How Real Are Composite Fermions?

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(Received 14 September 1993)

According to recent theories, a system of electrons at the half-filled Landau level can be transformed to an equivalent system of composite fermions at *zero* effective magnetic field. In order to test for these new particles, we have studied transport in antidot superlattices in a two-dimensional electron gas. At low magnetic fields electron transport exhibits well-known resonances at fields where the classical cyclotron orbit becomes commensurate with the antidot lattice. At $\nu=\frac{1}{2}$ we observe the same dimensional resonances. This establishes the semiclassical behavior of composite fermions.

PACS numbers: 73.40.Hm

During the past decade two-dimensional electron systems at low temperature and high magnetic field have repeatedly surprised us with exotic electron correlation phenomena. The quantum liquids of the fractional quantum Hall effect (FQHE) [1–3], the still enigmatic electron crystal [4] at very low filling factors, and the vanishing and reappearance of certain quantum Hall states in double layer electron systems [5–7] all reflect the dominance of electron-electron interaction at very high magnetic fields. Recently the nature of the electronic interaction at the half-filled Landau level has received much attention. There is now mounting evidence for a novel particle called a "composite fermion" [8] that plays a crucial role in the physics of two-dimensional (2D) electron systems in the lowest Landau level. In this paper we present results of an experiment that demonstrates the semiclassical motion of such a particle.

The significance of the physics at the half-filled Landau level was foreshadowed in exceptional electrical transport and surface acoustic wave anomalies exactly at $\nu=\frac{1}{2}$. At this filling fraction Jiang *et al.* [9] observed a deep minimum in the magnetoresistivity ρ_{xx} that persisted to unusually high temperatures, exhibiting a temperature dependence distinctly different from the neighboring FQHE states. Surface acoustic wave (SAW) experiments by Willett *et al.* [10] at $\nu=\frac{1}{2}$ revealed attenuation and velocity changes that were opposite to those observed in the regime of the FQHE liquids.

Independently, the hierarchical model of the FQHE that orders the various odd-denominator states at $\nu=p/q$ (p = integer, q = odd integer) had come under increasing criticism. Starting from the Laughlin liquids [11] condensed from electrons at $\nu=1/m$ and $\nu=1-1/m$, the higher order FQHE states are derived from lower order states as Laughlin states of fractionally charged quasiparticles [12,13]. In particular, the two prominent series of liquids at $\nu=p/(2p\pm1)$ represent a succession of parental and daughter states starting from $\nu=\frac{1}{3}$ and $\nu=\frac{2}{3}$ and converging towards $\nu=\frac{1}{2}$. However, questions were raised [14] regarding the density of quasiparticles and their apparent noninteracting nature.

Jain proposed an innovative model for these series of FQHE liquids based on hypothetical particles which he termed composite fermions [14]. The liquids of the FQHE are then derived as the integral quantum Hall effect of such composite fermions. These composites consist of an even number of magnetic flux quanta bound to an electron as a result of strong electron-electron interaction which had been contemplated earlier in a related context [15–19]. In a seminal paper Halperin, Lee, and Read [20] used a Chern-Simons gauge field construction to transform the state at exactly $\nu=\frac{1}{2}$ to a mathematically equivalent state of composite fermions with a well defined Fermi surface at vanishing magnetic field. Like magic, the magnetic field (two flux quanta per electron at $\nu=\frac{1}{2}$) is incorporated into the particles themselves and the resulting composite fermions move in an apparently vanishing external magnetic field.

The composite particles of these theories have been able to account for several of the previously puzzling features in the vicinity of $\nu=\frac{1}{2}$. The electronic transport anomaly at $\nu=\frac{1}{2}$ is explained in terms of the appearance of a metallic state and the suppression of electron localization [21]. The SAW data at this filling factor are interpreted as wave vector dependent relaxation of the composites that make up the Fermi sea [20] and the width of the SAW anomaly is consistent with the size of the postulated Fermi surface [22]. The tunneling experiment at $\nu=\frac{1}{2}$ between pairs of 2D electron systems by Eisenstein, Pfeiffer, and West [23] also finds an explanation in terms of the Fermi liquid at the half-filled Landau level [24]. And finally, the Halperin-Lee-Read theory provides a very natural interpretation of the observation by Du *et al.* [25] that the size of the energy gaps of the main sequence of FQHE states at $\nu=p/(2p\pm1)$ increases linearly with the magnetic field deviation from $B_{1/2}$ at $\nu=\frac{1}{2}$. It simply reflects the linearly increasing "Landau-level splitting" of composite fermions exposed to an effective magnetic field $B_{\mathrm{eff}}=B-B_{1/2}$.

