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Ultralow-temperature behavior of the $\nu=\frac{5}{2}$ fractional quantum Hall effect

P. L. Gammel, D. J. Bishop, J. P. Eisenstein, J. H. English,* A. C. Gossard,* R. Ruel, and H. L. Stormer
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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The newly discovered even-denominator fractional quantum Hall effect at filling factor $\nu=\frac{5}{2}$ has been studied at ultralow temperatures. While ρ_{xx} is not found to vanish in the temperature range studied, the minimum in ρ_{xx} is seen to drop at the lowest temperatures. While this drop is insufficient to determine the energy gap, Δ, it may be combined with the temperature dependence of the background resistivity to give a value of $\Delta \sim 26$ mK. Because of the high electron-phonon relaxation rate, $\tau_\epsilon^{-1}=(2.9\times10^9)T^3$ sec^{-1}K^{-3}, a minimum electron temperature of 9 mK could be obtained with a residual heat leak of 8×10^{-14} W. It appears likely that ρ_{xx} approaches zero as $T\rightarrow 0$.

Recent investigations[1,2] of very-high-mobility GaAs/$Ga_{1-x}Al_xAs$ heterojunctions have shown conclusive evidence for the presence of an even-denominator fraction in the fractional quantum Hall effect (FQHE). A pronounced minimum is seen to develop in ρ_{xx}, and an associated plateau appears in ρ_{xy} at the Landau-level filling fraction $\nu=\frac{5}{2}$. While such a state does not fit into the standard hierarchy[3-6] of the FQHE, new unpolarized spin-singlet states have been proposed[7] which may be stable at even-denominator filling fractions. The rapid collapse of the $\frac{5}{2}$ FQHE in tilted magnetic fields supports the suggestion of an unpolarized ground state.[8] However, the low-temperature scale involved ($T<50$ mK) has led to several problems in the measurement. First, the minimum in ρ_{xx} appears to be roughly temperature independent, and the increased "strength" of the $\nu=\frac{5}{2}$ state stems from an increase in the resistance of the adjacent maxima of ρ_{xx} as the temperature is lowered. This increase is presumed to be due to a rising background which competes with the FQHE. Thus, a direct measure of the energy gap from the temperature dependence of the minimum of ρ_{xx} is not possible. In addition, the weak electron-phonon coupling at these very low temperatures makes cooling the electrons a formidable task, and the true electron temperature is difficult to establish.

In order to address these issues, we have studied the $\nu=\frac{5}{2}$ state at lattice temperatures from 0.5 to 100 mK. The samples used in this work were cut from the same wafer as those reported on previously.[1] The single-interface GaAs/$Al_xGa_{1-x}As$ heterostructure had a mobility 1.3×10^6 cm^2/V sec and an areal density of approximately 3.0×10^{11} cm^{-2}. The precise density and indeed all of the details of the ultralow-temperature behavior was sensitive to the illumination conditions and magnetic field history. Reproducible results were obtained by illuminating the sample for more than 10 min with a red light-emitting diode (LED) while keeping the temperature below 50 mK. Any subsequent heating above this temperature would irreversibly weaken the feature at $\nu=\frac{5}{2}$. Furthermore, it was important to keep the range of the field sweeps small, so that the filling factor always remained between $\nu=3$ and $\nu=2$. Despite the sensitivity of the quantitative measurement to these details, it is important to realize that the qualitative feature at $\nu=\frac{5}{2}$ was present for all illumination conditions and any magnetic-field history.

