Capacitance spectroscopy of the fractional quantum Hall effect: Temperature dependence of the energy gap

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The energy gap in the fractional quantum Hall effect has been measured as a function of the magnetic field and the temperature by the method of capacitance spectroscopy. Variation of the magnetic field over a broad range does not affect the temperature dependence of the gap.

According to the present understanding (see, for example, some reviews[1,2]) the ground state of a system of 2D electrons under the conditions of the fractional quantum Hall effect is an incompressible electron liquid (a so-called Laughlin liquid). Quasiparticle states are separated from the ground state by an energy gap of $\Delta/2$. This gap arises exclusively from the electron–electron interaction and is one of the most important characteristics of the effect. A state of a fractional quantum Hall effect is usually observed when the filling factor ν of the magnetic-quantization levels is equal to a rational fraction p/q with an odd denominator q ($\nu=n_s hc/eH$, where n_s is the carrier density, and H the magnetic field). A deviation of the density n_s from the value $n_0=(p/q)eH/hc$ puts quasiparticles above the gap, and these quasiparticles have a fractional charge e/q. As a result, the energy density E of the system, reckoned from the ground state, varies linearly with the density: $E=q\Delta|n_s-n_0|/2$. There is accordingly a discontinuity $\delta\mu=q\Delta$ in the chemical potential $\mu=\partial E/\partial n_s$ at $n_s=n_0$. The system becomes incompressible ($\partial\mu/\partial n_s$ becomes infinite).

The energy gap has previously been determined either from the conductivity activation energy[1-3] or from the magnetoluminescence spectra.[4,5] The first of these methods, which has been used more often, is fundamentally unsuitable for measuring the temperature dependence of Δ. It was not until just recently that this dependence has been measured.[5] A method similar to the method of capacitance spectroscopy has recently been used to study the compressibility of a system of 2D electrons.[6] Structural features in the compressibility due to the fractional quantum Hall effect have been observed. An attempt at a quantitative analysis of these structural features has been made in a theoretical paper.[7]

We have now carried out the first measurements of the gap in the fractional quantum Hall effect by the method of capacitance spectroscopy. This method has been used previously to study the integer quantum Hall effect.[8,9] In this letter we are reporting results on the gap as a function of the magnetic field and the temperature for a filling factor of 1/3 ($p=1$, $q=3$).

The method of capacitance spectroscopy involves precise measurements of the capacitance between the 2D electron system and a metal electrode (gate) oriented parallel to this system. In a test sample of this sort, the electron density varies in proportion to the potential difference between the 2D electron system and the gate, as in an ordinary capacitor. However, this potential difference differs from the applied voltage V_g by an amount equal to the contact potential difference. As a result, the capacitance $C=dQ/dV_g$ found experimentally (Q is the charge of the 2D electron system) differs from its geometric value $C_g=\epsilon S/4\pi d$ by an amount due to the compressibility of the 2D electron system:[8] $1/C=1/C_g+(\partial\mu/\partial n_s)/e^2S$, where s is the area of the 2D electron system under the gate, d is the distance between the gate and the 2D electron system, and ϵ is the dielectric constant. The last term in this equation, which describes the correction to the geometric capacitance, is usually small. An integration of this correction over the density yields the change in the chemical potential of the 2D electron system:

$$\Delta\mu\simeq(e^2S/C^2)\int(C_g-C)dn_s. \tag{1}$$

We have studied 2D electron systems at single GaAs/AlGaAs heterojunctions. An auxiliary layer of GaAs was first grown on the surface of the material. Thin metal layers of area $s=0.92\times10^{-2}$ cm^2, which form a Schottky barrier with the GaAs, were deposited on the test samples to create the gate. The static voltage V_g applied between the gate and the 2D electron system made it possible to vary the density n_s continuously. The distance between the gate and the electron system was about 600 nm; the electron density at $V_g=0$ was 1.3×10^{11} cm^{-2}; and the mobility was a bit greater than 10^6 cm^2/(V$\cdot$ s). A bridge arrangement with a sensitivity of about 5×10^{-5} was used to measure the capacitance. The measurements were carried out at a frequency of 13 Hz. Both the capacitive signal and a signal shifted 90° with respect to it were measured. The amplitude of the alternating voltage across the sample was 15 mV. A test verified that a reduction of this voltage to 5 mV did not alter the results, at our accuracy level.

