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Manifestation of charge-flux duality in a 2D electron gas near filling factor $\nu = \frac{1}{2}$

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Abstract

In the present work we report an experimental investigation of mesoscopic fluctuations in AlGaAs/GaAs microstructures in the vicinity of the Landau level filling factor $\nu = \frac{1}{2}$. The fluctuations have been studied both in magnetoresistance and in resistance versus gate voltage dependencies. The ratio of the correlation magnetic field to the correlation electron density of these fluctuations is found to be equal to the magnetic flux quantum multiplied by two. This supports the prediction of a charge-flux duality of mesoscopic fluctuations in the vicinity $\nu = \frac{1}{2}$.

Keywords: Composite fermions; Mesoscopic fluctuations

The fractional quantum hall effect (FQHE) continues to be one of the most intriguing and challenging areas of research in solid state physics. Recently, with the introduction of the composite fermions theory [1,2] offering a seemingly very simple interpretation of the effect, there emerged a number of new interesting questions that needed to be investigated.

According to the composite fermion (CF) theory of the FQHE, in the region of real magnetic fields where the filling factor $\nu = \frac{1}{2}$, the liquid of electrons is equivalent to an ideal Fermi gas of quasiparticles (each associated with the charge e and two attached flux quanta, $2\Phi_0$) moving in an effective magnetic field $B_{\text{eff}} = B - B_{1/2}(N_s)$. The latter is determined both by the external field itself and by the local electron density ($B_{1/2} = 2hN_s/e$) so that real electron scattering on a smooth screened random potential and in a high external magnetic field can be converted into free quasiparticles scattering on a weak built-in effective random magnetic field.

It is well known that in small structures with random potential, sample specific interference of electron waves produces mesoscopic conductance fluctuations [3]. One can assume that the same would take place in a confined system with random magnetic field scattering (for example, in a micstructure with composite fermion liquid near $\nu = \frac{1}{2}$).

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The first experimental observation of conductance fluctuations in a microbridge near filling factor $\nu = \frac{1}{2}$ was reported in Ref. [4]. Ref. [5] gives the results of a more detailed study in which the properties of magnetoconductance fluctuations at $\nu = \frac{1}{2}$ and mesoscopic fluctuations of bare electrons at $B = 0$ were compared. Theoretically, the problem has been first considered in Ref. [6] where the intuitive expectation of mesoscopic fluctuations in a system with random magnetic field scattering has found support. Moreover in this work, a prediction was made that mesoscopic fluctuations of CF must exhibit a certain charge-flux duality. Indeed if one takes into account the relation between the flux $2\Phi_0$ and the electron charge assigned to a quasiparticle in the composite fermion liquid near the filling factor $\nu = \frac{1}{2}$ one can conclude that magnetoconductance fluctuations in a microbridge can be equally affected both by the change of the real magnetic flux through a sample or by the variation of the electron sheet density. In a sense changing electron density in this situation is simply an indirect method of changing the effective magnetic field experienced by composite fermions. Implantation of an additional charge $dQ = e/2$ into the sample area S would result in a variation by $2\Phi_0$ of the effective flux $\Phi_{\text{eff}} = SB_{\text{eff}}$. As with bare electrons the correlation magnetic field of magnetoconductance mesoscopic fluctuations of composite fermions is determined by the ratio Φ_0/S. Then, if the variation of gate voltage is converted into the variation of electron density, the ratio of the correlation magnetic field B_c to the correlation electron density N_{sc} is expected to be $2\Phi_0$:

$$B_c/N_{sc} = 2\Phi_0. \tag{1}$$

Because of the charge-flux duality of mesoscopic fluctuations of CF described above, Eq. (1) is expected to be valid even at a finite temperature provided it is low enough so as to not smear entirely the interference of CF. It should therefore be possible to test experimentally the main conclusions of Ref. [6] and the validity of Eq. (1) in particular. The present work has been performed with this object in view.

