Detection of Composite Fermions by Magnetic Focusing

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We report on transverse magnetic focusing experiments in two-dimensional electron systems in the vicinity of Landau level filling factor $\nu=\frac{1}{2}$. We observe quasiperiodic magnetic focusing peaks for $\nu<\frac{1}{2}$ and no periodic structure for $\nu>\frac{1}{2}$ in several double-constriction GaAs heterojunction samples. The quasiperiod and the direction of focusing in all of these samples are in good quantitative agreement with that expected from semiclassical transport by composite fermions of charge $-|e|$.

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A new kind of fermionic particle, "composite fermion" (CF), was proposed [1] as the fundamental origin of the fascinating phenomenon of the fractional quantum Hall effect (FQHE) [2]. In a two-dimensional electron system (2DES) subjected to a high normal magnetic field B at low temperatures, the electrons condense into composite fermions. A composite fermion is an electron carrying an even integer number ($2p$) of the vortices of the many-particle wave function, and often can be thought of as an electron binding $2p$ magnetic flux quanta ϕ_0 ($\phi_0=h/e$). Composite fermions are formed as a result of the Coulomb interaction between the electrons in a 2DES, and the liquid of strongly interacting electrons is equivalent to a gas of weakly interacting CF's. Since CF's do not experience the flux bound to them, they see an effective magnetic field

$$B^*=B\mp 2pn\phi_0\,, \qquad (1)$$

where n is the electron (and CF) density, and the $-$ ($+$) sign corresponds to the flux binding in the same (opposite) direction as the external field B. Correspondingly, the effective Landau level filling factor of composite fermions $\nu^*=n\phi_0/B^*$ is related to the electron filling factor $\nu=n\phi_0/B$ by $\nu=\nu^*/(2p\nu^*\pm 1)$. One of the principal features of the CF theory is the straightforward explanation of FQHE of electrons as the integer QHE of composite fermions [1]. An integer number of filled Landau levels of CF's ($\nu^*=i$) corresponds to the electron $\nu=i/(2pi\pm 1)$, which are precisely the sequences of fractions observed in experiments [1,3]. Transitions from one FQHE state to the next within the sequence are expected to occur at $\nu^*=i+\frac{1}{2}$, according to the "law of corresponding states" [4]; this is also in agreement with experiments [5].

For the simplest case of $p=1$ in Eq. (1), the FQHE sequences $\nu=i/(2i\pm 1)$ converge towards $\nu=\frac{1}{2}$ as $i\to\infty$. Experimentally, it has been known for some time that in very low disorder 2DES samples the diagonal resistance R_{xx} remains finite and exhibits a deep, broad minimum at $\frac{1}{2}$, while the Hall resistance R_{xy} is linear in B near $\frac{1}{2}$ and develops no plateau to the lowest temperatures [6]. More recently, in nonlocal magnetotransport experiments [7] it was found that the FQHE edge conduction is suppressed near $\frac{1}{2}$, and certain attenuation and propagation velocity anomalies were reported [8] near $\frac{1}{2}$ in surface acoustic wave experiments. Recently, using a Chern-Simons field theoretical formulation [9,10], Halperin, Lee, and Read [11] and Kalmeyer and Zhang [12] have proposed that CF's form a Fermi sea near $\nu=\frac{1}{2}$ and that this is the origin of the "metallic behavior" seen in experiments. Following the work of Halperin, Lee, and Read several new experimental possibilities to detect directly composite fermions became apparent.

In this paper we report the observation of composite fermions in transverse magnetic focusing experiments. Specifically, (i) we observe quasiperiodic resistance peaks in the focusing geometry near $\nu=\frac{1}{2}$, where B is much too high for focusing of electrons, yet B^* is small, as needed for CF focusing. (ii) The quasiperiodic structure is observed only on one side of $\frac{1}{2}$ corresponding to focusing of negatively charged particles, as expected for CF's. (iii) The value of the quasiperiod is consistent with that expected from a simple semiclassical picture of focusing of spin-polarized CF's with density equal to that of 2D electrons. Thus, these experiments provide direct microscopic confirmation of the existence of composite fermions by demonstrating that negatively charged fermionic carriers form a Fermi sea near $\nu=\frac{1}{2}$ and experience an effective magnetic field $B^*=B(1-2\nu)$, in agreement with Eq. (1).

