Collapse of the Even-Denominator Fractional Quantum Hall Effect in Tilted Fields

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The newly discovered *even-denominator* fractional quantum Hall effect at filling factor $\nu=\frac{5}{2}$ is found to collapse rapidly as the magnetic field is tilted away from the normal to the two-dimensional–electron-gas plane. No similar effect has been reported in tilted-field studies of the spin-polarized, odd-denominator effect at $\nu=\frac{2}{3}$ and $\frac{1}{3}$. Since a primary result of such tilting is increased spin splittings, the collapse of the $\nu=\frac{5}{2}$ effect strongly suggests that the underlying state is *not* spin polarized. Condensation into such a quantum liquid must involve substantial spin reversal.

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The recent discovery[1] of a plateau in the Hall resistance of two-dimensional electron systems (2DES) centered at $\rho_{xy}=(h/e^2)/\frac{5}{2}$, corresponding to the even-denominator rational quantum number $f=\frac{5}{2}$, has provoked reexamination of the basic theoretical picture of the fractional quantum Hall effect (FQHE). It is now widely accepted that the FQHE results from the condensation of the 2DES into an incompressible quantum liquid state at special values of the Landau-level filling factor $\nu=nh/eB$, with n the 2D density and eB/h the Landau-level degeneracy. In Laughlin's original work[2] this condensation was determined only for Landau-level filling factors $\nu=1/m$ with $m=3,5,7$, etc. The restriction to exclusively odd values of m arose from the requirement of exchange antisymmetry for the variational wave functions describing the fully spin-polarized Fermi quantum liquid state. Extensive experimental and theoretical work[3] has resulted in a hierarchical model of parent and daughter FQHE states encompassing all rational filling factors $\nu=p/q$ with q exclusively odd. While no fundamental principle has been found forbidding an even-denominator FQHE, the impressive amount of evidence in favor of solely odd denominators rendered the discovery of an even-denominator FQHE at $\nu=\frac{5}{2}$ startling.

There are significant differences between the recent magnetotransport experiments of Willett *et al.*[1] and earlier FQHE studies. Among these are the very low temperatures ($\simeq 25$ mK) required to observe the $\nu=\frac{5}{2}$ FQHE and the low magnetic fields ($\simeq 5$ T) needed to obtain $\nu=\frac{5}{2}$ filling ($n=3\times10^{11}$ cm^{-2}). Furthermore, the filling factor $\nu=\frac{5}{2}=2+\frac{1}{2}$ implies that the Fermi level lies in the second $(4>\nu>2)$ rather than the lowest Landau level $(2>\nu)$. Prior to the work of Willett *et al.* experimental proof of the existence of any fractional Hall plateaus in the second Landau level was lacking, although suggestive data[4] had been published. The experimental situation was matched by theoretical work[5–7] revealing greatly reduced or vanishing stability margins for the $\nu=\frac{7}{3}$ and $\frac{8}{3}$ FQHE states as compared to their robust $\nu=\frac{1}{3}$ and $\frac{2}{3}$ counterparts in the lowest Landau level.

The low magnetic fields associated with $\nu=\frac{5}{2}$ filling factor make the usual assumption of complete spin polarization (of those electrons in the second Landau level) worth reexamining. Spin reversal has already been suggested[8,9] as a possible mechanism for the production of reduced quasiparticle energy gaps at low fields. Formation of spin-reversed pairs of electrons might in fact provide a mechanism for even-denominator quantization if the pairs could be regarded as bosons and a Laughlin-type wave function were applicable.[10,11] Very recently Haldane and Rezayi[12] have shown that, for a certain model interaction, a half-integral FQHE can exist. The explicit state they consider is an unpolarized spin singlet which, it is argued, is favored in the second Landau level and by the reduced Zeeman energy at low fields. Since they ignore the Zeeman energy in their calculation, it is not possible to assess the stability of the proposed state. The degree to which Haldane and Rezayi's model approximates real Coulomb interactions between 2D electrons has been questioned.[13] In this Letter we present strong experimental evidence that the ground state for the $\nu = \frac{5}{2}$ FQHE is, in fact, not spin polarized.