To eliminate resistive effects due to the small value of the conductivity[10] σ_{xx}, we carried out measurements at moderately low temperatures. The corresponding boundary value of the temperature was determined from the absence of the 90° signal for each magnetic field.

Figure 1a shows some typical experimental curves. The only structural feature in the capacitance occurs near $\nu=1/3$ ($n_0\simeq9.7\times10^{10}$ cm^{-2} at $H=12$ T) at temperatures below ~3 K. The observed structural feature has a minimum of finite width, and at low temperatures there are two side maxima; the shape is completely analogous to that observed in Ref. 6. It can be seen from these results that the jump in the chemical potential is smeared along the density scale under these experimental conditions. This smearing is apparently due primarily to fluctuations in the potential in the test sample.[7] The temperature smearing is much less, in our opinion. We do not see a temperature dependence of the total width of the structural feature, measured as the distance between the points at which the temperature dependence of the capacitance vanishes. Because of the smearing of the jump in the chemical potential, it is not

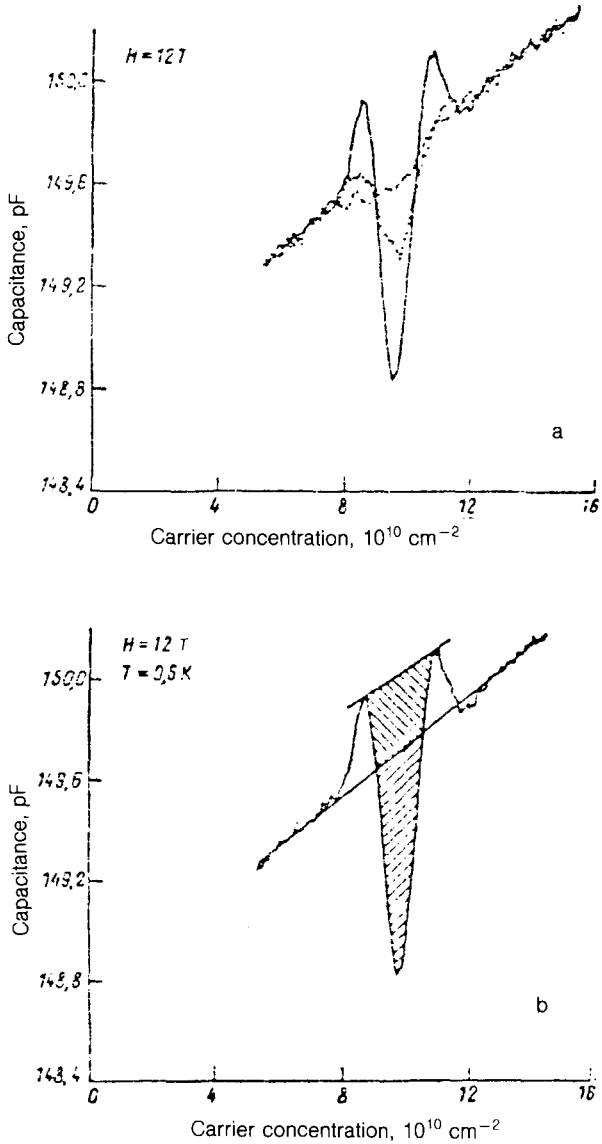

FIG. 1. a: Experimental value of the capacitance versus the carrier density near a filling factor 1/3 at various temperatures. Solid curve—$T=0.5$ K; dotted curve—$T=1.2$ K; dashed curve—$T=2.1$ K. The magnetic field is $H=12$ T. b: Illustration of two different methods for determining the gap size $\Delta = \delta\mu/3$. The value of $\delta\mu$ is found in accordance with Eq. (1), in which the integral is assumed to be equal to the area of the hatched regions. Lower hatched region—Δ_1; both—Δ_2. The magnetic field is $H=12$ T, and the temperature is $T=0.5$ K.

totally clear within which limits on the density we should integrate the signal in order to determine the value of Δ. We used two methods, which we regard as the most natural ones under the actual conditions (Fig. 1b). These methods also make it possible to eliminate the change in the chemical potential of the 2D electron system in the absence of the fractional quantum Hall effect. While the two methods yielded different absolute values for the gap, they revealed the same temperature dependence for it.