Although there is considerable experimental support for composite fermions, it is natural to wonder just how real these particles are. It seems unsatisfactory to simply regard them as a convenient mathematical construct. In fact, it would be far more satisfying if we could detect a

0031-9007/93/71(23)/3850(4)$06.00

semiclassical aspect of the composites. Since the $\nu=\frac{1}{2}$ state is proposed to be largely equivalent to a metal at zero magnetic field, one wonders whether experiments that usually reveal the semiclassical motion of electrons could not be performed on these new particles. Experiments that come to mind are transverse focusing [26] and transport through surface gratings [27,28] or antidot superlattices [29]. These experiments are performed in the ballistic regime where the electronic mean free path is larger than the characteristic length scale of the experiment and the electronic transport can be treated semiclassically.

Electronic transport through antidot superlattices yields particular strong dimensional resonances. The resistivity of the patterned two-dimensional electron gas shows a sequence of strong peaks at low magnetic field. A simple geometrical construct reveals that the resonances occur when the classical cyclotron orbit, $r_c=m^* \times v_f/eB=\hbar k_F/eB$ [m^* is the effective mass, v_F is the Fermi velocity, $k_F=(2\pi n_e)^{1/2}$ is the Fermi wave vector, and n_e is the electron density], encircles a specific number of antidots. The inset in Fig. 1 illustrates the configurations for $s=1$, 4, and 9 dots. According to a simple electron "pinball" model [29], at these magnetic fields the orbit is minimally scattered by the regular dot pattern, electrons get "pinned," and transport across the sample is impeded. In a more sophisticated model the resistivity peaks arrive from the correlation of chaotic, classical trajectories [30].

We have used such an antidot superlattice to first establish the semiclassical behavior of electrons around $B=0$ and then probe the equivalent semiclassical behavior of these bizarre composite particles around $\nu=\frac{1}{2}$. One of the particularly telling signatures for the composite fermions we expect to find is their modified resonant field as compared to the resonances of the usual electrons. Not only should the peaks around $B=0$ reoccur symmetrically around $\nu=\frac{1}{2}$ but their spacing should differ by exactly a factor of $\sqrt{2}$ between electrons and composites. This is due to the spin alignment of the fermions, which increases their Fermi velocity v_F by a factor of $\sqrt{2}$ as compared to the unpolarized electron systems [20].

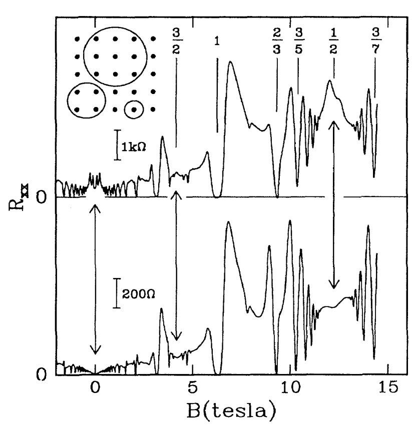

FIG. 1. Comparison of the magnetoresistance R_{xx} of the bulk two-dimensional electron gas (lower trace) and the R_{xx} of the $d=600$ nm period antidot superlattice (upper trace) at $T=300$ mK. The bulk R_{xx} was measured in a rectangular strip containing approximately three squares. The antidot superlattice was nearly a square. The fractions near the top of the figure indicate the Landau-level filling factor. Inset: Schematic of commensurate orbits encircling $s=1$, 4, and 9 antidots.