Magnetic focusing of 2D electrons at low B was first observed and studied in semiconductor heterostructures by van Houten *et al.* [13]. The sample geometry is shown in Fig. 1; the current is passed through the left constriction, and the voltage developed across the right constriction is measured as a function of B. In the linear regime, the measured voltage is proportional to the applied current so that the ratio is a (nonlocal) resistance. Classically, electrons coming out of the left constriction with the Fermi velocity execute cyclotron motion, and are focused into the right constriction when B is such that the cyclotron diameter of an electron on the Fermi surface $2R$ times an integer j is equal to the constriction separation L: $2jR=L$ (assuming specular reflections from flat gates). Since $R=\hbar k_F/eB$, and in GaAs, where the conduction band is nearly isotropic, the Fermi wave vector

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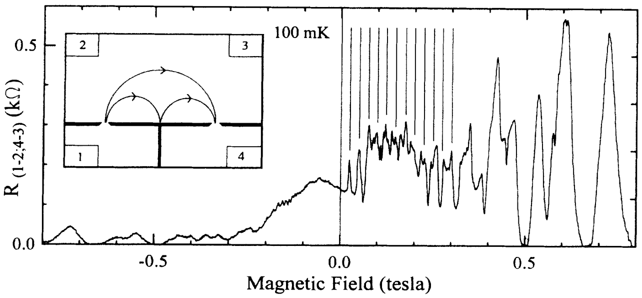

FIG. 1. Four-terminal magnetoresistance of the sample with constriction separation $L \simeq 4.25$ μm. Magnetic focusing of electrons occurs for positive magnetic field. The vertical lines are equidistant and spaced by 25 mT. The inset shows schematic sample geometry. The dark regions were etched and gates were deposited in etch trenches. The four Ohmic contacts are numbered.

$k_F = (2\pi n)^{1/2}$, resistance exhibits periodic focusing peaks at fields $B_j = j\Delta B$, with the period $\Delta B = 2\hbar k_F/eL$. It should be noted that the focusing occurs only in one direction of B; in the opposite field direction the electrons coming out of the left constriction are deflected to the left and no peaks are observed.

This classical focusing occurs up to a magnetic field where R is approximately equal to the width of the undepleted opening in the constriction d; that is, the number of classical focusing peaks is given by $\approx L/2d$. The scattering length of electrons has to be greater than L in order for focusing to occur; therefore sufficiently low temperature T is required. Magnetic focusing at low T in very low disorder 2DES is a more complex phenomenon, and, semiclassically, is caused by interference of coherently excited quantized magnetic boundary states; the peaks develop structure and become less periodic; some peaks may be nearly missing and the others are very strong. However, quasiperiodicity may still be apparent for several peaks, and a Fourier transform usually reveals a quasiperiodic component with the same ΔB as at higher T. This is discussed in detail in Ref. [13].

These considerations are readily extended to a Fermi sea of composite fermions. Now focusing peaks occur at $B_j^* = j\Delta B^*$, with the period $\Delta B^* = 2\hbar k_F^*/eL$, where k_F^* is the Fermi wave vector of CF's, and B^* is given by Eq. (1). For the case of $p=1$ (ν near $\frac{1}{2}$), composite fermions are likely to be spin polarized so that $k_F^* = \sqrt{2}k_F = 1/l_{1/2}$, where $l_{1/2}$ is the magnetic length at $\frac{1}{2}$, and therefore $\Delta B^* = \sqrt{2}\Delta B$. In other words, the jth CF focusing peak is expected to occur at $B_j = B_{1/2} + j(2\hbar/eLl_{1/2})$, and thus ΔB^* is given by the fundamental constants, the magnetic field at $\nu = \frac{1}{2}$, and, the least accurately known, the constriction separation L.

