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Transport anomalies in the lowest Landau level of two-dimensional electrons at half-filling

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We observe deep minima in the diagonal resistivity ρ_{xx} of a two-dimensional electron system in GaAs at Landau-level filling factor $\nu=\frac{1}{2}$ and $\frac{3}{2}$. The anomalies saturate at nonzero values of ρ_{xx} as $T\rightarrow 0$ and persist up to temperatures of ~ 10 K. In spite of the strength of the ρ_{xx} features, no indication of plateau development is visible in the Hall resistance ρ_{xy}. These structures at half-filling appear to have their origin in a novel many-particle state distinctly different from the fractional quantum Hall effect.

Traditionally, Landau-level filling factor $\nu=\frac{1}{2}$ has played an important role in theory and experiment of magnetotransport on two-dimensional (2D) electron systems. At $\nu=\frac{1}{2}$ the lowest singularity in the density of states is half filled and any single-particle transport model will predict a strong maximum in the diagonal conductivity. For short-range scattering, in fact, this peak conductivity is found theoretically to be quantized, depending on the Landau-level index and the value of natural constants.[1] Even in the presence of strong electron-electron correlation, $\nu=\frac{1}{2}$ is expected to assume a singular position since any ground state has to map onto itself by electron-hole symmetry. With the discovery of the fractional quantized Hall effect[2] (FQHE), this most rudimentary fractional filling factor has received diminishing attention since there existed ample evidence in experiment and theory alike for the existence of exclusively odd-denominator rational FQHE states.[3-6] Within the theory for the FQHE,[4-6] $\nu=\frac{1}{2}$ has taken the role of an accumulation point for odd-denominator fractions providing the possibility for spontaneous phase separation[6] and the formation of domains of adjacent odd-denominator FQHE states.

The recent discovery of the first even-denominator fractional quantum number at $\nu=\frac{5}{2}$ in the first excited Landau level[7] has created considerable uncertainty as to the consequences of electron-electron correlations at $\nu=\frac{1}{2}$. The incorporation of the spin degree of freedom[8-12] into the theory of the FQHE has circumvented the odd-denominator rule and created the possibility for the formation of condensed quantum liquids at any rational filling factor—including those with even denominators. While this generalization has created the potential for a FQHE state at $\nu=\frac{1}{2}$ and at its equivalent $\nu=\frac{3}{2}$ in the upper spin state, the theory is insufficiently developed to make any quantitative prediction. In fact, recent numerical few-particle calculations indicate a ground state distinctly different from a FQHE state. Electron-pair correlations at $\nu=\frac{1}{2}$ are found to be "Wigner crystal-like"[13] and there appears to be a preference for the formation of small regular electron clusters.[13,14]

Experimentally there has been very little activity for $\nu=\frac{1}{2}$. Past transport experiments on two-dimensional systems have mentioned weak and broad depressions[7] in ρ_{xx} at $\nu=\frac{1}{2}$ in stark contrast to the deep and sharp minima of the neighboring FQHE states. The lack of any associated structure in ρ_{xy} was in accord with the weakness of the features in ρ_{xx}. This led to the speculation that the broad basin around $\nu=\frac{1}{2}$ was merely caused by an accumulation of unresolved odd-denominator FQHE states in its vicinity.[7] Recently evidence has been presented for the existence of a $\nu=\frac{1}{2}$ plateau in the Hall resistance of a quasi-one-dimensional electron system.[15] However, it is believed that this anomaly is intimately related to the reduced dimensionality of the specimen.

In this paper we present magnetotransport data on a very low-disorder 2D electron system and observe, different from any earlier attempts, deep low-temperature minima in ρ_{xx} at $\nu=\frac{1}{2}$ and $\frac{3}{2}$. In spite of the fact that their strength *exceeds* the strength of neighboring FQHE states, which are accompanied by well-developed quantized ρ_{xy} plateaus, no such plateaus are found at these even-denominator filling factors. The ρ_{xx} structures, while superficially resembling the transport features of the FQHE, persist up to temperatures of ~ 10 K where all signs of FQHE states have vanished. At low temperature the minima do not approach $\rho_{xx}=0$ but saturate at nonzero values. These strong transport anomalies cannot be of single-particle origin, but appear to be the result of a novel electron-electron correlation phenomenon in the ground Landau level of the 2D electron system, distinctly different from the FQHE.

