

Fractional quantum Hall effect in tilted magnetic fields

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We have studied the dependence of the fractional quantum Hall effect on a tilted magnetic field. The activation energies for the Landau-level filling factors $\nu = \frac{2}{3}$ and $\nu = \frac{1}{3}$ have been measured. By tilting the field we could observe an increase of the activation energy for $\nu = \frac{2}{3}$, whereas the activation energy for $\nu = \frac{1}{3}$ decreased slightly. Changes could also be observed for the minima of the filling factors $\nu = \frac{4}{3}$, $\frac{5}{3}$, $\frac{2}{3}$, and $\frac{1}{3}$. The data suggest a different behavior of "electronlike" fractional states and of "holelike" fractional states in a tilted field.

The fractional quantum Hall effect (FQHE) was first observed by Tsui, Störmer, and Gossard in 1982.¹ The phenomenon is characterized by the formation of plateaus in the Hall resistivity ρ_{xy} and the vanishing of the diagonal resistivity ρ_{xx} and the conductivity σ_{xx} at fractional Landau-level occupancies $\nu = nh/eB = p/q$, where p is an integer, q an odd integer, and n the two-dimensional carrier density. The present understanding of the effect is that the system forms a new ground state which is a quantum liquid, arising from the strong Coulomb interaction between the electrons. The existence of a finite-energy gap has been shown² separating the ground state and the lowest excited states, which are associated with the excitation of fractionally charged quasiparticles, quasielectrons, and quasiholes. Within this picture the FQHE at a filling factor of $\nu = \frac{1}{3}$ could be explained. By invoking the so-called electron-hole symmetry the effect at $\nu = \frac{2}{3}$ was understood.³ In the hierarchical model⁴ other p/q fractional numbers consist of the two hierarchies of continued fractional filling factors derived from $\frac{1}{3}$ and $\frac{2}{3}$. Thus an understanding of the $\nu = \frac{1}{3}$ and $\nu = \frac{2}{3}$ states is extremely important for a full understanding of the FQHE.

The temperature dependence of the minima in ρ_{xx} and σ_{xx} at $\nu = \frac{1}{3}$ and $\frac{2}{3}$ has been extensively studied^{5,6} to obtain information on the magnitude of the energy gap. At very low temperatures a behavior was found which could be attributed to a hopping conduction mechanism as in the integral quantum Hall effect. However, the results are neither very consistent nor accurate. At higher temperatures ($0.3 \text{ K} < T < 1 \text{ K}$) an activated behavior has been observed. The activation energy deduced should be a measure for the finite energy gap predicted by the theories. Boebinger, Chang, Störmer, and Tsui⁵ found that the states with $\nu = \frac{1}{3}$ and $\frac{2}{3}$ had the same activation energy when they occurred at the same magnetic field. This is consistent with the picture of an electron-hole sym-

metry. In contrast, Wakabayashi *et al.* published values for the activation energies, which are smaller for $\nu = \frac{2}{3}$ if compared with the $\nu = \frac{1}{3}$ data.

Here we report on a different experiment. We studied the effect of a tilted magnetic field on the FQHE in detail. One experiment done at a fixed tilt angle of $\theta = 60^\circ$ which indicates an improvement of the resistivity at $\nu = \frac{7}{3}$ and $\nu = \frac{8}{3}$ has been published by Nicholas *et al.*⁷ However, systematic studies were not possible since the device could not be rotated in a magnetic field. In our measurements, a rotating gear enabled a continuous tilting of the specimens relative to the direction of the magnetic field. The samples used in our experiments were made from two GaAs-GaAlAs heterojunctions. The first had an electron density of $1.4 \times 10^{11} \text{ 1/cm}^2$, a mobility of $600\,000 \text{ cm}^2/\text{Vs}$, and a spacer of 43 nm, the second an electron density of $0.81 \times 10^{11} \text{ 1/cm}^2$, a mobility of $450\,000 \text{ cm}^2/\text{Vs}$, and a spacer of 75 nm. The majority of the measurements were made with circular Corbino geometry devices (true circular enclosed contact geometry). A Hall-bar sample, although less intensively studied, gave very similar results. The temperature was measured by the ³He pressure and was checked at zero magnetic field with a calibrated germanium resistor. In order to avoid electron heating effects the voltage drop across the Corbino ring, with a source-drain distance of 200 μm , was kept below 100 μV . All the measurements were made with a standard lock-in technique at frequencies of about 10 Hz.