To insure good thermal contact, the sample was indium soldered to a well annealed residual-resistivity ratio (>1000) silver bar which was attached to a nuclear demagnetization refrigerator via a low resistance (<10 nΩ) compressional collar. The nuclear cooling was provided by 0.5 mol of $PrNi_5$ magnetized in an initial field of 30 kG. Thermometry was provided by a ^{3}He-melting-curve gauge located in a low field region, but well anchored thermally to the same silver bar as the sample. With this configuration, the lattice temperature could be held below 1 mK for about 24 h while sweeping the magnetic field at the sample. To avoid rf heating of the electron gas, three stages of electrical filtering were employed. Room-temperature, 30 MHz filters were used and each line was a lossy coax down to 20 mK, with a 6 dB point at 20 MHz. To enhance losses, and for thermal contact, the coaxes were clamped at several points, and split with a large area epoxy feedthrough at the mixing chamber. The sample itself was completely enclosed in a metal can, with 10 kHz low pass filters on each line into the can. Each lead was brought onto a large area (5 cm^2, 50 pF) copper pad attached to the silver bar before the final connection to the sample.

The experiment consisted of temperature and power dependence of ρ_{xx} and ρ_{xy} as shown in Fig. 1. The sample, a 5×5-m^2 square, had six indium contacts around its perimeter. The results for ρ_{xx} described here represent the voltage and current combination which showed the most strongly developed minimum in ρ_{xx} at 10 mK. The variations between different combinations were large, and were attributed to sample inhomogeneities. The ρ_{xy} contacts shown were the ones which used the same current leads as the ρ_{xx} measurement and showed the smallest admixture of ρ_{xx}. However, this admixture was always substantial, and probably affects the shape of the plateau in ρ_{xy} near $\nu=\frac{5}{2}$ in Fig. 1. From the magnitude of the effect on ρ_{xy} from the nearby maxima in ρ_{xx}, we can estimate the amount of mixing. The actual plateau in ρ_{xy}

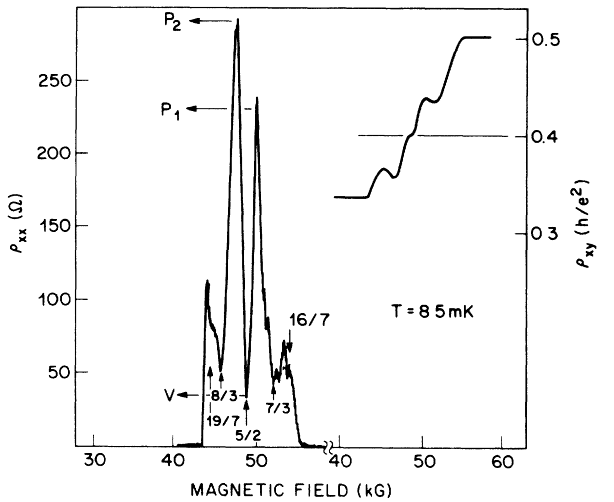

FIG. 1. In the region between filling factors $\nu=2$ and $\nu=3$, ρ_{xx} shows a number of distinct minima at very low temperatures. The locations of various FQHE states are shown. At $\nu=\frac{5}{2}$ a developing plateau is also present in ρ_{xy}. However, our sample shows considerable admixture of ρ_{xx}, which artificially flattens the plateau in ρ_{xy}.

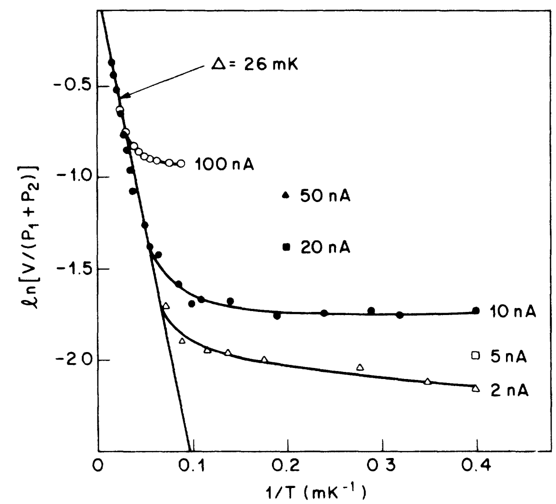

FIG. 2. The strength of the $\nu=\frac{5}{2}$ minimum in ρ_{xx}, defined as the ratio of the minimum to the adjacent maxima is shown vs the inverse lattice temperature for a variety of values of the transport current. At high temperatures, this is suggestive of an energy gap of 26 mK. At low temperatures, the electrons are heated above the lattice temperature.

