Thermally-Activated Coulomb Drag in Higher Landau Levels

K. Muraki[1, 2], J.G.S. Lok[1], S. Kraus[1], W. Dietsche[1], K. von Klitzing[1], D. Schuh[3], M. Bichler[3], and W. Wegscheider[3]

[1] *Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany*
[2] *NTT Basic Research Laboratories, 3-1 Morinosato-Wakamiya, Atsugi 243-0198, Japan*
[3] *Walter-Schottky-Institut, Technische Universtät München, 85748 Garching, Germany*

Coulomb drag in double-layer two-dimensional electron systems (2DESs) [1], in which a current driven in one layer causes a voltage in the other layer via interlayer electron-electron scattering, has been used to study interlayer interactions, while the technique is also a sensitive probe of the density response and hence correlations within each layer. Here, we present systematic studies of Coulomb drag in the quantum Hall systems over unprecedentedly wide ranges of temperature (50 mK < T < 16 K) and filling factor ($1 < \nu < 14$). The data reveal in the higher ($N \geq 1$) Landau levels the presence of anomalous drag which grows upon decreasing T and then turns to decrease for $T \to 0$. In stead of commonly assumed power law, we find that the low-T behavior is well described by thermal activation. We ascribe this anomalous drag to scattering of electrons or holes between localized states at the Fermi level and delocalized states at the Landau level center. The sign change of drag with the filling factor difference [2] is discussed in terms of the electron-hole asymmetry in the relative positions of the Fermi level and the delocalized states.

The sample studied is an independently-contacted double-layer 2DES in 25-nm GaAs quantum wells separated by an 18-nm AlGaAs barrier. We observe that the drag in the lowest ($N = 0$) Landau level ($\nu = 3/2$) well follows a power law, $\rho_T \propto T^{4/3}$ (ρ_T: transresistivity), for $T < 1.2$ K in an excellent agreement with the theoretical predictions for composite fermions [3]. The power law indicates continuous density of states and gapless excitations available for the interlayer scattering. By contrast, for higher ($N \geq 1$) Landau levels, the power-law is relevant only in the high T regime (> 2 K), and the low-T drag is dominated by an anomalous contribution which grows upon decreasing T and then turns to decrease upon further reducing T. Instead of a power law usually expected for Coulomb drag, we find that this anomalous drag follows the thermal activation, $\rho_T \propto \exp(-\Delta/T)$, on the low-$T$ side, suggesting a finite energy gap (Δ) between the Fermi level and the states involved in the scattering. Systematic studies of the activation energy as a function of the filling factor show that the anomalous drag reflects the electron-hole asymmetry associated with the positions of the Fermi level with respect to the delocalized states. As the magnetic field is increased, the anomalous drag is taken over by normal power-law-like behavior, with simultaneous disappearance of the negative drag. We argue that this probes the crossover from a disorder-induced incompressible liquid at low fields to an interaction-induced compressible liquid at high fields, which results from the interplay of disorder and screening [4].

[1] Gramila *et al*., Phys. Rev. Lett. **66**, 1216 (1991).

[2] Feng *et al*., Phys. Rev. Lett. **81**, 3219 (1998); Lok *et al*., Phys. Rev. B **63**, 041305 (2001).

[3] Sakhi, Phys. Rev. B **56**, 4098 (1997); Ussishkin and Stern, *ibid*. **56**, 4013 (1997).

[4] Cooper and Chalker, Phys. Rev. B **48**, 4530 (1993).

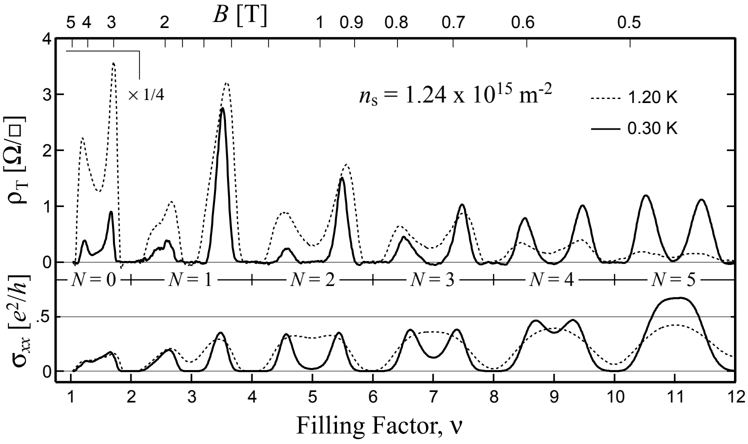

FIG. 1 Transresistivity ρ_T (top) and longitudinal conductivity σ_{xx} (bottom) of the front layer as a function of filling factor ν, measured for matched densities of 1.24 x 10^{15} m^{-2}. Sample is a 25-nm GaAs double quantum well structure with an18-nm AlGaAs barrier. σ_{xx} is calculated from matrix inversion of measured ρ_{xx} and ρ_{xy}.

