. The fluctuations are observed as functions of both the carrier density of each layer, and perpendicular magnetic field. The magnitude of the fluctuations is much larger than expected from the theory of 'diffusive' drag and the temperature dependence is stronger than theoretically predicted. We account for this enhancement by considering the 'ballistic' nature of the drag in our system. We also present results on the fluctuations at large magnetic fields, where the lowest Landau level is half filled so that coherent drag occurs between composite fermions. The magnitude of fluctuations is seen to be greatly enhanced compared with the small field case, although fluctuations of composite fermion drag show much better agreement with the theory developed for the 'diffusive' drag regime.

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1. Introduction

Coulomb drag is the phenomenon where momentum is transferred between electrons in electrically isolated conductors via electron–electron (e–e) interactions. A typical measurement circuit is shown in Fig. 1: a current I_1 is passed through one of the layers, the 'active' layer, of a system composed of two parallel 2DEGs. Momentum transfer between electrons in the active layer and the second 'passive' layer then results in a voltage V_2. Thus, by measuring this voltage in the passive layer, one can calculate the Coulomb drag resistivity, $\rho_D = -V_2W/I_1L$ (W and L are the sample width and length, respectively), which is a direct measure of the strength of e–e interactions between the layers.

Measurements of Coulomb drag were first suggested several decades ago [1,2], although it was some time before samples of sufficient quality and complexity could be made in order to observe this effect. Since then, much experimental and theoretical work has been done concerning drag (for a review, see Ref. [3]), including recent observations of Bose-condensation of interlayer excitons [4], Wigner crystal formation in 1D wires [5], and large enhancements of the drag near $\nu = \frac{1}{2}$ [6]. Of particular relevance to this paper are the theories predicting the effects of coherent transport in the layers on drag—reproducible drag resistivity fluctuations, analogous to universal conductivity fluctuations (UCF) seen in single-layer samples. We earlier reported the first observation of these fluctuations, and their measurement as a function of temperature [7]. Here we describe these measurements in greater detail, as well as the study of their behaviour as a function of the conductivity of the layers constituting the double-layer system. We also report the study of Coulomb drag fluctuations in the first half-filled Landau level at strong magnetic fields.

The origin of fluctuations in the drag resistivity is similar to those seen in the single-layer resistivity: interference of electron waves over the coherence length, L_φ. However, the fluctuations in the drag do differ significantly from UCF. Whilst the fluctuations of the drag are small in absolute magnitude (typically, for our samples, $\Delta\rho_D \sim 10\,\mathrm{m}\Omega$, whilst $\Delta\rho \sim 100\,\mathrm{m}\Omega$) the fluctuations of the drag can greatly exceed

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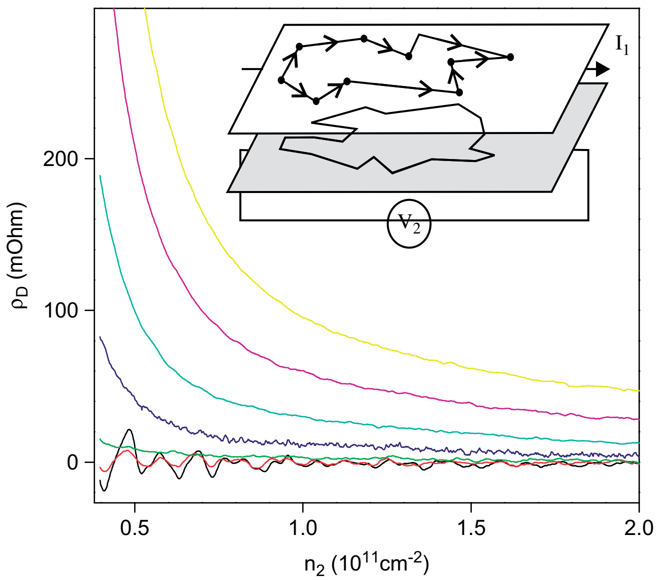

Fig. 1. Drag resistivity as a function of passive-layer carrier concentration for different temperatures: $T = 5, 4, 3, 2, 1, 0.4$, and 0.24 K, from top to bottom. Inset: schematic of drag measurement, where I_1 is the current in the active layer and V_2 is the voltage in the passive layer. (Figure adapted from Ref. [7].)

the average value of drag resistivity. Thus, as the concentration or magnetic field are varied, the drag resistivity changes its sign randomly, but reproducibly, between negative and positive.