Two different types of microbridges have been used. The structures of the first type (see the inset to Fig. 1a) were designed to allow four terminal measurements and had the lithographical length $L = 1$ μm and lithographical width $W = 1.2$ μm. The bridges of the second type (see the inset to Fig. 1b) with the length $L = 2$ μm and width $W = 1$ μm had only the current probes. The actual widths of the microbridges could be determined from Shubnikov–de Haas oscillations in weak magnetic fields and for the structures of the second type they varied from 0.3 to 0.5 μm. The microbridges were fabricated by means of electron lithography and plasma chemical etching on top of a 2D electron gas in AlGaAs/GaAs heterolayer with the spacer thickness of 60 nm. The electron density and electron mobility in the original heterolayers were $(1\text{–}2)\times 10^{11}\ \text{cm}^{-2}$ and $(2\text{–}4)\times 10^{5}\ \text{cm}^2/\text{Vs}$ correspondingly. The microbridges were etched in the middle between the voltage probes of a conventional rectangular Hall bar with the dimensions $100\times 50\ \mu\text{m}^2$. At the final stage of preparation the structures were covered by an Au/Ni metal gate. The measurements were carried out at temperatures from 30 mK to 4.2 K in magnetic fields up to 15 T. The alternative driving current of frequency 3–6 Hz was kept as low as 0.5–1 nA to preclude electron heating. The results for one sample of type I and two samples of type II are presented.

Fig. 1 shows the typical $R_{xx}(B)$ curves for the two types of samples. The general view of the magnetoresistance dependence in Fig. 1b is indicative of the presence of a potential barrier between the macroscopic part of the sample and the bridge. The effect of this barrier can only be avoided by the use of voltage probes attached directly to the bridge (Fig. 1a). The deep minimum in the vicinity of $\nu = \frac{1}{2}$ (Fig. 1b) coincides in magnetic field with the minimum $\nu = \frac{3}{2}$ in the rest of the sample and is therefore the consequence of measuring the resistance of the bridge in series with the resistance of the macroscopic parts adjacent to the voltage probes.

Both the curves in Fig. 1 exhibit magnetoresistance fluctuations in the vicinity of $\nu = \frac{1}{2}$. It was found that when the gate voltage was changed the pattern of the fluctuations in the structures of type I would begin to modify continuously with time so that one could not obtain a good enough match between two different sweeps. On the contrary, the structures of type II were very stable and there was generally a very good reproducibility of curves

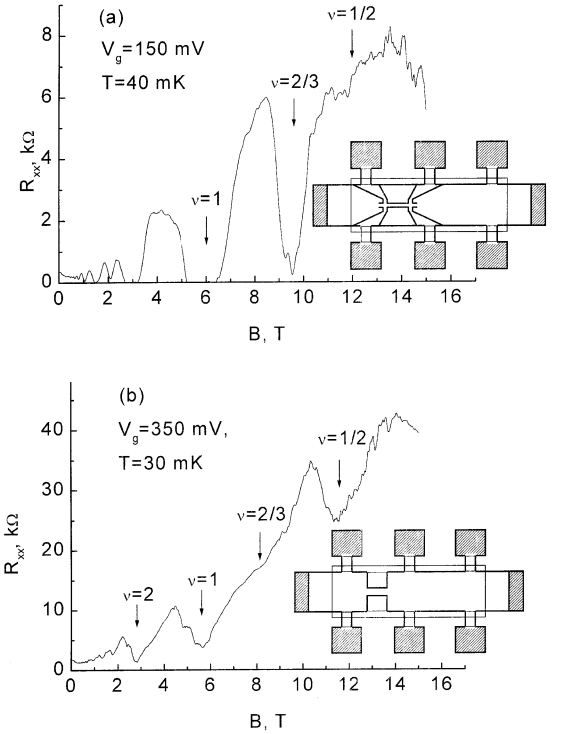

Fig. 1. Magnetoresistance $R_{xx}(B)$: (a)sample I, $T = 40$ mK, $V_g = 150$ mV, and (b)sample II-1, $T = 30$ mK, $V_g = 350$ mV. The insets show the top view of the experimental samples of type I (a) and type II (b).