The antidot superlattice was fabricated on a high quality modulation-doped GaAs/AlGaAs heterostructure with electron density $n_e=1.45\times10^{11}$ cm^{-2} and mobility $\mu=7.8\times10^6$ cm^2/V sec prior to processing. The antidot superlattice was initially defined as an array of holes by standard electron-beam lithography on a 125×125 μm^2 area. The holes were then transferred to the 2D electron gas via reactive ion etching, producing cylindrical holes with minimal undercutting. The antidot region was defined as a bridge between two large two-dimensional electron gases by photolithography. The period of antidots ranged from $d=500$ to $d=700$ nm with the dot sizes of 100–200 nm. The electron-beam exposure and the etch depth were varied to optimize the size of the well-established antidot oscillations for electrons around $B=0$. All experiments were performed in a 15 T magnet with the sample immersed in pumped ^{3}He at 300 mK following a brief illumination from a light emitting diode. Because of a slight density gradient across the 2 in. GaAs wafer, the density in the superlattice varied slightly between samples from 1.45 to 1.52×10^{11} cm^{-2}.

Figure 1 shows the magnetoresistance R_{xx} of a $d=600$ nm period antidot superlattice in comparison with R_{xx} of the unprocessed bulk part of the sample, devoid of dots. The exceptional quality of the sample is demonstrated by two clear sequences of FQHE states in the bulk R_{xx} around half filling, reaching filling factors as high as $\nu=\frac{9}{17}$. A similarly pronounced series of FQHE states is observed in the upper trace through the antidots. However, a striking difference in R_{xx} is apparent near $B=0$, $\nu=\frac{3}{2}$, and $\nu=\frac{1}{2}$. The bulk sample clearly exhibits local minima at these field positions, whereas the resistance in the antidot trace shows overall maxima with peaks of varying strength superimposed at the same fields. The features around $B=0$ are clearly identifiable as the well-known dimensional resonances of the electrons followed by the appearance of Shubnikov-de Haas oscillations in higher magnetic field. The peaks around $\nu=\frac{1}{2}$ are the sought after dimensional resonances of composite fermions. A direct comparison between electron and composite resonances is made in Fig. 2.

Figure 2 shows four sets of R_{xx} data taken around $B=0$ and $\nu=\frac{1}{2}$ on four different specimens in the absence of a superlattice (a) and with three different antidot superlattices of periodicity 700, 600, and 500 nm [(b)–(d)]. The origin, $B=0$, resides at the center of the figure and the lower traces in each section represent the electron transport data taken for positive and negative magnetic fields. The well-established electron dimension-

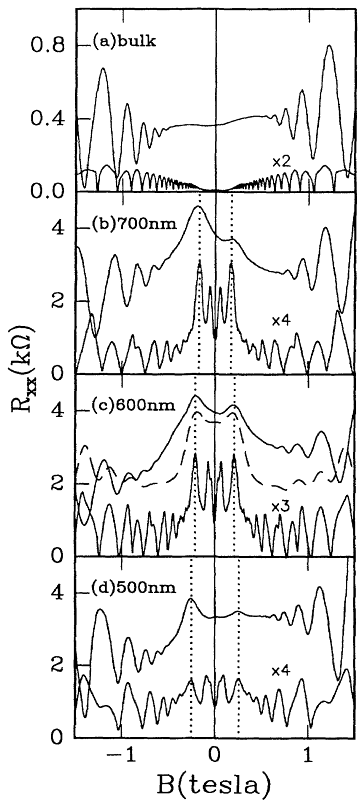

FIG. 2. Expanded views of the magnetoresistances near $\nu=\frac{1}{2}$ and $B=0$ for (a) bulk, (b) 700 nm, (c) 600 nm, and (d) 500 nm period antidot superlattices. The $\nu=\frac{1}{2}$ results are shown as upper traces in each figure. They have been shifted to zero and the field scale has been divided by $\sqrt{2}$ for comparison. The vertical scale reflects the resistance for the $\nu=\frac{1}{2}$ traces. The electron traces have been multiplied by the factor shown in the figure. The dashed curve in (c) shows simulated smearing by Fourier filtering of the electron trace.

al resonances are clearly visible for all periods [(b)-(d)]. They are of course absent in the unprocessed specimen of Fig. 2(a). The top trace of each section represents R_{xx} around $\nu=\frac{1}{2}$. To shift the traces down to $B=0$ we first define the exact magnetic field position $B_{1/2}$ at half filling from nearby, well-established FQHE features around $\nu=\frac{1}{2}$ and translated to $B=0$. Concomitantly, the magnetic field scale is compressed by a factor of $\sqrt{2}$ to account for the expected difference in k_F between electrons and composites. In comparing the dimensional resonances around $B=0$ with those around $\nu=\frac{1}{2}$ we observe excellent agreement between the strong $s=1$ features of the electrons and the peaks in the respective traces at half filling. This is compelling evidence that these magnetoresistance peaks around $\nu=\frac{1}{2}$ are due to antidot dimensional resonances of composite fermions.