Our explanation of the giant drag fluctuations takes into account that, unlike UCF, the drag fluctuations are not only an interference but also fundamentally an interaction effect. In conventional drag structures the electron mean free path l is much larger than the separation d between the layers, and therefore large momentum transfers $\hbar q$ between electrons in the layers become essential. According to the quantum mechanical uncertainty principle, $\Delta r \Delta q \sim 1$, electrons interact over small distances $\Delta r \ll l$ when exchanging large values of momentum. As a result the local properties of the layers, such as the local density of electron states (LDoS), become important in the interlayer e–e interaction. These local properties at the scale $\Delta r \ll l$ exhibit strong fluctuations [8] that directly manifest themselves in the fluctuations of the Coulomb drag, which are enhanced compared with the prediction for the diffusive regime, $l \ll d$ [9].

2. Samples

The samples studied in this work are AlGaAs–GaAs double-layer structures, where the carrier concentration of each layer can be independently controlled by gate voltage over the range $n = 2.0\text{–}0.4 \times 10^{11}\,\mathrm{cm}^{-2}$, with a corresponding change in the mobility from 6.7 to $1.2 \times 10^5\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$. The GaAs quantum wells are 200 Å in thickness, and are separated by an $Al_{0.33}Ga_{0.67}As$ 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.

3. Weak *B*-field

Fig. 1 shows the drag resistivity dependence upon the carrier concentration of the passive layer for different temperatures in the temperature range above 1 K, where the conventional T^2 and $n_2^{-1.5}$ dependences [10,11] are seen. However, as the temperature falls below 500 mK (the bottom two graphs of Fig. 1) reproducible fluctuations appear in the drag resistivity.

The appearance of the fluctuations is better seen in Fig. 2. In panel A the fluctuations in ρ_D as a function of concentration are seen to be reproducible, and increase in magnitude with decreasing temperature. The inset shows the non-monotonic behaviour of the drag resistivity for two values of concentration, indicated by the dashed lines in panel A. At high temperatures the drag resistivity shows the usual monotonic T^2 behaviour, but as the temperature decreases the magnitude of the drag resistivity increases with decreasing temperature and the drag becomes increasingly negative or positive, dependent upon the carrier concentration and *B*-field. The fluctuations are also seen in the drag magnetoresistivity, shown in panel B of Fig. 2. The temperature dependence of these fluctuations is similar to that seen in panel A, and for a given T the fluctuations of drag resistivity in concentration and magnetic field are of similar magnitude.

In Ref. [9] the variance of Coulomb drag fluctuations is calculated for the so-called diffusive regime, $l < d$. In this case the drag is determined by global properties of the layers, averaged over a region $\Delta r \gg l$. The expected variance of drag fluctuations (at low T when the fluctuations exceed

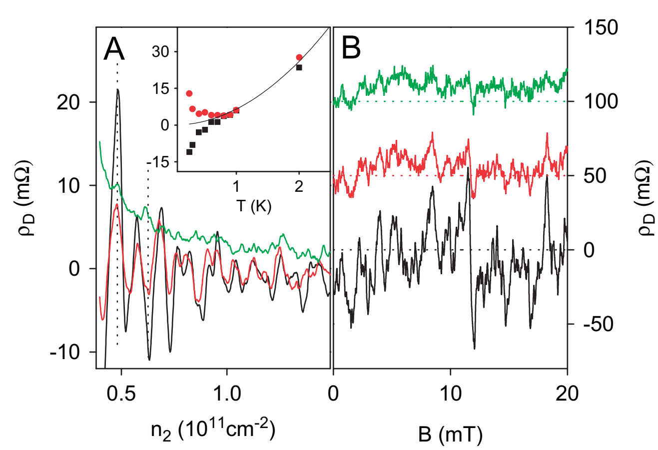

Fig. 2. Drag resistivity measured at low temperatures as a function of passive-layer concentration; $T = 1$, 0.4, and 0.24 K, from top to bottom. Inset: ρ_D as a function of T for two values of n_2 denoted by the dotted lines in panel A; solid line is the expected T^2 dependence of the average drag. (B) ρ_D as a function of B; $T = 0.4, 0.35$, and 0.24 K, from top to bottom. (Graphs for higher T are vertically offset for clarity.) Single-layer concentration for each layer is $5.8 \times 10^{10}\,\mathrm{cm}^{-2}$. (Figure adapted from Ref. [7].)

the average) in the diffusive regime for our experimental conditions is $\sim 6\times10^{-11}\,\mu S^2$, which is approximately eight orders of magnitude smaller than the variance of the observed drag fluctuations. We have observed similar fluctuations in ρ_D in two different samples, confirming the discrepancy with the theoretical prediction [9].