should in fact be flatter than the data shown. While the value of this developing plateau is equal to $\frac{2}{5}(h/e^2)$ to within 0.5%, no results on ρ_{xy} will be discussed here due to the problems of separating the temperature dependence of ρ_{xy} and ρ_{xx} in the presence of this mixing.

The frequency dependence of the sample response was checked over the entire temperature range. The frequency response could be described by a temperature-dependent series inductance, where the characteristic frequency, ~300 Hz, increased by about a factor of 2 at the lowest temperature in the range 0.5–100 mK. This implies a value for the series inductance of $\sim 10^{-2}$ H. At present we do not understand the origin of this inductance. To avoid phase shifts a frequency was chosen (5.5 Hz), where the response was frequency independent over the whole range.

The ρ_{xx} data shown in Fig. 1 have a great deal of structure between filling factors $\nu=2$ and $\nu=3$. In addition to the $\nu=\frac{5}{2}$ state described here, the locations of other high-order odd-denominator fractions are also indicated. The structure in ρ_{xx} at these points is reproducible, but also essentially temperature independent at the lowest temperatures. No associated quantization is seen in ρ_{xy}. The structure of ρ_{xx} near $\nu=\frac{5}{2}$ is similar to that discussed previously.[1] There, most of the temperature dependence is in the height of the adjacent maxima, while the minimum remains roughly constant. This is true for our data too, although the minimum drops approximately as $\sim\ln(T)$ below 30 mK. The comparatively slow drop in the minimum is presumably due to a rising background competing with the FQHE as seen for other odd-denominator fractions.[9] We define the "strength" of the feature in ρ_{xx} as $2V/(P_1+P_2)$ where V, P_1, and P_2 are as shown in Fig. 1.

In Fig. 2, the strength of the $\nu=\frac{5}{2}$ minimum is plotted against $1/T$ for a variety of transport currents. At high temperatures, the data approach a universal curve independent of transport current which is well described as an activated process. Defining the strength of the feature as $e^{-\Delta/T}$, the characteristic energy gap is then $\Delta=26\pm 2$ mK. Note that this may differ by a factor of 2 from other authors,[9] who define the energy gap from $e^{-\Delta/2T}$. At lower temperatures, the strength of the minimum saturates at a value which depends on the transport current used. This is due to electron heating. While electron heating in our geometry is probably generated predominantly near the contacts, we will analyze our results by assuming the thermal relaxation of the electrons to the lattice can be described by a simple two bath model, where the electron temperature, T_e, is well defined and exceeds the lattice temperature, T_l. Equilibrium is reached when the electron-phonon relaxation rate balances the heat input to the sample: $d\dot{Q}=\tau_\epsilon^{-1}C_e dT_e$. C_e is the electronic specific heat, and τ_ϵ^{-1} is the electron-phonon relaxation rate. Following Wennberg *et al.*[10] who examined electron heating for the zero-field case, we take $C_e=\gamma T$ and $\tau_\epsilon^{-1}=\alpha T^p$. The electron heating is given by $\dot{Q}=\alpha'(T_e^\beta-T_l^\beta)$, where $\dot{Q}$ is the total power incident on the system, $\beta=p+2$ and $\alpha'=\alpha\gamma/(p+2)$. Here, we will only fit the data in the limit $T_l=0$.

