Observation of an Even-Denominator Quantum Number in the Fractional Quantum Hall Effect

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An even-denominator rational quantum number has been observed in the Hall resistance of a two-dimensional electron system. At partial filling of the second Landau level $\nu = 2 + \frac{1}{2} = \frac{5}{2}$ and at temperatures below 100 mK, a fractional Hall plateau develops at $\rho_{xy} = (h/e^2)/\frac{5}{2}$ defined to better than 0.5%. Equivalent even-denominator quantization is absent in the lowest Landau level under comparable conditions.

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The observation of exclusively *odd-denominator* rational quantum numbers in the fractional quantum Hall effect[1-3] (FQHE) represents a surprising experimental fact. This transport phenomenon manifests itself in two-dimensional electron systems at low temperatures and in high magnetic fields as minima in the diagonal resistivity ρ_{xx} and concurrent plateaus in the Hall resistance ρ_{xy} quantized to $(h/e^2)/(p/q)$. These characteristic features occur at fractional Landau-level filling $\nu = p/q$, where q is always odd ($\nu = nh/eB$, n is the areal density, and eB/h is the Landau-level degeneracy). The FQHE is presently accepted as being the consequence of the formation of an incompressible quantum fluid.[4] The ground state is well described by Laughlin's many-particle wave function[5] which, because of the requirement of antisymmetry under particle exchange, applies exclusively to odd-denominator fractional Landau-level filling. This odd-denominator restriction propagates to the hierarchical model[2] of daughter states which embraces all odd-denominator rational fractions and is well supported by numerical few-particle calculations.[4,6,7] While at present there exists ample evidence in theory and experiment alike for the absence of even-denominator quantum numbers, no physical symmetry has been found to exclude them *a priori*. In fact, recent work[8,9] has pointed to the possibility of condensation at $\nu = \frac{1}{2}$ although perhaps without display of the FQHE. Under these circumstances firm experimental evidence for an even-denominator rational quantum number will require a reevaluation of our understanding of two-dimensional electrons in the quantum limit.

The possibility of observing the FQHE at even-denominator filling factors has been suggested by some experimental findings. A minimum in ρ_{xx} has been noted by Ebert *et al.*[10] at $\nu = \frac{3}{4}$ in the lowest Landau level. More recently, Clark and co-workers[11,12] have conjectured that a family of even-denominator fractions may exist in the second Landau level at $\nu = \frac{9}{4}, \frac{5}{2}, \frac{11}{4}$, as displayed by weak minima in ρ_{xx}. Since minima in ρ_{xx} at such high filling factors are notoriously wide and invariably shift significantly with temperature, their association with a particular fractional filling is problematic. Only quantization of ρ_{xy} to the correct fractional value provides firm evidence for the existence of a given fractional state. Such crucial evidence has been lacking.

In this Letter we present experimental evidence for the appearance of the characteristic features of the FQHE at an even-denominator filling factor. This unexpected phenomenon occurs in the first excited Landau level $4 < \nu < 2$ at a filling factor $\nu = 2 + \frac{1}{2} = \frac{5}{2}$. Transport experiments show a plateau developing in ρ_{xy} centered at $(h/e^2)/\frac{5}{2}$ to within 0.5% concomitant with a deep minimum in ρ_{xx}. An equivalent quantization is not observed in the lowest Landau level $\nu < 2$ at similar temperatures. While all of the data reported here were obtained from a molecular-beam-epitaxy–grown single-interface GaAs/AlGaAs heterostructure of mobility 1.3×10^6 cm^2/V s and areal density 3.0×10^{11} cm^{-2}, similar but somewhat weaker structures were observed in two other samples. Low-temperature illumination for several minutes with a light-emitting diode is necessary to produce the persistent carrier concentration and mobility given above. These parameters are found to depend slightly on the precise illumination conditions.