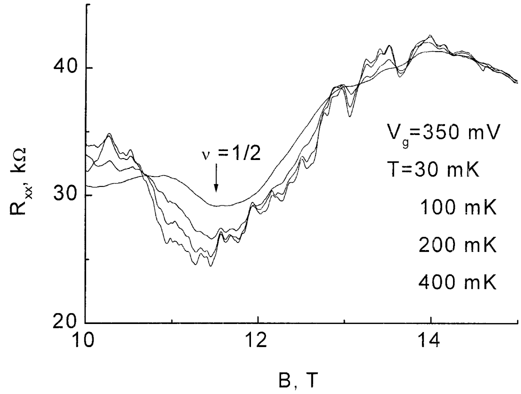

Fig. 2. Sample II-1, $R_{xx}(B)$ near $\nu = \frac{1}{2}$ for several temperatures.

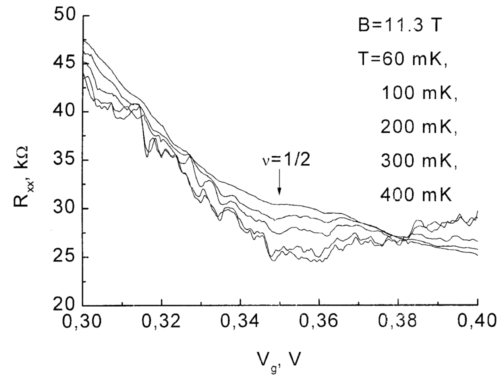

Fig. 3. Sample II-1, $R_{xx}(V_g)$ near $\nu = \frac{1}{2}$ for several temperatures.

unless one did not want to change the state of the sample on purpose. Apart from this the properties of the fluctuations were the same for the two types of the structures used. Below we use for illustration the dependencies obtained on a structure of type II.

Figs. 2 and 3 show series of $R_{xx}(B)$ and $R_{xx}(V_g)$ dependencies taken at different temperatures in the vicinity of $\nu = \frac{1}{2}$ for small variations of magnetic field and gate voltage. As the temperature increases the amplitude of the fluctuations decreases and at $T > 400$ mK they die out completely. Fig. 4 shows the temperature dependence of the average amplitude of the fluctuations. One can see that the average amplitude and its variation with temperature are practically the same for the fluctuations in magnetic field and gate voltage dependencies of R_{xx}. At the same time the temperature dependence itself is different from that observed for mesoscopic fluctuations of electrons in weak magnetic fields [7] where in one-dimensional systems the average amplitude changes with temperature as $T^{-1/2}$. In Fig. 4, a very weak temperature dependence observed at temperatures lower than 100 mK changes to a much stronger one $\Delta R_{xx} \sim T^{-(1 \pm 0.5)}$ at higher temperatures. Such temperature dependence might be attributed to some unusual behaviour of the CF coherence length which however we cannot at present account for. We notice that for samples with a considerably higher disorder no such anomaly in the fluctuations amplitude temperature dependence has been reported [5].

In order to test Eq. (1) we have investigated several different states of sample II-1, one state of sample II-2 and one state of sample I. The state of a sample could be altered either by LED illumina-

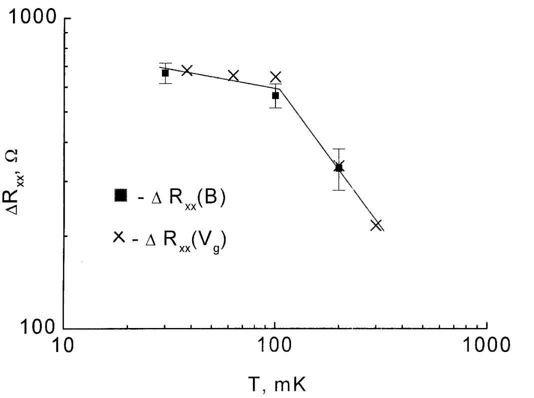

Fig. 4. The fluctuations average amplitude temperature dependence derived from $R_{xx}(B)$ and $R_{xx}(V_g)$ curves in Figs. 2 and 3.