The samples were fabricated from a very low disorder GaAs heterostructure material described previously [6]. The double-constriction geometry was defined by standard electron-beam lithography on a preetched mesa with Ohmic contacts. The smallest defined features were 100 nm in size. The double constriction was then chemically etched ~240 nm (~60 nm short of the 2DES plane), and Ag gates were deposited in the etched trenches. The optimal etch depth and the size of the opening between the gates were established in experiments on a single constriction in the QHE regime. The length of the central gate was varied in different samples, but the separation between the gates was kept constant at 750 nm; this resulted in the undepleted region between the gates being on the order of 200 nm, as determined from the $B=0$ resistance of the constrictions. The three Ag gates were contacted independently and were used to establish resistance quantization at $B=0$ [14] and to fine tune the constrictions near $\nu = \frac{1}{2}$. 2DES with $n \approx 1.0 \times 10^{11}$ cm^{-2} and $\mu \approx 2 \times 10^6$ cm^2/V s (elastic scattering length 12 μm) were prepared in heterojunctions by exposure to light from a red light emitting diode. Measurements were performed in a top-loading-into-mixture (TLM-400) dilution refrigerator with sample probe wires filtered at mK T, so that total electromagnetic background at the sample's contacts is believed to be ~2 μV rms. Four-terminal magnetoresistance of the samples $R_{(I^+-I^-;V^+-V^-)}$ (see Fig. 1) was measured with a lock-in amplifier at ~4 Hz with applied current ranging from 2 nA at low B to 0.1 nA near $\nu = \frac{1}{2}$.

A total of ten double-constriction samples were studied, five of them with very short central gate lengths, implying $L \leq 1.6$ μm. These five samples showed substantial asymmetry of resistance upon B reversal, both at low B and for $\nu <$ or $> \frac{1}{2}$, for B^* positive and negative. No clear focusing resistance peaks were observed, however, both at low B and near $\frac{1}{2}$. The other five samples had L between 2.6 and 5.3 μm. Figure 1 shows the resistance at low B for one of the samples with $L \simeq 4.25$ μm. There are three clear focusing peaks, and a total of about twelve quasiperiodic peaks can be identified. For this sample, the simple classical estimate given above yields that focusing can be expected up to $B \sim 0.2$ T, roughly consistent with the data. The structure on the peaks is believed to arise from the quantum interference effects; its amplitude grows with B similar to the experiments and theoretical modeling of Ref. [13]. The spacing $\Delta B = 25$ mT is in good agreement with the expected period for this L and $n = 0.98 \times 10^{11}$ cm^{-2}. The $\nu = 8$ minimum in R_{xx} occurs at 0.50 T; other QHE states are present at higher B.

Figure 2 shows the four-terminal magnetoresistance of the same sample in the vicinity of $\nu = \frac{1}{2}$; the direction of B corresponds to positive in Fig. 1. The structure on the high-B side of $\frac{1}{2}$ exhibits several apparently quasiperiodic peaks: The vertical lines are equally spaced by $\Delta B^* = 36$ mT and almost every line can be identified with a resistance peak. This apparent quasiperiodicity is also confirmed by a Fourier transform, which yields a peak at 28 T^{-1} = (36 mT)$^{-1}$. The quasiperiod is very close to $\sqrt{2}\Delta B = 35.4$ mT, as expected from transport by spin-polarized composite fermions. The structure on the low-