In Fig. 3, the results of the electron heating experiment are plotted. The data are consistent with the simple heating model, with $p=3$, and $\alpha=2.9\times 10^9$. This assumes γ to be given by the zero-field heat capacity. The heating is the sum of the power generated by the transport current, using a characteristic sample impedance of $\rho_{xy}=10$ kΩ and an external heat leak into the sample. From the deviation of the data at the lowest power levels from the simple power law, we can estimate the external heat leak to be 8×10^{-14} W. The power law we find, $p=3$, is the same

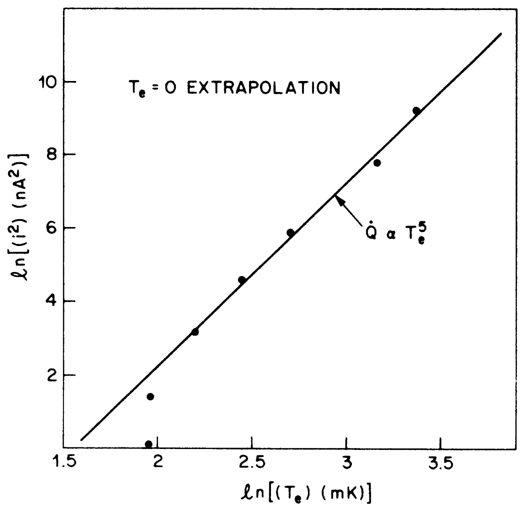

FIG. 3. The minimum electron temperature reached when the lattice temperature had been held below 0.5 mK for several hours is shown vs transport current. The power law is suggestive of electron heating limited by an electron-phonon relaxation rate, $\tau_\epsilon - 1 = 2.91\times10^9 T^3$ $\sec^{-1}K^{-3}$. The deviation at low powers can be explained by a residual heat leak of 4×10^{-14} W.

as has been seen previously in this and other systems. The relaxation rate, $\tau_\epsilon^{-1} = (2.9\times10^9)T^3$ $\sec^{-1}K^{-3}$, is unusually high. In metal films, Roukes *et al.*[11] found a relaxation rate $\tau_\epsilon^{-1} = 9\times10^7 T^3$ $\sec^{-1}K^{-1}$ and in a GaAs/$Al_xGa_{1-x}As$ multilayer structure Wennberg *et al.*[10] measured $\tau_\epsilon^{-1} = 2.5\times10^6 T^3$ $\sec^{-1}K^{-3}$. It is this large rate which allows us to reach an electron temperature of 9 mK. Note however, that at the lowest electron temperature, the electron-phonon relaxation time is approaching 1 msec.

There are several possible explanations for this rapid relaxation rate. The measured relaxation rate is similar to that calculated by Price[12] using a model of piezoelectric coupling of acoustic phonons to the electrons ($\tau_\epsilon^{-1} = 6.6\times10^8 T^3$ $\sec^{-1}K^{-3}$). He finds that in this temperature range, the usual deformation coupling to longitudinal acoustic phonons is negligible. Comparing our data to those of Wennberg *et al.*,[10] we see an enhancement factor of $\sim 10^3$ over the zero field case. This is much larger than is expected from the enhanced density of states at half-integral filling factor. While the exact value of this enhancement is unknown, current understanding[13] would be more consistent with a value of less than 10. It may be that Wennberg *et al.* have underestimated the relaxation rate at zero field, since the electron-phonon lifetime predicted from their data would be quite large ($\sim$1 sec) at the lowest temperatures. It may also be that their measurements on low-mobility multilayers cannot be compared to our data on much higher mobility, single interface samples.

In conclusion, we have measured the ultralow-temperature properties of the FQHE at filling factor $\nu = \frac{5}{2}$. The data are consistent with an activated process with an energy gap $\Delta = 26$ mK. Cooling is limited by electron-phonon relaxation, with a rate $\tau_\epsilon^{-1} = 2.9\times10^9 T^3$ $\sec^{-1}K^{-3}$. At the lowest electron temperature, 9 mK, the electron-phonon relaxation time exceeds 1 msec.

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*Present address: Department of Physics, University of California, Santa Barbara, CA 93106.

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