Figure 2 shows the size of the energy gap determined in this manner as a function of the magnetic field. The absolute values of the gap, Δ_2, are very close to those found

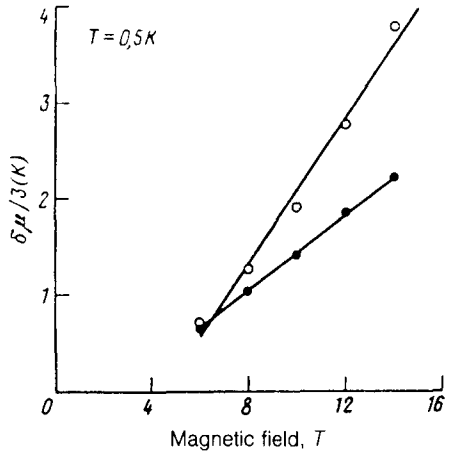

FIG. 2. Magnetic-field dependence of the gap size as determined by two methods. Squares—Δ_1; circles—Δ_2. $\nu = 1/3$, $T = 0.5$ K.

from the activation conductivity for test samples with the same carrier mobility.[3] The threshold values of the magnetic field are also approximately the same.

Figure 3 shows the temperature dependence of the normalized gap size Δ_2 for four values of the magnetic field. The normalization was made to the value measured at $T = 0.5$ K. At this temperature, there are no resistive effects in magnetic fields below 12 T. That the gap has a temperature dependence in our experiments is not surprising, since the temperature is not very low in comparison with the quasiparticle activation energy $\Delta/2$. On the other hand, it is fairly easy to see that the presence of quasiparticles might affect the value of the gap which arises from the electron–electron interaction (as in superconductors, for example). An unexpected result is the universal nature of the temperature dependence in the various fields, in which the size of the gap varies by a factor of several units. We cannot offer a plausible explanation for this

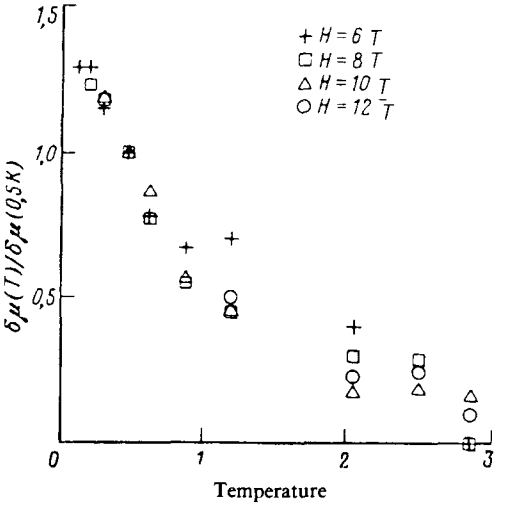

FIG. 3. Temperature dependence of the relative gap size $\Delta_2(T)/\Delta_2(0.5\ \text{K})$ for various magnetic fields: +—$H = 6$ T; □—$H = 8$ T; △—$H = 10$ T; ○—$H = 12$ T.

effect at the moment, but it does not contradict common sense: The excitation spectrum of an incompressible Laughlin liquid has a rather complicated wave-vector dependence, with a "roton" minimum.[11] We are studying only a fragment of the spectrum, corresponding to quasiparticles (corresponding to large values of the wave vector). It is nevertheless clear from our results that the gap has a nontrivial temperature dependence and that this dependence requires a special theoretical analysis, which has not yet been carried out. We would add that our results correlate with the magnetooptic results of Ref. 5, although in our case the transition along the temperature scale is broader. Part of the reason may be the smaller gap in our samples. For example, the temperature at which the gap disappears, as determined by the optical method[5] for the fraction 2/3, symmetric with $\nu = 1/3$, in a field of 15 T is also approximately equal to 3 K, despite the fact that the magnitude of the gap at 0.5 K is about 10 K.

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