Our experiment is performed on an exceptionally high-quality, modulation-doped GaAs/(AlGa)As heterostructure with a zero-field mobility of 9.7×10^{6} $\mathrm{cm^2/V\,sec}$ at a carrier density of 1.7×10^{11} $\mathrm{cm^{-2}}$. These values are achieved after a standard short-period illumination with visible light. A ^{3}He-^{4}He dilution refrigerator, a pumped ^{3}He refrigeration system, and a vapor-cooled ^{4}He system, are used to cover a temperature range from 80 mK to 10 K in various magnets with fields up to 31 T. Transport measurements are performed in the standard van der Pauw geometry on a 4×4 $\mathrm{mm^2}$ specimen with eight symmetrically placed In contacts, using lock-in techniques at frequencies between 3 and 13 Hz. Depending on the temperature range, current levels of 10 to 100 nA are used to avoid electron heating.

Figure 1 shows an overview of the diagonal resistivity ρ_{xx} at $T=80$ mK. The familiar pattern of minima indicating the integral quantum Hall effect (IQHE) and FQHE stands out. The appearance of FQHE features at odd-denominator filling factors as high as $\nu=\frac{6}{11}$ and at relatively modest magnetic fields attests to the exceptional quality of the specimen. The sample also manifests a high homogeneity by displaying almost identical transport patterns for several different contact configurations. All features of the data are reproducible after repeated (~20 times) cycling to room temperature.

A surprising observation is made at $\nu=\frac{1}{2}$ (and $\nu=\frac{3}{2}$). Deep minima develop in ρ_{xx} at these two *even-denominator* filling factors, comparable in depth to the neighboring minima associated with the odd-denominator FQHE. In spite of the appreciable depth of the structures in ρ_{xx}, there are no plateaus, nor any discernible indication of plateau development, visible in ρ_{xy} (Fig. 2). This is in contrast to the well-known interrelation between ρ_{xx} and ρ_{xy} in the FQHE, where plateaus in ρ_{xy} develop at a rather modest strength of the concomitant minima in ρ_{xx}.[16] The disparity is most evident when we compare the features of the $\nu=\frac{5}{9}$ and $\frac{4}{9}$ FQHE states with the features at $\nu=\frac{1}{2}$ in Fig. 2. The ρ_{xx} minimum at $\nu=\frac{4}{9}$ is accompanied by a well-developed plateau in ρ_{xy} and a plateau emerges also at $\nu=\frac{5}{9}$. The minimum at $\nu=\frac{1}{2}$, on the other hand, although it exceeds those neighboring ρ_{xx} features in depth, lacks any sign of plateau development in ρ_{xy}. In the upper spin level of the lowest Landau level, a similar statement can be made for $\nu=\frac{3}{2}$ and its relation to the neighboring odd-denominator FQHE states.

The structures at filling factors $\nu=\frac{1}{2}$ and $\frac{3}{2}$ differ from the FQHE in other ways. Figure 2 shows, as an example, the T dependence of ρ_{xx} in the vicinity of $\nu=\frac{1}{2}$. As T is lowered to 90 mK, the diagonal resistivity in the neighboring FQHE states drops exponentially toward $\rho_{xx}=0$ with a rate characteristic for the energy gap of the associated quasiparticle excitation. On the other hand, ρ_{xx} at $\nu=\frac{1}{2}$ shows no discernible T dependence at low temperatures and reaches a nonzero value as $T\rightarrow0$. At the other end of the temperature spectrum the minima surprisingly persist up to $T\sim10$ K at which all features of the FQHE have completely disappeared and only structures of the IQHE remain (Fig. 3). The strength of the $\nu=\frac{1}{2}$ minima varies approximately linearly with temperature (inset to Fig. 3) which differs greatly from the exponential dependence of the FQHE features. These observations clearly rule out the accumulation of weak, higher-order odd-denominator fractions in the vicinity of $\nu=\frac{1}{2}$ (and $\nu=\frac{3}{2}$) as the origin of the minima at these even-denominator filling factors.

An interesting feature emerges at the center of the $\nu=\frac{1}{2}$ structure at the lowest temperatures. A small cusp protrudes at $T\sim1$ K which appears to be superimposed on the wider, roughly parabolic minimum. It continues to sharpen down to ~400 mK but does not show any further development at lower temperatures. We have carefully studied the current and T dependence of the cusp in a