Figure 1 shows σ_{xx} for three different temperatures. The lower half of the figure has the sample perpendicular to the magnetic field direction, and in the upper half the sample is tilted by an angle of 48.2° . The magnetic field axes are scaled in such a way that the Shubnikov-de Haas minima related to integer filling factors appear at the same positions. One sees very clearly that the minimum at a filling factor of $\nu = \frac{2}{3}$ is deeper in the case of the tilt-

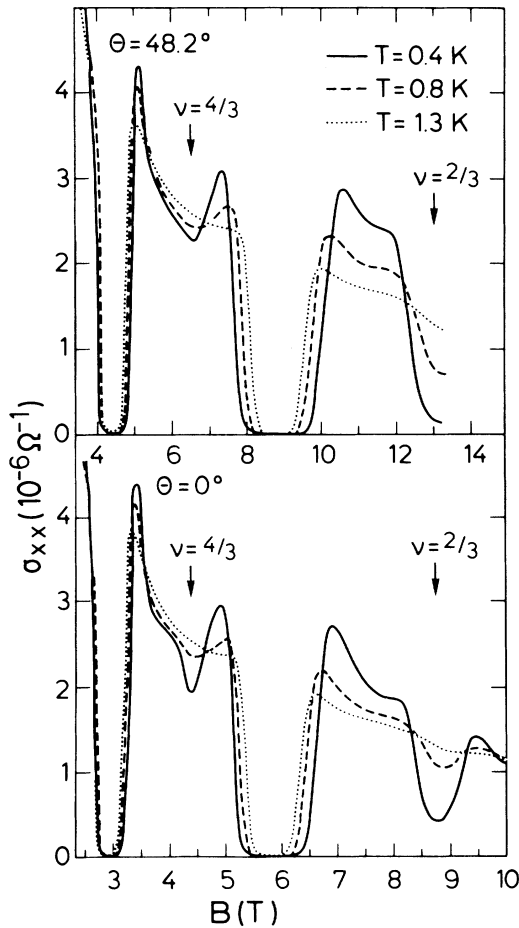


FIG. 1. Conductivity σ_{xx} as a function of the magnetic field for three different temperatures T and for two tilt angles θ . The carrier density and the mobility of the sample at $T=4$ K are $n_s = 1.4 \times 10^{11}$ $1/\text{cm}^2$ and $\mu = 600000$ cm^2/Vs .

ed sample. At the lowest temperature the minimum for the filling factor $\nu = \frac{4}{3}$ shows the opposite behavior. At $\theta = 0^\circ$ a clear minimum can be seen, whereas it has almost vanished for the tilted case. In order to obtain a quantitative description of this behavior the temperature dependence of the minimum at $\nu = \frac{2}{3}$ was measured at various tilt angles, as shown in Fig. 2. The activation energy W is determined from $\sigma_{xx} = \sigma_0 \exp(-W/T)$ and a fit to the measured points, represented by the straight lines. The fitted activation energies plotted against the total magnetic field show an increase by almost a factor of 2 by tilting the sample (Fig. 3).