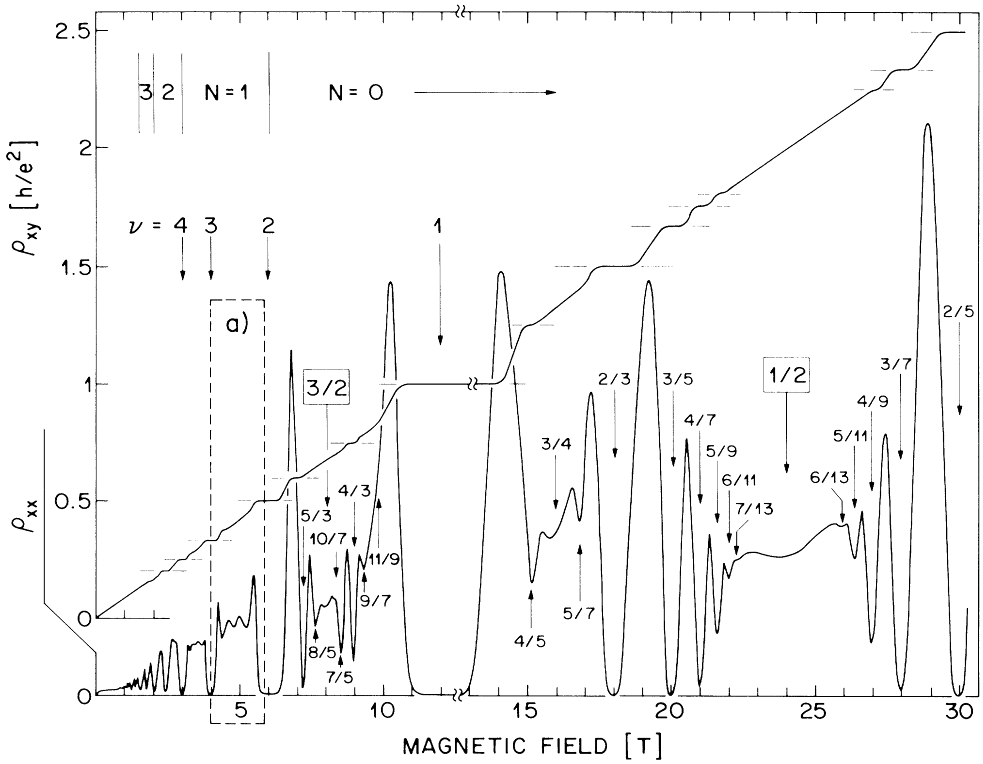

FIG. 1. Overview of diagonal resistivity ρ_{xx} and Hall resistance ρ_{xy} of sample described in text. The use of a hybrid magnet with fixed base field required composition of this figure from four different traces (breaks at $\simeq 12$ T). Temperatures were ≈ 150 mK except for the high-field Hall trace at $T = 85$ mK. The high-field ρ_{xx} trace is reduced in amplitude by a factor 2.5 for clarity. Filling factor ν and Landau levels N are indicated.

Transport measurements were performed at magnetic fields up to 30 T and at temperatures down to 20 mK with two different dilution-refrigerator–magnet systems. Great care has been exercised in order to assure thermal equilibrium between the 2D electrons and the crystal lattice. Since large changes in resistivity were observed upon cooling of the crystal lattice from 40 to 25 mK (as measured with a nearby carbon resistance thermometer) a gross electron-lattice disequilibrium seems unlikely.

Figure 1 displays the low-temperature diagonal and Hall resistivities over a wide range of magnetic field and filling factor. In Fig. 2, the interval $3 > \nu > 2$ is expanded, revealing our most startling result. The ρ_{xy} data at 25 mK show a plateau forming at the field corresponding to $\nu = \frac{5}{2}$, intersected by the classical Hall line determined from the measured 2D density. More importantly, this plateau is centered at $\rho_{xy} = (h/e^2)/\frac{5}{2}$ to within 0.5%. Simultaneously a deep relative minimum is found in ρ_{xx}. While not yet fully developed, these features emerge in a manner analogous to conventional odd-denominator FQHE states. Taken together, these data provide striking evidence for an even-denominator FQHE.

To highlight further the ρ_{xy} data contained in Fig. 2, the positions of the high-order odd-denominator fractions $\frac{32}{13}$ and $\frac{33}{13}$ are indicated ($\frac{5}{2} \pm 1.5\%$). No features are found in ρ_{xy} at these fractions which lie well clear of the observed $\frac{5}{2}$ plateau. From this it can be assumed that the $\frac{5}{2}$ plateau is not likely the consequence of two high-order odd-denominator plateaus blending together to form an apparent, but spurious, plateau at $\nu = \frac{5}{2}$.