Varying the Zeeman splitting provides a test of the spin-reversal hypothesis. Changing the 2D carrier density would shift the magnetic field at which $\nu = \frac{5}{2}$ filling occurs and so later the spin splittings. However, the correlation energy of the state and the Landau-level spacings would also change and it would be difficult to isolate the spin effect. A simpler method for examining the spin splittings in a 2DES is to tilt the external magnetic field away from the normal to the 2D plane.[14] The spin Zeeman energy is independent of the direction of the magnetic field, while for an ideal 2D system all orbital parameters (Landau-level spacings and degeneracies, Coulomb energies, etc.) depend only on the perpendicular component of the field. A given Landau-level filling factor ν occurs at a higher total field (by the factor $1/\cos\theta$, with θ measured from the normal) when the sample is tilted. Therefore, for any fixed filling factor the spin Zeeman energies increase with tilt. If the $\nu = \frac{5}{2}$ FQHE state requires a significant number of reversed spins, flipped at the expense of liquid condensation energy, tilting the field should inhibit, or even quench, the state.

The GaAs/AlGaAs heterostructure used in this investigation has been described elsewhere.[1] The low-temperature 2D carrier concentration $n = 3\times10^{11}$ cm^{-2} and high mobility $\mu = 1.3\times10^{6}$ cm^2 V^{-1} s^{-1} are established by illumination with a red light-emitting diode. Since these sample parameters depend slightly on both the illumination and cool-down conditions, tilting of the sample must be done *in situ* at low temperatures. Earlier experiments by Clark *et al.*[4] have, in fact, examined a ρ_{xx} minimum at $\nu = \frac{5}{2}$ at two tilt angles obtained in two independent runs. Aside from the uncertainty associated with such a cycling procedure, the minimum was very weak and therefore no conclusion was drawn from the data. To achieve *in situ* tilting, we employ a simple spring-loaded paddle, upon which the sample is mounted, that can be rotated in a yoke via a string pulled from atop the cryostat. The sample is enclosed in an rf shield and coaxial leads fitted with low-temperature rf filters are employed. With a 10-nA, 17-Hz measurement current no observable electron heating is detected in resistivity measurements at 25 mK. Determination of the tilt angle can be made in several ways. Measuring the slope of the low-field Hall resistance, the period of the low-field Shubnikov–de Haas oscillations, or the field locations of the $\nu = \frac{5}{3}$ and $\nu = \frac{5}{2}$ minima in ρ_{xx} all give the same result.

Figure 1 shows diagonal-resistivity ρ_{xx} data at 25 mK over limited field ranges for different values of the tilt angle θ. For each angle the field range was adjusted to scan filling factors $3 > \nu > 2$, thus maintaining the Fermi level E_F in the lower spin subband of the second Landau level. The data at $\theta = 0$ show the same basic structure observed earlier.[1] The deep minimum at 4.8 T, having grown rapidly below 100 mK, corresponds to $\nu = \frac{5}{2}$ filling. Associated with this minimum in ρ_{xx}, a plateau in the Hall resistance forms within 0.5% of $\rho_{xy} = (h/e^2)/\frac{5}{2}$. Adjacent to the $\nu = \frac{5}{2}$ minimum in ρ_{xx} at 4.8 T are additional minima at 4.5 and 5.1 T near filling factors $\frac{19}{7}$ and $\frac{7}{3}$, respectively. These minima shift considerably with temperature and are not accompanied by well-defined Hall plateaus that straddle the classical Hall line.

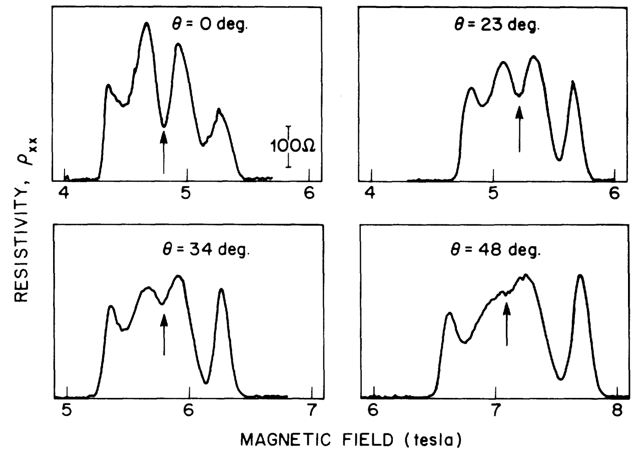

FIG. 1. Diagonal-resistivity ρ_{xx} data for various tilt angles θ at 25 mK. Arrows mark field positions of $\nu = \frac{5}{2}$ filling factor. Resistivity minima above and below the $\nu = \frac{5}{2}$ feature occur near $\nu = \frac{7}{3}$ and $\frac{19}{7}$, respectively.