Table 1
The values of B_c/N_{sc}

Sample	T (mK)	$R_{1/2}$ (kΩ)	B_c/N_{sc}, Φ_0
II-1	30	23	2.38
II-1	30	23	1.85
II-1	30	24	2.37
II-1	30	27	2.04
II-1	40	57	2.3
II-1	100	27	2.18
II-2	40	50	1.83
I	50	10	1.8

tion or by changing the electron density with gate voltage. By means of the latter the resistance of sample II-1 at $\nu = \frac{1}{2}$ could be varied in the range 30–60 kΩ. In a state thus obtained, the dependencies $R_{xx}(B)$ and $R_{xx}(V_g)$ were measured in a narrow interval of filling factor ~ 0.1 around $\nu = \frac{1}{2}$. The values of B_c and N_{sc} were derived from these dependencies using conventional correlation analysis [3]. These values were then used to determine the ratio (1) for a given state and sample. The values of B_c/N_{sc} obtained in this manner are shown in Table 1. The observed scatter of the values may be due to the error associated with the procedure of separation of mesoscopic fluctuations from the background of smooth nonmonotonic components. As seen in Figs. 2 and 3 these components remain unaltered at temperatures where the mesoscopic fluctuations are already completely suppressed and therefore we infer that they must have a different origin. On the whole, the experimental values of B_c/N_{sc} agree closely with the theoretically predicted value $2\Phi_0$ [6].

If the notion of a Fermi surface is applicable to CF, then apart from the R_{xx} fluctuations in gate voltage dependencies described in Ref. [6] there might still be another and more conventional type of mesoscopic fluctuations near $\nu = \frac{1}{2}$ resulting from the CF wave length variation. The contribution of this latter mechanism to the ratio (1) has not been analysed in [6] but it seems likely that it would be sensitive to the state and parameters of a sample. Since no such sensitivity was observed in our experiment we will not discuss the second mechanism in this letter though it should be taken into account in further investigations of the problem. In weak magnetic fields, where for bare electrons only the second mechanism works, the ratio (1) in our samples is about an order of magnitude less than for fluctuations at $\nu = \frac{1}{2}$.

A similar result has been recently reported in [8] where at $\nu = \frac{1}{3}$ the resonance tunneling via a state bound to an antidot in the center of a microstructure has been studied. The ratio of the resonance tunneling periods in magnetic field and in gate voltage has been found to be equal $3\Phi_0$. So in two different physical situations (the $\frac{1}{3}$ state of the FQHE in Ref. [8] and a gapless energy spectrum at $\nu = \frac{1}{2}$ in our case) the ratio of B_c to N_{sc} is found to be equal to the magnetic flux quantum multiplied by the inverse of the filling factor. In our opinion this fact is not a coincidence and can be taken to mean that in the conditions of FQHE the interference effects are determined by the value of the filling factor regardless of the character of the energy spectrum. Yet further experimental and theoretical studies are needed to prove it conclusively.

In conclusion, we have investigated mesoscopic resistance fluctuations in AlGaAs/GaAs microstructures in the vicinity of $\nu = \frac{1}{2}$. The ratio of the correlation magnetic field of these fluctuations to the correlation electron density is found to be equal to the magnetic flux quantum multiplied by two. This supports the predicted charge-flux duality of mesoscopic fluctuations in the vicinity of the filling factor $\nu = \frac{1}{2}$ [6].

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