Figure 4 represents two curves for the second sample. The minimum at $\nu = \frac{2}{3}$ is again deeper in the case of the tilted specimen, whereas at $\nu = \frac{1}{3}$, which could be observed in this sample at a relatively low magnetic field because of the low carrier concentration, the opposite behavior is seen, with the minimum becoming weaker, as was found for the case of $\nu = \frac{4}{3}$ in Fig. 1. The activation energy for $\nu = \frac{1}{3}$ shows a slight decrease of the energy for the

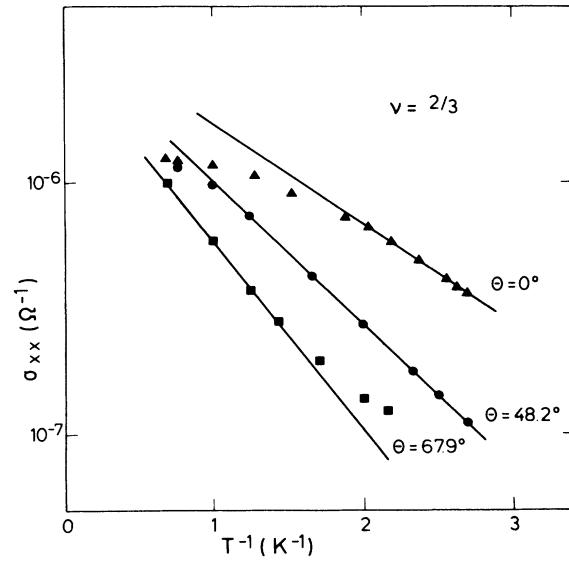


FIG. 2. Examples of temperature dependences of the σ_{xx} minimum at $\nu = \frac{2}{3}$ for the sample of Fig. 1 for three different tilt angles θ . The straight lines representing fits with $\sigma_{xx} = \sigma_0 \exp(-W/T)$ are used for the determination of the activation energy W .

tilted sample from $W = 1.67$ K at $\theta = 0^\circ$ to $W = 1.52$ K at $\theta = 63.7^\circ$.

In order to study the behavior at higher fractional filling factors the electron densities and mobilities were increased by illumination with a red light-emitting diode. Minima at filling factors $\nu = \frac{5}{3}$, $\frac{2}{3}$, and $\frac{3}{5}$ could then be observed. Only small changes occurred on tilting the samples. The minima at $\nu = \frac{5}{3}$ and $\frac{3}{5}$ became slightly deeper in the case of a tilted sample, whereas the minimum at $\nu = \frac{2}{3}$ was less pronounced. This observation is consistent

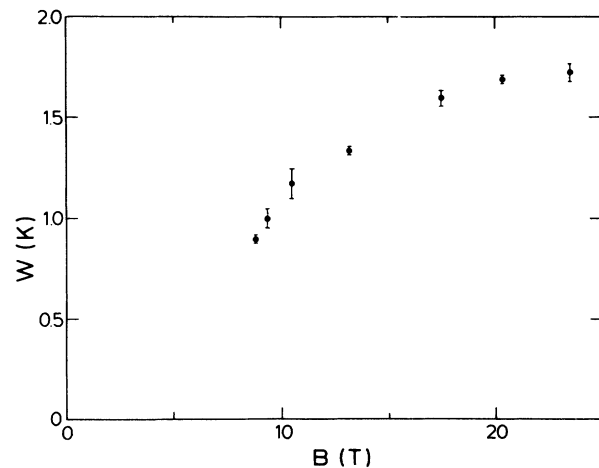


FIG. 3. Activation energies W for $\nu = \frac{2}{3}$ vs total magnetic field. The measure energy for the lowest magnetic field corresponds to a tilt angle of $\theta = 0^\circ$, whereas for the highest magnetic field value the tilt angle was 67.9° .