It is evident from the data shown in Fig. 1 that the $\nu = \frac{5}{2}$ minimum rapidly shrinks as the tilt angle θ increases. This collapse of the ρ_{xx} minimum is accompanied by the disappearance of the associated Hall plateau (not shown in the figure). By contrast, the minima adjacent to the $\nu = \frac{5}{2}$ structure are either unaffected or actually strengthen with tilt. While the tilt dependence of the minima near $\nu = \frac{7}{3}$ and $\frac{19}{7}$ varies somewhat from run to run, the qualitative collapse of the $y = \frac{5}{2}$ FQHE does not.

It would be desirable to measure an activation energy associated with the minimum in ρ_{xx} to study quantitatively the collapse of the $\nu = \frac{5}{2}$ FQHE. Unfortunately, this is not possible since the value of ρ_{xx} at the minimum does not fall significantly as the temperature T is reduced to around 20 mK. It is the maxima immediately adjacent to the $\nu = \frac{5}{2}$ minimum that rise dramatically as T falls. We speculate that the lack of a true zero-resistance state developing at $\nu = \frac{5}{2}$ down to 25 mK is due to a competition between the tendency for the average resistivity to rise as a result of increasing localiza-

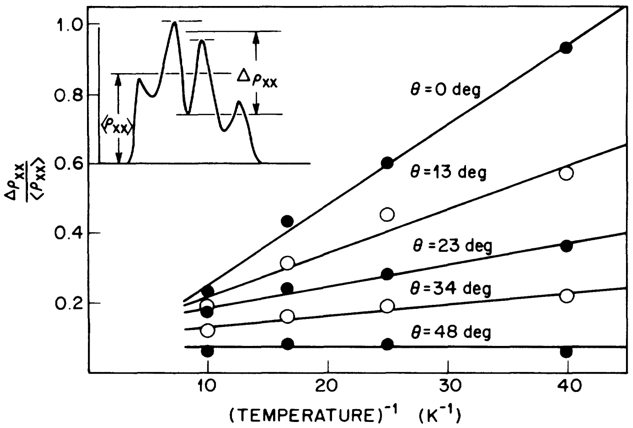

FIG. 2. Temperature dependence of the strength of the $\nu=\frac{5}{2}$ FQHE for various tilt angles. Inset: definition of the strength ratio $\Delta\rho_{xx}/\langle\rho_{xx}\rangle$.

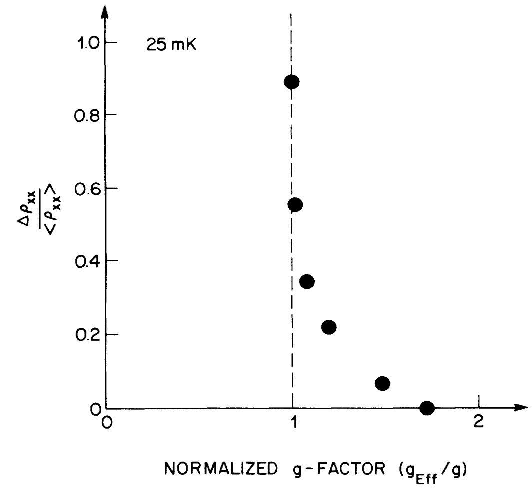

FIG. 3. Strength of the $\nu=\frac{5}{2}$ FQHE at 25 mK vs normalized g factor defined as $g_{\rm eff}/g=1/\cos\theta$. Vertical dashed line indicates perpendicular-field case.

tion, and the development of a zero-resistance state due to the formation of an energy gap. Support for this picture comes from studies around $\nu=\frac{7}{2}$ in this sample and from the $\nu=\frac{5}{2}$ effect in other, lower-quality samples. In both cases the minima "float" upward as the temperature is reduced. This phenomenon is not unique to the even-denominator states but has also been observed[15] at less-developed odd-denominator fractions such as $\nu=\frac{2}{7}$. In the present sample this same upward floating appears in conjunction with the collapse of the amplitude of the $\nu=\frac{5}{2}$ feature as the sample is tilted. Given this situation, we define the strength of the $\nu=\frac{5}{2}$ FQHE as the ratio $\Delta\rho_{xx}/\langle\rho_{xx}\rangle$ of the amplitude of the minimum in ρ_{xx} to the average value of ρ_{xx} between the maxima and the minimum. The temperature dependence of this ratio for various tilt angles is shown in Fig. 2 along with an inset defining the strength ratio. Note that Fig. 2 is *not* an Arrhenius plot. As the figure reveals, the strong temperature dependence of $\Delta\rho_{xx}/\langle\rho_{xx}\rangle$ at zero tilt is rapidly quenched as θ increases.