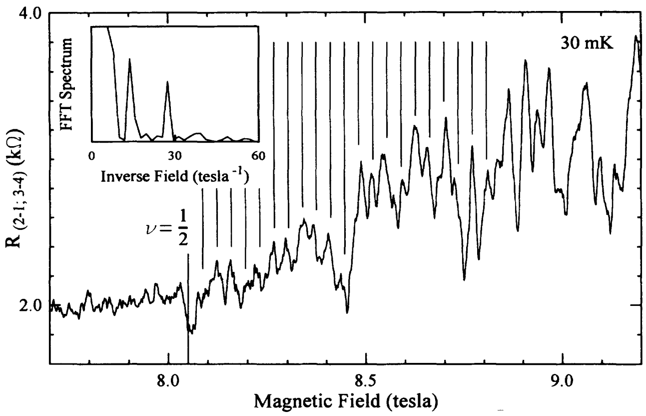

FIG. 2. Composite fermion magnetic focusing spectrum for sample of Fig. 1. The vertical lines are equidistant, with spacing of 36 mT. The direction of B is the same as positive field in Fig. 1; thus CF's are expected to be deflected to the right (as in Fig. 1) for $B > B$ ($\nu=\frac{1}{2}$). The inset shows the Fourier transform spectrum for $\nu < \frac{1}{2}$.

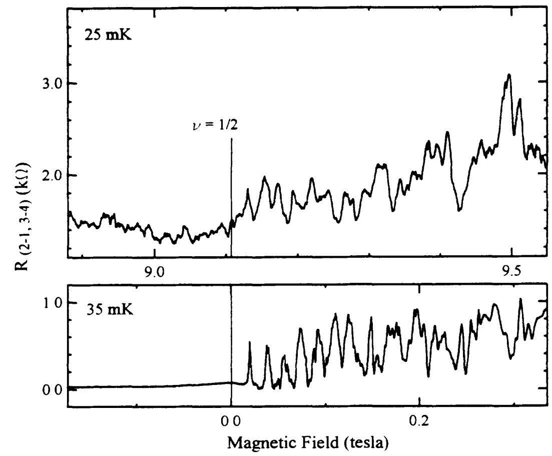

FIG. 3. Composite fermion magnetic focusing spectrum (upper panel) compared with electron focusing spectrum (lower panel) for sample with constriction separation $L \simeq 5.3$ μm. The lower trace was obtained with -300 mV gate voltage to simulate the constriction narrowing for CF's. The B scale is smaller by a factor of 0.75 in the upper panel.

B side of $\frac{1}{2}$ is qualitatively different from that on the high-B side: The magnitude of the resistance fluctuations is small and there is no periodicity associated with it; Fourier spectrum of the data for $\nu > \frac{1}{2}$ displays no apparent peak besides the usual "background" structure at low inverse fields. The origin of the relatively weak structure in R for $\nu > \frac{1}{2}$ is not understood at present; it may be universal conductance fluctuations [15]. Above ≈ 8.8 T FQHE minima in R_{xx} coexist with the focusing peaks, similar to the case of electron focusing and integer QHE at low B; about twelve more peaks with average spacing of 34 mT can be identified in this regime.

Figure 3 gives the resistance near $B=0$ and near $\nu=\frac{1}{2}$ for another sample with $L \simeq 5.3$ μm. There are several apparently quasiperiodic peaks in both traces and Fourier transform yields $\Delta B = 18$ mT at low B and $\Delta B^* = 24$ mT near $\frac{1}{2}$. The asymmetry of the data for $\nu < \frac{1}{2}$ and $\nu > \frac{1}{2}$ is quite evident, as is the correspondence between the first several peaks in both traces. The low-B data were obtained with a negative voltage (300 mV) applied to the gates so as to simulate effective constriction narrowing for composite fermions [16]. We also note that path length of particles for classical focusing orbits is approximately the same for all focusing peaks; it is ≈ 8 μm for $L \simeq 5.3$ μm.

These observations make a compelling case that the resistance peaks near $\frac{1}{2}$ in these samples are quasiperiodic in B and, therefore, in B^*. The precise positions of the filling factor $\nu=\frac{1}{2}$ given in the figures were determined as to agree with the equal spacing of the vertical lines, and the position of the first focusing peak was usually apparent in the data taken at different T. For each sample, the shown position of $\frac{1}{2}$ is in good agreement (typically, to within ± 50 mT) with the positions of the prominent QHE states at $\nu=2$, 1, $\frac{2}{3}$, and $\frac{2}{5}$. The resistance peaks near $\nu=\frac{1}{2}$ are quite sensitive to temperature: they are nearly washed out by 100 mK (compared with ~ 3 K for electrons at low B); as T is varied, some peaks grow stronger, some become weaker, and others do not change much unless T is varied significantly. The precise positions of the peaks also seem to fluctuate a little. However, quasiperiodic intervals of B are always apparent, and Fourier spectra show clear quasiperiodicity of the structure present only for $\nu < \frac{1}{2}$, and not present for $\nu > \frac{1}{2}$, even in the data where quasiperiodic peaks may not be readily apparent.