As the expected fluctuations of the drag conductivity share the same origin as UCF in the conductivity, we have compared the drag fluctuations with the fluctuations seen in the single-layer resistivity of the same structure (Fig. 3). We estimate the expected variance of the single-layer conductivity fluctuations using the relation $\langle \Delta\sigma_{xx}^2\rangle = (e^2/h)^2(L_T/L)^2$, where $L_T=(\hbar D/k_B T)^{1/2}$ is the thermal length and L is the size of the sample [12]. This expression produces a value of $0.8\,\mu S^2$, which is in good agreement with the measured value of $0.6\,\mu S^2$. The typical 'period' of the drag fluctuations (the correlation field, ΔB_c) is similar to that of the UCF [13], indicating that both depend upon the same L_φ and have the same quantum origin.

To address the question of the discrepancy between the magnitude of drag fluctuations in theory [9] and our observations, we stress that the theoretical prediction for the variance was obtained under the assumption of small interlayer momentum transfers, $q \ll 1/l$. In all regimes the momentum transfers are limited by $q<1/d$. In the diffusive regime, $l<d$, this relation also means that $q<1/l$, that is, interlayer e–e interactions occur at distances $\Delta r>l$ and involve scattering by many impurities in the individual layers. In the opposite situation, $l \gg d$, the transferred momenta will include both small and large q-values: $q<1/l$ and $1/l<q<1/d$. As small q cannot explain the large fluctuations of the drag [9], we suggest that it is large momentum transfers with $q>1/l$ which give rise to the observed effect. In this case the two electrons interact at a distance Δr that is smaller than the average impurity separation and, therefore, it is the local electron properties of the layers which determine the fluctuations of the drag. In Ref. [8] it is shown that the fluctuations of the local properties are larger compared to those of the global properties that are responsible for the drag in the diffusive case of e–e interaction.

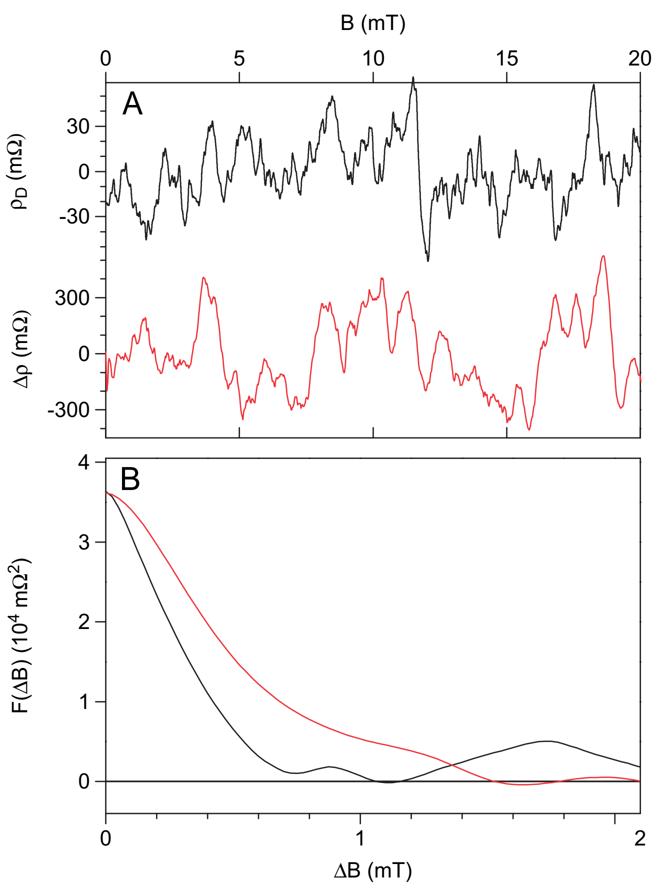

Fig. 3. (A) Comparison of single-layer resistivity fluctuations (bottom) and drag resistivity fluctuations (top); $T = 240$ mK. The values of $\Delta\rho$ are found by subtracting the background single-layer resistance of 500 Ω. (B) Autocorrelation functions, $F(\Delta B)$, of graphs in (A). $F(\Delta B)$ of drag resistivity fluctuations (lower curve) is multiplied by 80.