The effect of tilting is to amplify the spin splittings by a factor $1/\cos\theta$. This may be regarded as increasing the g factor to an effective value $g_{\rm eff}=g/\cos\theta$ at constant perpendicular magnetic field. It is illuminating then to plot the strength $\Delta\rho_{xx}/\langle\rho_{xx}\rangle$ versus the ratio $g_{\rm eff}/g$. This is shown in Fig. 3 for the 25-mK data. Plotted in this way, the collapse of the $\nu=\frac{5}{2}$ FQHE appears precipitous. The state appears to be only marginally stable even for the $\theta=0$ case. In fact, the data suggest that any *reduction* of g would significantly strengthen the effect. Taken together, the data presented in Figs. 1–3 are strong evidence for a $\nu=\frac{5}{2}$ FQHE state with highly incomplete, or even zero spin polarization. Such polarization obviously requires spin reversal. To produce a completely unpolarized state at $\nu=\frac{5}{2}$, one-half of the electrons occupying the second Landau level must be flipped, the fully filled lowest Landau level being already unpolarized. Figure 3 suggest that the energetic cost of such a spin reversal cancels a large fraction of the available condensation energy.

The qualitative collapse with tilt of the $\nu=\frac{5}{2}$ FQHE state contrasts sharply with the enhancement of the ρ_{xx} feature near $\nu=\frac{7}{3}$ and the roughly angle-independent minimum near $\nu=\frac{19}{7}$. We have also measured the activation energy of the $\nu=\frac{5}{3}$ FQHE in this same sample at $\theta=0$ and 34° and find it unchanged. The $\nu=\frac{5}{2}$ state is believed to be a spin-polarized FQHE state equivalent to the canonical $\nu=\frac{1}{3}$ state. As such it is not expected to be destabilized by increased spin splittings. There are, however, additional effects of tilting beyond the obvious enhancement of the spin-flip energy. The presence of an in-plane magnetic field component creates both diamagnetic energy shifts as well as Landau-level and electric-subband mixing.[16] One result of these mixings is a compression of the electron wave function perpendicular to the 2D plane, in effect creating a more "ideal" 2D system. This is expected to enhance the strength of the FQHE by increasing the quasiparticle energy gaps.[17,18] Experimental studies[19,20] of the odd-denominator FQHE in tilted fields show enhancements of the $\nu=\frac{2}{3}$ FQHE and little effect on the $\nu=\frac{1}{3}$ state. Being spin-polarized quantum liquids, the tilt enhancement of the Zeeman energy does not directly affect these FQHE states. Interestingly, recent data[19] on the $\nu=\frac{4}{3}$ FQHE show a weakening with tilt. Although this is not understood, these low-field ($\simeq 4.5$ T) data may also suggest a role for reversed spins. In fact, recent suggestions[21] for unpolarized states at families of *odd-denominator* filling factors may stimulate future experiments in this direction. The qualitative collapse of the even-denominator $\nu=\frac{5}{2}$ FQHE reported here is strong, if not incontrovertible, evidence for an unpolarized ground state.

In summary, we have observed a rapid collapse of the newly discovered even-denominator FQHE at $\nu = \frac{5}{2}$ in tilted fields. Other resistivity features near $\nu = \frac{7}{3}$ and $\frac{19}{7}$, as well as the FQHE at $\nu = \frac{5}{3}$, do not show any signs of such a collapse. Our data demonstrate that the $\nu = \frac{5}{2}$ state differs qualitatively from the odd-denominator states that have been studied in tilted fields. These results strongly suggest that the $\frac{5}{2}$ FQHE does not originate from a spin-polarized state but represents the first observation of a nonpolarized 2DES quantum fluid. While this conclusion leads credence to the spin-singlet quantum liquid recently proposed by Haldane and Rezayi, the data do not allow for discrimination between different unpolarized ground-state wave functions.

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