Quasiperiods ΔB and ΔB^*, determined from the low-B and $\nu < \frac{1}{2}$ magnetic focusing data, respectively, are summarized for the five long-L samples in Fig. 4. It is apparent that $\Delta B^* \approx \sqrt{2}\Delta B$. The quasiperiodic resistance peaks in the two shortest L samples (2.6 and 3.1 μm) are few and not as well defined as in the other three samples; ΔB and ΔB^*, therefore, have a large uncertainty ($\sim 20\%$) for these two samples. The constriction spacing L was taken to be equal to the distance between the mid-openings. It was determined from the electron micrographs, calibrated by atomic force microscope images of the same lithographies as the actual samples; we estimate the uncertainty in the absolute values of L to be ± 0.3 μm.

The observation of quasiperiodic focusing peaks, present on the high-B side of $\nu=\frac{1}{2}$ and absent on the low-B side, with the quasiperiod $\Delta B^* \approx \sqrt{2}\Delta B$, makes a compelling case for the transport by composite fermions. The only conceivable alternative interpretation of the data could be resonant tunneling from one edge channel to another [17], across one of the constrictions, via states

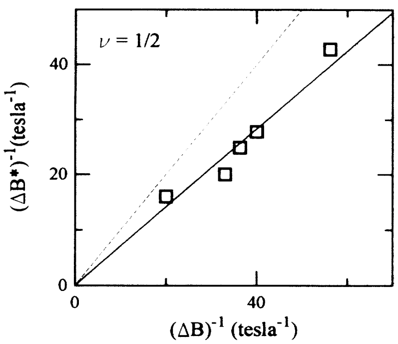

FIG. 4. Composite fermion quasiperiod ΔB^* plotted vs electron quasiperiod ΔB for five samples. The solid line has the expected slope of $1/\sqrt{2}$; the dashed line has a slope of 1 and is shown for comparison.

quasibound on a hill of the disorder potential, created in the 2DES plane by ionized donors of the δ doping. However, this can be ruled out on the basis of the following considerations. (i) There is no reason why interedge resonant tunneling should occur only for $\nu < \frac{1}{2}$; indeed, one would expect resonant tunneling to be much more pronounced at the QHE plateaus [18], and, in particular, on the low-ν side of the plateaus. (ii) One would expect resonant tunneling to be masked by the bulk conduction near $\frac{1}{2}$ since the edge and bulk states are strongly coupled in this regime [7]; indeed, no quasiperiodic structure near $\nu = \frac{1}{2}$ has been seen in experiments on single-constriction samples. (iii) The size of the impurity-bound electron orbits required to give periodicity of 24 mT (as in sample of Fig. 3) is 0.50 μm, which is greater than the undepleted region between the gates; such a potential hill, if placed in the opening of a constriction, would quench transport through the constriction altogether. (iv) It is most unlikely that the size of the potential hill would happen to be "just right" and would, moreover, exhibit right dependence on L in every one of the several samples studied.

The number of apparently quasiperiodic CF focusing peaks in Figs. 2 and 3 (particularly in Fig. 2) is greater than the number of apparently quasiperiodic electron focusing peaks at low B. This is not fully understood at present, but can be due to the fact that optimization of the parameters of the constrictions was done in experiments in the QHE regime, as opposed to optimization at low B. Also, the effective width of the constrictions is smaller for CF's than for electrons and therefore more focusing peaks can be expected for CF's than for electrons [16].

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