Using a Kubo formula analysis [14–17] a theoretical expression for the drag conductivity is obtained (for an in depth description see Ref. [7] and associated supporting online material). In making a qualitative estimate three factors have to be taken into account: (i) the inter-layer matrix elements of the Coulomb interaction $\mathscr{D}_{ij}$; (ii) the phase space (the number of electron states available for scattering); and (iii) the electron–hole (e–h) asymmetry in both layers. The physical quantity that measures the degree of e–h asymmetry is the non-linear susceptibility Γ of the 2D layer. The e–h asymmetry appears in Γ as a derivative of the density of states ν and the diffusion coefficient D: $\Gamma \propto \partial(\nu D)/\partial\mu$, and it is this quantity that is responsible for the fact that drag fluctuations can exceed the average. As $D\nu \sim g$, where g is the dimensionless conductivity, and the typical energy of electrons is the Fermi energy, E_F, we have $\partial(\nu D)/\partial\mu \sim g/E_F$ for the average drag. The typical energy scale for the interfering electrons, however, is $E_T(L_\varphi)$ [12], which is much smaller than E_F and therefore a mesoscopic system has larger e–h asymmetry.

Under the condition of large momentum transfer between the layers, fluctuations in Γ are similar to the fluctuations of the LDoS, which can be estimated as $\delta\nu^2 \sim (\nu^2/g)\ln(\max(L_\varphi, L_T)/l)$ [8]. Also, the interaction in the ballistic regime can be assumed to be constant, $\mathscr{D}_{ij} \approx -1/\nu\kappa d$, as q is limited by $q \leqslant 1/d$. Finally, fluctuations of the drag are suppressed by L_φ/L and L_T/L_φ due to inelastic scattering over the distance L_φ and thermal smearing over $E_T(L_\varphi)$, respectively. Combining the above arguments we find

$$\langle \Delta\sigma_D^2\rangle = N\frac{e^4}{g^2\hbar^2(\kappa d)^4}\frac{(k_B T)^2}{E_T^2(L_\varphi)}\frac{l^4 L_\varphi^2}{d^4 L^2}, \qquad (1)$$

where N is a numerical coefficient.

Compared to the diffusive situation [9] the fluctuations described by our model are greatly enhanced. Large momentum transfers lead to the appearance of three extra factors in Eq. (1), each leading to an increase in the size of fluctuations: (i) l^4/d^4, which is also present in the average drag in the ballistic regime [14]; (ii) the phase space factor T/E_T; and (iii) the factor g^2 due to fluctuations of the local non-linear susceptibility. Physically, local fluctuations are enhanced since the random quantity Γ is now averaged over a small part of the ensemble, allowing one to detect rare impurity configurations.

In addition to explaining the large magnitude of the fluctuations, this model also predicts a non-trivial temperature dependence of their magnitude. This comes from the conventional change in the temperature dependence of L_φ [18]: at low temperatures, $k_B T\tau/\hbar \ll 1$, the usual result is $L_\varphi \propto T^{-1/2}$, while for $k_B T\tau/\hbar > 1$ the temperature dependence changes to $L_\varphi \propto T^{-1}$ [19]. Consequently, the temperature dependence of the variance of the drag fluctuations is expected to change from T^{-1} at low T, to T^{-4} at high T. This temperature dependence is very different from the T-dependence of drag fluctuations in the diffusive regime, $\langle \Delta\sigma_D^2 \rangle \propto T^{-1}$.

To test the prediction of Eq. (1), the T-dependence of $\langle \Delta\sigma_D^2 \rangle$ has been analysed, Fig. 4. The variance is calculated in the limits of both $T\tau_\varphi < 1$ (solid line, $\tau_\varphi^{-1} \propto T$) and $T\tau_\varphi > 1$ (dashed line, $\tau_\varphi^{-1} \propto T^2$), using $N \simeq 10^{-4}$. In fitting the drag variance we have found τ_φ to agree with theory to within a factor of two [13], which is typical of the agreement found in other experiments on determining τ_φ [20]. Thus, the temperature dependence of the observed drag fluctuations strongly supports the validity of our explanation.