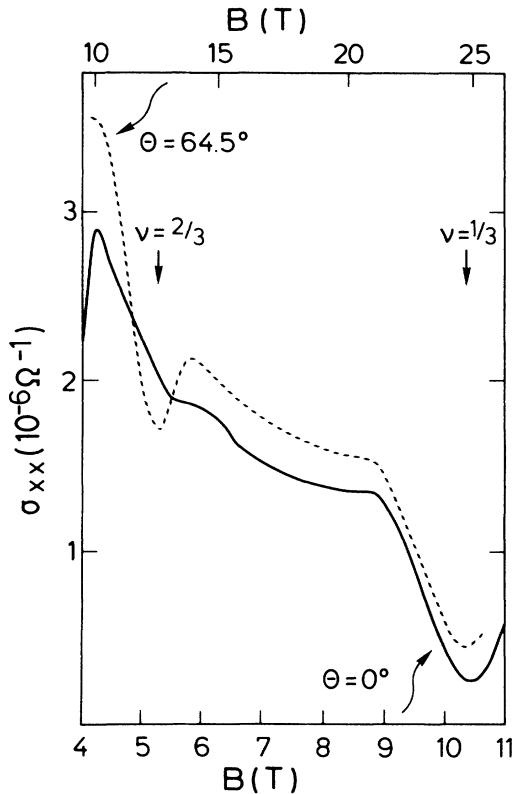


FIG. 4. Conductivity σ_{xx} as a function of the magnetic field for two tilt angles θ at a temperature of $T=0.45$ K. The carrier density and the mobility of the sample at $T=4$ K are $n_s=0.81 \times 10^{11}$ $1/\text{cm}^2$ and $\mu=450\,000$ cm^2/Vs .

with a general picture of the results in which the activation energies of the holelike fractional states $\nu=1-p/q$ are increased by tilting the magnetic field, and those of the electronlike states are decreased.

In order to explain these phenomena we consider the changes brought about by tilting the magnetic field. First, the total field corresponding to a given filling factor will increase, leading to an increase in the spin splitting and hence less overlap of adjacent spin states. If this were the dominant factor, however, we would not expect a systematic difference in the behavior of $\nu=2/3$ and $4/3$. The second change is the introduction of a field component parallel to the heterojunction interface. This alters the energies and wave functions for the motion in the z direction, producing a more strongly confined wave function.

It will alter both the magnitude of the electron-electron interactions, and the interaction with scattering centers. Variational calculations suggest⁸ that a parallel field component of 20 T will almost halve the z extension of the wave function in the samples studied here. The calculations of Yoshioka⁹ and Zhang and Das Sarma¹⁰ then show that this should increase the gap energy of the fractional state by about 20%, starting from a value of 0.5 for the parameter β , by which the three dimensionality of the system is taken into account. Yoshioka⁹ shows that this increase should be similar for the fractional states at filling factors $\nu=1/3$ and $\nu=2/3$. We observed a much bigger increase than expected for the activation energy at the filling factor of $\nu=2/3$, whereas at $\nu=1/3$ no increase could be seen. Thus, following the calculations of Yoshioka⁹ and Zhang and Das Sarma¹⁰ the observed effects cannot be explained by the change of the z extension of the wave function. The change in the influence of the scattering centers will also lead to a change in the effective disorder present. Changes in the asymmetry of the conductivity, which are thought to be due to an asymmetric density of states, have been observed in the integer quantum Hall regime¹¹ when the z wave function is altered by a back gate voltage. The present asymmetry between the electronlike and holelike fractions may then be a similar effect, determined by the relative importance of attractive and repulsive scattering centers, which is changed by the change in the mean position of the wave function relative to the interface. The development of asymmetries has also been seen when the carrier concentration is increased with light,⁷ where it has been found that $2/3$ can dominate over $4/3$. This has also been observed in the samples studied here.

Perhaps the broken symmetry of the tilted field configuration is itself enough to introduce the asymmetric behavior of the electronlike and holelike quasiparticles. This question remains to be answered by theory.

In conclusion, a large increase in the activation energy of the fractional state $\nu=2/3$ is observed by tilting the magnetic field, and a slight decrease for $\nu=1/3$. The minimum for $\nu=4/3$ was less pronounced with increasing tilt angle. Small changes could be seen also for $\nu=5/3$, $2/5$, $3/5$ in the illuminated samples. We conclude that the excitation energies of the holelike fractional states increase with increasing magnetic field component parallel to the two-dimensional electron gas, whereas the excitation energies of the electronlike states decrease. This behavior appears to demonstrate the destruction of electron-hole symmetry in the FQHE by a tilted magnetic field.

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