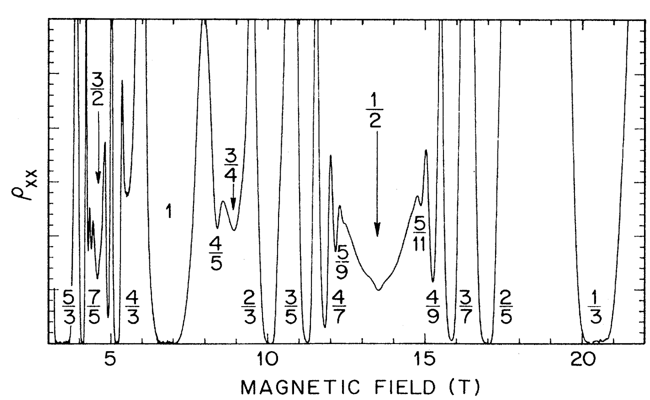

FIG. 1. Overview of diagonal resistivity ρ_{xx} at $T=80$ mK. Data for $\nu>1$ are amplified by a factor of 2 for clarity.

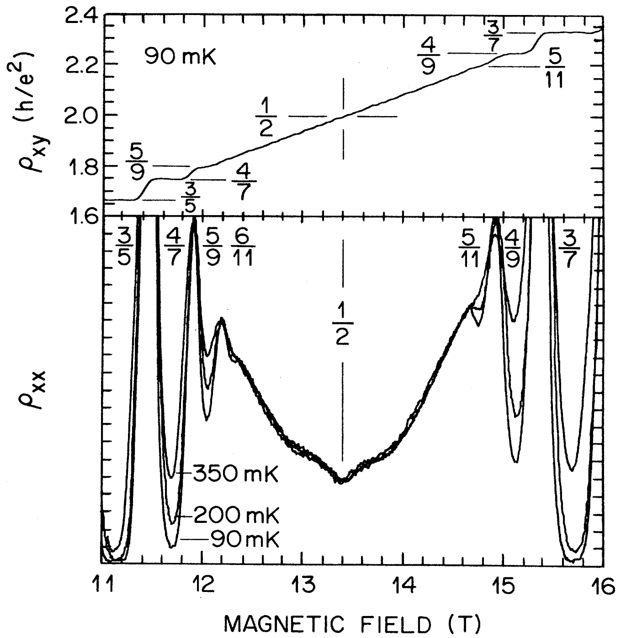

FIG. 2. Temperature dependence of ρ_{xx} in the vicinity of filling factor $\nu=\frac{1}{2}$ (bottom) and Hall resistance ρ_{xy} at $T=90$ mK (top).

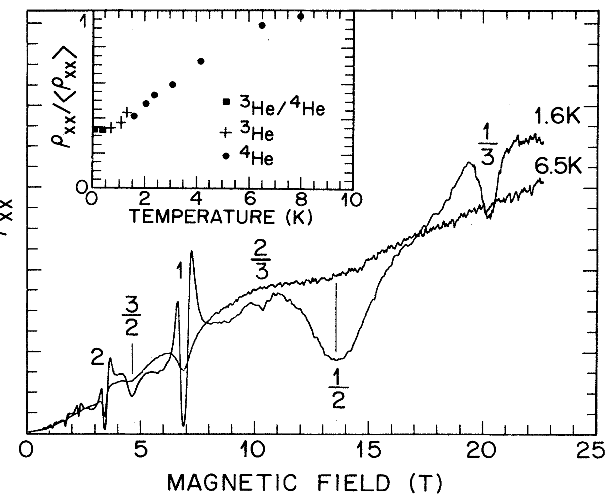

FIG. 3. High-temperature behavior of ρ_{xx} showing minima at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ in the absence of FQHE features. The inset quantifies the T dependence at $\nu=\frac{1}{2}$ showing the value of ρ_{xx} normalized to the value of the high-temperature background $\langle\rho_{xx}\rangle$ at $\nu=\frac{1}{2}$. The data are taken in three different refrigeration systems as indicated.

separate refrigerator down to 25 mK and can exclude electron heating effects from being the source for this saturation. The minimum at $\nu=\frac{3}{2}$ does not develop the same fine structure. This may be due to the much lower magnetic field at this filling factor.

While Fig. 1 shows clearly the existence of strongly developed minima at $\nu=\frac{1}{2}$ and $\frac{3}{2}$, there are also signs for the emergence of similar structures at other even-denominator filling factors. A much weaker minimum at $\nu=\frac{3}{4}$, mentioned earlier in the literature,[17,18] and a broad structure around $\nu\sim\frac{1}{4}$ (not shown in Fig. 1) are two examples of such features. Similar to the primary minima in ρ_{xx} at half-filling, they are comparatively wide and persist to much higher temperatures than the neighboring FQHE states. It remains to be seen whether there is a common origin to all these even-denominator effects and whether or not some of the weaker ρ_{xx} features (e.g., $\nu=\frac{3}{8}$) presently attributed to higher-order odd-denominator FQHE states (at $\nu=\frac{4}{11}$) are ultimately not of a similar even-denominator origin.