Figure 2 also shows that the strong temperature dependence of the $\frac{5}{2}$ minimum in ρ_{xx} commences below 100 mK, indicating a very small associated energy scale. Although not shown in the figure, the plateau in ρ_{xy} at $\nu = \frac{5}{2}$ exhibits the same temperature dependence as the minimum in ρ_{xx}. Above about 100 mK the plateau disappears and the Hall resistance follows the classical line. The development of the resistivity feature is noteworthy. Instead of forming a zero in ρ_{xx}, the minimum itself remains roughly constant while the adjacent flanks rise steeply as the temperature is reduced. The same phenomenon has been observed at odd-denominator fractions as well.[13] Such behavior results from the competition between the tendency for the ρ_{xx} background to rise as the temperature falls and the development of the resistivity minimum.

In addition to the plateau at $\nu = \frac{5}{2}$ there is other evidence of the FQHE in the first excited Landau level, $4 > \nu > 2$. As shown in Fig. 2, there are broad minima

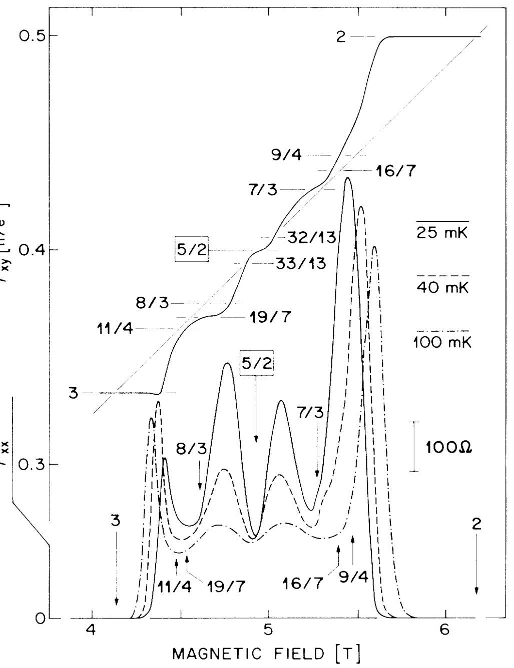

FIG. 2. Diagonal resistivity ρ_{xx} and Hall resistance ρ_{xy} [enlarged section (a) of Fig. 1] at $T=100$ to 25 mK. Filling factors ν are indicated in ρ_{xx} while quantum numbers p/q are shown in ρ_{xy}.

near $\nu=\frac{9}{4}$ and $\frac{11}{4}$ which shift considerably with temperature. By the lowest temperatures a plateau, off the classical line, has formed at $\frac{19}{7}$ corroborating the earlier work of Clark *et al.*[12] and a much weaker one is appearing near $\nu=\frac{7}{3}$. Thus, aside from $\nu=\frac{5}{2}$, we have no evidence for an even-denominator FQHE in the range $3>\nu>2$.

At high temperature ($\simeq 100$ mK) ρ_{xx} data from the higher spin state of the first excited Landau level, $4>\nu>3$, are broadly similar to the range $3>\nu>2$. A minimum is found at $\nu=\frac{7}{2}$ as well as in the vicinity of $\nu=\frac{13}{4}$ and $\frac{15}{4}$. Lowering the temperatures causes an overall increase in resistivity over the entire range without significant enhancement of the fractional features. Only weak structure in ρ_{xy} is found at $\nu=\frac{7}{2}$. Potential observation of the FQHE at $\nu=\frac{7}{2}$ awaits samples of higher quality.