In addition to the T-dependence of the drag fluctuations, we have also observed a dependence of the magnitude of the drag on the conductivity of each of the layers. Fig. 5 shows the fluctuations of the drag conductivity as the B-field is varied, for different values of the active- and passive-layer conductivities. These fluctuations are attained

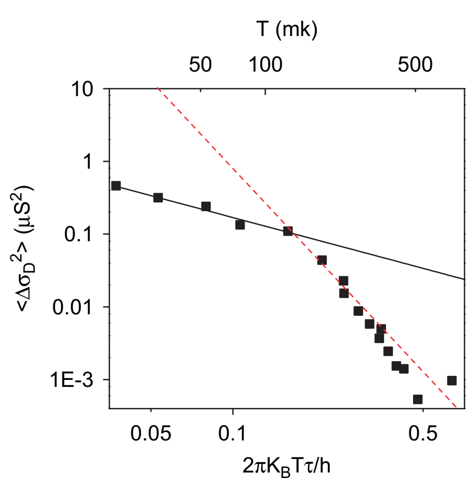

Fig. 4. The variance of the drag conductivity fluctuations (squares) plotted against temperature. The solid and dashed lines are calculated using Eq. (1) with the diffusive and ballistic asymptotes of $\tau_\varphi(T)$, respectively. $n = 5.8 \times 10^{10}\,\mathrm{cm}^{-2}$. (Figure adapted from Ref. [7].)

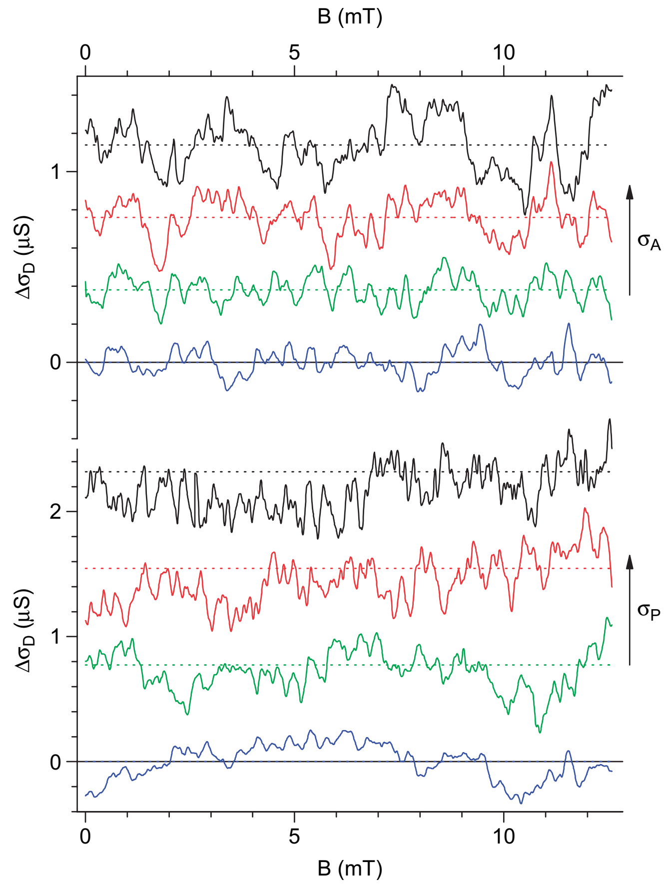

Fig. 5. Top: drag magnetoconductivity fluctuations, $\Delta\sigma_D(B)$, for different values of active-layer conductivity, σ_A; $\sigma_A = 10, 5.6, 3.8, 2.2\,\mathrm{mS}$ from top to bottom, $\sigma_P = 2.4\,\mathrm{mS}$. Bottom: drag magnetoconductivity fluctuations for different values of passive-layer conductivity, σ_P; $\sigma_P = 11, 6.4, 4.3, 2.4\,\mathrm{mS}$ from top to bottom, $\sigma_A = 2.2\,\mathrm{mS}$. $T = 240\,\mathrm{mK}$.

after subtracting an average background value of the drag conductivity, which is small in comparison to the fluctuations in σ_D. It can be seen that the magnitude of the fluctuations increases with increasing conductivity of either the active or passive layers. The increase of $\langle \Delta\sigma_D^2 \rangle$ with increasing σ_A, σ_P follows from Eq. (1) and the g dependences of $L_\varphi \propto g$, $l \propto g^{3/4}$ and $D \propto g$. It is interesting to note that the mesoscopic 'fingerprint' of the drag fluctuations are affected by both σ_A and σ_P. This is a characteristic feature of the drag fluctuations, which originate from the interference pattern of both layers.