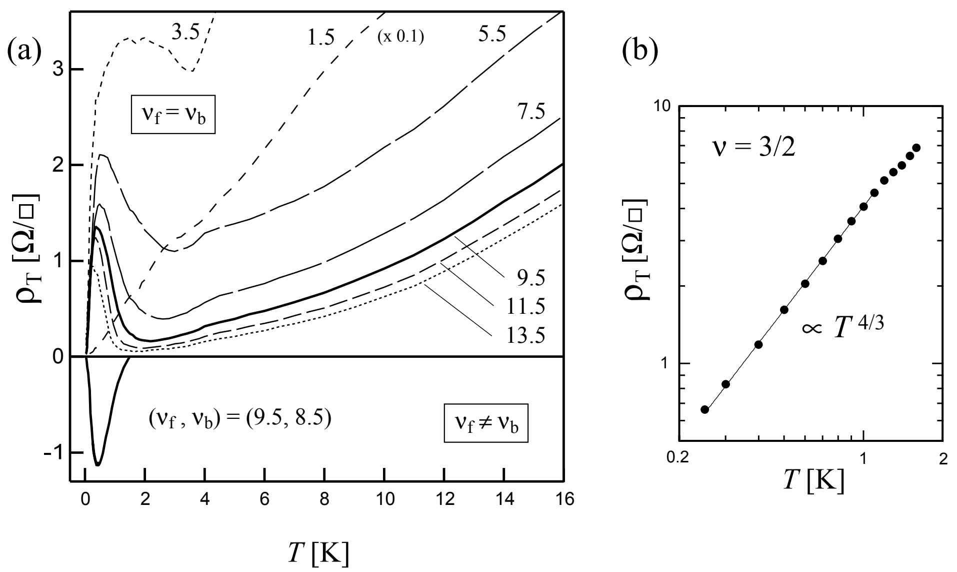

FIG. 2 (a) Temperature dependence of ρ_T for various half-integer fillings. Upper panel shows data for matched densities, while lower pannel shows negative drag for mismatched densities. The data for the mismatched densities are shown only for $T < 1.2$ K, above which ρ_T turns to positive and follows the curve for the matched densities. The data reveal two contributions to the drag in higher ($N \geq 1$) Landau levels, and the equivalence of the anomalous contribution on the low-T regime and the negative drag for mismatched densities, both of which grow anomalously with decreasing T. The anomalous contribution is absent in the lowest ($N = 0$) Landau level.
(b) Log-log plot of ρ_T for ν = 3/2, demonstrating the power law, $\rho_T \propto T^{4/3}$, in excellent agreement with the theoretical predictioins for composite-fermion liquid.

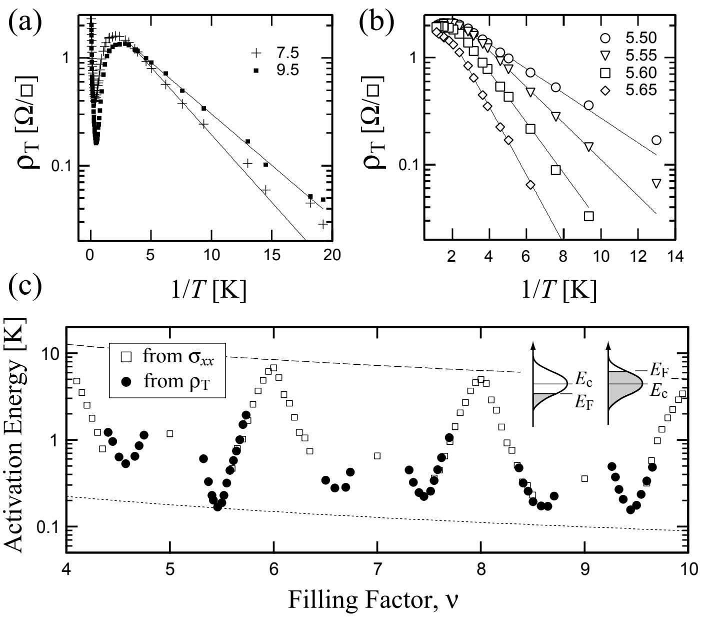

FIG. 3 Arrhenius plot of ρ_T vs. $1/T$ for (a) ν = 7.5 and 9.5 and (b) ν = 5.50 - 5.65. The data reveal thermal activation behavior, $\rho_T \propto \exp(-\Delta/T)$.
(c) Comparison of the activation energies Δ for ρ_T (closed circles) and U for σ_{xx} (open squares) of the front layer, plotted as a function of ν. The dashed and dotted lines represent the cyclotron and bare Zeeman energies in GaAs. When the Fermi level (E_F) is not too close to an integer, the activation energy U corresponds to the energy difference between E_F and the energy of the extended states, E_c. [inset of (c)].