Transport measurements in tilted magnetic fields have recently been employed to provide first insight into the spin properties of certain FQHE states.[19] In particular, the rapid collapse of the $\nu=\frac{5}{2}$ FQHE states under tilt is interpreted as a strong indication of a spin-unpolarized or partially spin-polarized ground state.[19] We have applied this tool to the new transport anomalies at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ by measuring ρ_{xx} at 450 mK in magnetic fields inclined by 45° and 60° with respect to the sample normal. All features in the vicinity of $\nu=\frac{1}{2}$ and $\frac{3}{2}$ including their relative strength are exactly reproduced—even the cusplike fine structure.

From these observations we may conclude that there exist distinct states at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ in the lowest Landau level. These novel ρ_{xx} minima at half-filling appear to be of many-particle origin since any single-particle model will predict a peak in σ_{xx} leading to a maximum in ρ_{xx} in contrast to experiment. The close resemblance in the shape of the structures at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ suggest a common origin, whereby the $\nu=\frac{3}{2}$ state in the upper spin level is a mere copy of the $\nu=\frac{1}{2}$ state in the lower spin level. Within each of these many-particle states the electron spins seem to be totally polarized since the transport features are unaffected by tilting of the magnetic field. And finally, the states at half-filling are distinctly different from the FQHE states as can be deduced from their unusual T dependence in ρ_{xx} and the lack of plateaus in ρ_{xy}.

Early Hartree-Fock calculations by Kuramoto and Gerhardt[20] predicted the existence of two degenerate square charge-density waves (CDW) at $\nu=\frac{1}{2}$, with a density pattern dual to each other. Within this approximation, the density of states vanishes at exactly half-filling. Little is known about the transport properties of such a CDW state. However, with the recently acquired knowledge about the effect of gaps in the density of states on magnetotransport in 2D systems, it is conceivable that our data at $\nu=\frac{1}{2}$ and $\frac{3}{2}$ are related to such a CDW state.

Along with the recent search for a wave function[9-12] to describe the first even-denominator FQHE in the second Landau level at $\nu=\frac{5}{2}$, there have been several studies on the possibility for electron condensation at $\nu=\frac{1}{2}$. Various candidates for the $\nu=\frac{1}{2}$ ground states with different spin polarizations have been proposed. None of the totally spin-polarized states shows satisfactory overlap with the result of few-particle calculations using a physically realistic Hamiltonian.[12] The experimental data suggest that, indeed, such a FQHE state is not realized in our 2D system, at least at magnetic fields $B\gtrsim 4.5$ T.

Numerical few-particle calculations themselves have shown somewhat erratic behavior[13,21-23] at $\nu=\frac{1}{2}$. In contrast to the well-studied states at $\nu=\frac{1}{3}$, results at half-filling are found to be strongly dependent on geometry and on particle number. The most extensive few-particle numerical calculations at $\nu=\frac{1}{2}$ have recently been performed by Fano, Ortolani, and Tossati.[13] Their results portray a rather peculiar electronic state. These authors find a ground state whose pair correlations are Wigner crystal-like at least for their finite-size system. There appears to exist a gap for quasiparticle excitations analogous to the gap in the FQHE state. However, these quasiparticles are very extended objects and may resist localization by potential fluctuations.

Several of our experimental findings are in accord with these theoretical results. A highly correlated ground state, not too dissimilar to a FQHE state, may well lead to a reduction in σ_{xx} and, hence, to a minimum in ρ_{xx}. The "deformability" of the system, on the other hand, could prevent ρ_{xx} from attaining vanishing values and ρ_{xy} from being quantized, as observed in the experiment. The relatively high stability of the $\nu=\frac{1}{2}$ state and the origin of the fine structure remains unclear.

A very large gap at $\nu=\frac{1}{2}$, larger than the biggest

FQHE gap at $\nu = \frac{1}{3}$, is derived from a very recent calculation using an analytical method.[14] In this model the state is not homogeneous but consists of small electron clusters. The transport properties of such a conglomerate are presently unknown but probably rather different from the transport behavior of FQHE states.

In conclusion we have observed strong transport anomalies in the lowest Landau level of a 2D electron system at half-filling. The transport features deviate considerably from those of the FQHE states indicating the formation of a distinctly different correlated state at $\nu = \frac{1}{2}$ and $\frac{3}{2}$.

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