4. Strong *B*-field

Fig. 6 shows reproducible fluctuations of the drag resistivity near filling factor $\nu = \frac{1}{2}$. These fluctuations are seen both by varying the concentration and magnetic field. Note that the size of these fluctuations is greatly enhanced, by three orders of magnitude, in comparison to those seen at small B. (It is interesting to note that a similar increase was observed in the average drag resistivity at $\nu = \frac{1}{2}$ [6].) In Fig. 6 the fluctuations of the drag in both concentration

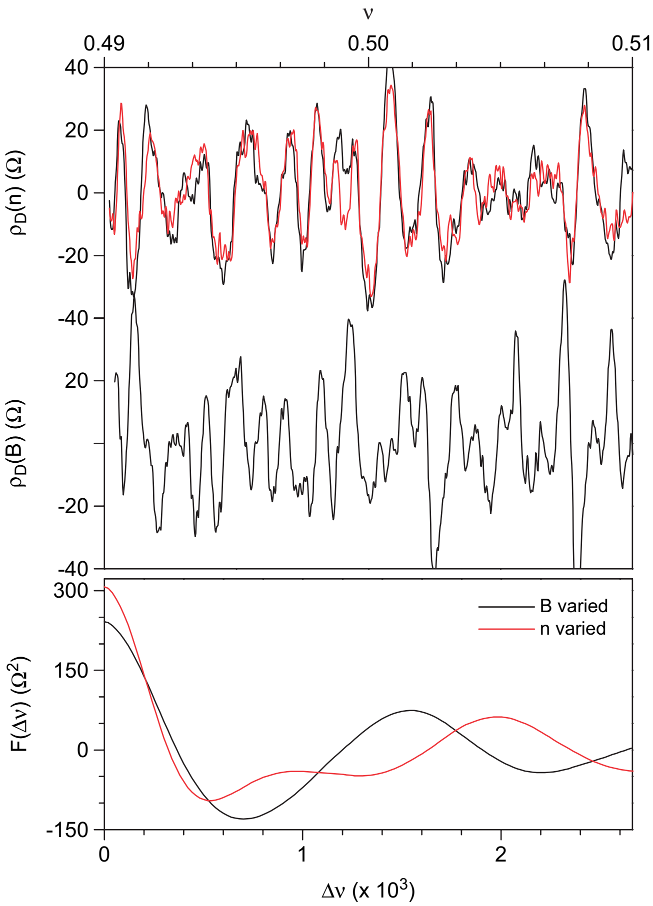

Fig. 6. (A) Comparison of drag resistivity fluctuations near $\nu = \frac{1}{2}$ as a function of concentration (top) and magnetic field (bottom); $T = 50\,\text{mK}$. A repeat measurement of $\rho_D(n)$ is shown to demonstrate reproducibility. (B) Autocorrelation functions, $F(\Delta\nu)$, of graphs in (A).

and magnetic field are plotted as a function of ν, and it is immediately seen that their 'periods' are very close. This is confirmed in the comparison of their autocorrelation functions, Fig. 6, bottom panel. This similarity represents one of the main properties of the fluctuations of the composite fermions: $B_c/n_c = 2\Phi_0$, where B_c and n_c are the correlation magnetic field and correlation concentration, respectively, and Φ_0 is the quantum of magnetic flux. This property of the fluctuations of the resistivity of the composite fermions in single-layer systems was discussed in Refs. [21,22]. The estimated value of L_φ for composite fermions found from the correlation fields in Fig. 6 is $\sim 1\,\mu\text{m}$ at $T = 50\,\text{mK}$.