Having evidence for an even-denominator fraction within the first excited Landau level, we reexamined the lowest Landau level for equivalent features. Using the same specimen, we focused on $\nu<1$. As Fig. 1 shows there exist a broad basin in ρ_{xx} around $\nu=\frac{1}{2}$, but no inflection occurs in ρ_{xy}. In fact, in this field range, ρ_{xy} follows the classical Hall line. Furthermore, the broad feature around $\nu=\frac{1}{2}$ is in stark contrast to the much sharper neighboring odd-denominator minima which have now been observed with denominators up to $q=13$ (Fig. 1). The absence of a quantized plateau in ρ_{xy} and the uncharacteristically wide depression in ρ_{xx}, in spite of the fact that higher magnetic fields vastly amplify FQHE features,[14] suggests a characteristic difference between electron correlation in the lowest and first excited Landau levels. A similar observation can be made around $\nu=\frac{3}{2}$ which was closely investigated at temperatures as low as 25 mK without showing evidence for even-denominator quantization.

With the resolution of increasingly higher-order odd-denominator fractional states of the sequences[3] $\nu=(m+1)/(2m+1)$ and $\nu=m/(2m+1)$ $(m=1,2,3,\dots)$, which converge toward $\nu=\frac{1}{2}$, the broad basin in its vicinity may actually be caused by even higher-order, yet unresolved members of the same sequences. Such a conjecture is supported by distinct features now observed around $\nu\simeq\frac{3}{4}$. With our high-mobility sample, we discovered representatives of both odd-denominator sequences converging towards $\nu=\frac{3}{4}$. Distinct minima are observed at $\nu=\frac{4}{5}$ and $\nu=\frac{5}{7}$ associated with plateaus (not shown in Fig. 1) quantized to the appropriate values to better than 1%.

To summarize our results, in the first excited Landau level we have firm evidence for fractional quantization of the Hall effect to an even-denominator fraction, $\nu=\frac{5}{2}$, with no other even-denominator fraction apparent at $\nu=p/4$ for temperatures as low as $\simeq 20$ mK. In spite of our resolving several new fractions in the lowest Landau level, no evidence for even-denominator quantization exists presently for $\nu<2$.

Although no physical principle has been found excluding the observation of even-denominator fractions in the FQHE, there exists presently no theoretical model describing such states. Theory has been very successful in developing an understanding of odd-denominator fractions in terms of a highly correlated quantum fluid existing specifically at primitive odd-denominator filling $(\nu=\frac{1}{3},\frac{1}{5},\dots,1-\frac{1}{3},1-\frac{1}{5},\dots)$.[5] Laughlin's wave function fulfills the requirement for antisymmetry of the wave function only for odd-denominator rational filling. The same restriction applies to the hierarchy of fractional daughter states $(\nu=\frac{2}{5},\frac{3}{5},\frac{2}{7},\frac{3}{7},\dots)$ derived from those primitive parental ground states.

Generalization of this theoretical model to include even-denominator quantum numbers requires the particles to be bosons rather than fermions. Such possibilities have been discussed previously by Halperin[15] who proposes bound-electron pairs as such candidate bosons. Given the low field at which we find the $\nu=\frac{5}{2}$ FQHE and the consequent small spin Zeeman energies, already predicted to influence the FQHE state,[16] potential pairing mechanisms involving spin-reversed electrons cannot be rejected *a priori.* Numerical few-particle calculations[4] have led to considerable progress in quantifying the properties of the fractional states. None of these elaborate techniques has hinted towards the existence of even denominators. A recent cooperative ring exchange theory[17] may allow for quarter fraction, but makes no mention of $p/2$. However, most of these calculations have focused on the lowest Landau level, where even-denominator quantization indeed remains unobserved. Studies for higher Landau levels rest largely on a generalization[18] of Laughlin's quantum fluid. Numerical calculations for the second Landau level[19] find condensed ground states at filling factors $\nu=\frac{7}{3}, \frac{8}{3}, \frac{11}{5}, \frac{14}{5}, \frac{16}{7}$, and $\frac{19}{7}$. However, there is no evidence for the existence of even-denominator quantum numbers found in these numerical results.

Our observation of the first even-denominator quantum number, $p/q=\frac{5}{2}$, shows that fractional quantization of the Hall effect is not limited to odd-denominator fractions. If the odd-denominator FQHE is any guide, we must expect to find more and possibly different even denominators in the future. It remains to be seen whether a common theoretical description can be found or whether one is dealing with two distinctively different "new states of matter."[5]

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