It is tempting to compare the amplitude of the fluctuations with the predictions for the magnitude of the fluctuations of drag resistivity arising between CFs [23]. This theory has also been developed for the diffusive regime of drag, $d \gg l$, and so one would expect that the fluctuations of the drag would be larger in experiment, similar to the small magnetic field case. To compare the results with the theory one has to find the dimensionless conductance of CFs, $g_{cf} = e^2/4h\sigma_{xx}$, which is ~ 5 in our experiment. Using this value of g_{cf}, we can estimate the magnitude of the drag fluctuations according to Ref. [23], which appears to be of the same order as that seen in experiment. This, at first surprising, agreement with the theory can be related to the fact that CFs have a smaller mean free path than bare electrons, and thus are in the diffusive regime for drag, $l \ll d$. In order to get the large value of L_φ, the CF, with a small g_{cf}, should have a relatively large coherence time. It will be interesting in the next stage of experiments to investigate in more detail the processes that control the dephasing of CFs, especially in the situation of Coulomb drag.

To summarize, we have seen reproducible fluctuations of the Coulomb drag conductivity with varying carrier concentration and magnetic field. In weak fields their magnitude is much larger than expected for the diffusive regime of e–e interactions, $l \ll d$. We explain this by the sensitivity of mesoscopic drag in the ballistic regime, $l \gg d$, to local properties of the system. Contrary to UCF, fluctuations of the drag are larger than the average, so that drag resistivity randomly changes its sign. Another difference from UCF is that the fluctuations of the drag resistivity are controlled by the carrier concentration of both layers. Finally, we have observed fluctuations of the drag in strong magnetic fields around $\nu = \frac{1}{2}$, where drag occurs between interacting composite fermions. We have observed a large enhancement of the drag fluctuations relative to the weak field case, although its magnitude is much closer to the predictions of the theory developed for the diffusive regime.

References

[1] M.B. Pogrebinskii, Sov. Phys. Semicond. 11 (1977) 372.
[2] P.J. Price, Physica B 117 (1983) 750.
[3] A.G. Rojo, J. Phys. Condens. Matter 11 (1999) R31.
[4] M. Kellogg, J.P. Eisenstein, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. 93 (2004) 036801.
[5] M. Yamamoto, M. Stopa, Y. Tokura, Y. Hirayama, S. Tarucha, Science 313 (2006) 204.
[6] M.P. Lilly, J.P. Eisenstein, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. 80 (1998) 1714.
[7] A.S. Price, A.S. Savchenko, B.N. Narozhny, G. Allison, D.A. Ritchie, Science 316 (2007) 99.
[8] I.V. Lerner, Phys. Lett. A 133 (1988) 253.
[9] B.N. Narozhny, I.L. Aleiner, Phys. Rev. Lett. 84 (2000) 5383.
[10] T.J. Gramila, J.P. Eisenstein, A.H. MacDonald, L.N. Pfeiffer, K.W. West, Phys. Rev. Lett. 66 (1991) 1216.
[11] M. Kellogg, J.P. Eisenstein, L.N. Pfeiffer, K.W. West, Solid State Comm. 123 (2002) 515.
[12] B.L. Al'tshuler, P.A. Lee, R.A. Webb (Eds.), Mesoscopic Phenomena in Solids, North-Holland, New York, 1991.
[13] Further experimental and theoretical details are available as supporting material on Science Online.
[14] A. Kamenev, Y. Oreg, Phys. Rev. B 52 (1995) 7516.
[15] L. Zheng, A.H. MacDonald, Phys. Rev. B 48 (1993) 8203.
[16] A.-P. Jauho, H. Smith, Phys. Rev. B 47 (1993) 4420.
[17] K. Flensberg, B.Y.-K. Hu, A.-P. Jauho, J.M. Kinaret, Phys. Rev. B 52 (1995) 14761.
[18] B.N. Narozhny, G. Zala, I.L. Aleiner, Phys. Rev. B 65 (2002) 180202.

[19] B.L. Altshuler, A.G. Aronov, in: A.L. Efros, M. Pollak (Eds.), Electron–Electron Interactions in Disordered Systems, North-Holland, Amsterdam, 1985.
[20] C.W.J. Beenakker, H. van Houten, in: H. Ehrenreich, D. Turnbull (Eds.), Solid State Physics, Academic Press Limited, 1991.
[21] V.I. Fal'ko, Phys. Rev. B 50 (1994) 17406.
[22] Z.D. Kvon, E.B. Olshanetsky, G.M. Gusev, J.C. Portal, D.K. Maude, Phys. Rev. B 56 (1997) 12112.
[23] B.N. Narozhny, I.L. Aleiner, A. Stern, Phys. Rev. Lett. 86 (2001) 3610.