Although the peak positions of the fermion resonance are in good agreement with the expected value, the width tends to be much broader than the electron resonance and the higher order peaks are not observed. This is probably due to the difference in mean free path between electrons and fermions. Since the $\nu=\frac{1}{2}$ state is equivalent to a metal at zero magnetic field, "resistivity" and "mobility" measurements can be made for the composite fermions. Van der Pauw measurements on the unprocessed sample at $\nu=\frac{1}{2}$ yield a resistivity of 350 $\Omega/\square$ equivalent to a mobility $\mu=1.23\times10^5$ cm^2/V sec. The corresponding fermion mean free path, $l=\hbar\sqrt{2}k_F\mu/e$, is approximately 2 μm. This contrasts sharply with the electron mean free path of ~ 50 μm at zero magnetic field. Thus, it should be no surprise that the fermion features are so much broader than the electron features and that higher order peaks are absent. To simulate such a smearing of the fermion resonance, we plot in Fig. 2(c) the electron data as a dashed trace after Fourier filtering it and removing frequencies greater than 1 kG. The resulting resemblance with the composite resonance is very striking.

A more detailed analysis of the shape of the peaks around $\nu=\frac{1}{2}$ is beyond the scope of this paper. However, we would like to point out an intriguing asymmetry. In all our data we find the lower magnetic field peaks, for both field directions, to exceed the higher field peak by as much as a factor of 10 [see Fig. 2(d)]. The origin of this effect remains unclear. Furthermore, not only are the $s=1$ peaks present around $\nu=\frac{1}{2}$, the overall resistance behavior around $B=0$ is reflected in the transport around $\nu=\frac{1}{2}$ in the unprocessed as well as the processed samples. This shows the similarity of transport in the extended region around $B=0$ and $\nu=\frac{1}{2}$. On the other hand, the temperature dependence of both phenomena differs considerably. While the electron resonances around $B=0$ are known [29] to persist up to temperatures as high as 40 K, we observe composite fermion resonances to disappear above ~ 1 K.

Finally to further quantify our findings, we plot in Fig. 3 the main peak positions for the electron resonance and the fermion resonance as a function of inverse lattice period, $1/d$. These axes were chosen since the $s=1$ resonances occur at $B=m^*v_F/de=\hbar k_F/de$ and at $B_{\mathrm{eff}}=\sqrt{2}\hbar k_F/de$ for electrons and fermions, respectively. To correct for the slight differences in the density between samples ($\sim 3\%$), the peak positions have been normalized with respect to the density of the $d=500$ nm antidot sample. The solid (dashed) line indicates the calculated electron (fermion) peak positions using $k_F=(2\pi n_e)^{1/2}$. The slopes of the two lines differ exactly by a factor of $\sqrt{2}$, reflecting the spin polarization of the fermion system. Good agreement between the experimental and the calculated peak positions further reinforces the existence of dimensional resonance of composite fermions.

Another interesting feature of our data is the fermion resonance at $\nu=\frac{3}{2}$. We expect the antidot oscillations to occur also in higher Landau and spin levels. The Fermi wave vector for composite fermions at $\nu=n+\frac{1}{2}$ is reduced by a factor of $\nu^{-1/2}$ as compared to k_F of the Fermi surface at $B=0$. In fact, a peak can be seen in Fig. 1

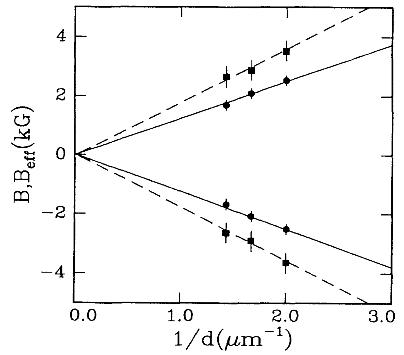

FIG. 3. Main resonance positions around $B=0$ (circles) and around $\nu=\frac{1}{2}$ (squares) as a function of inverse antidot period $1/d$. The vertical scale represents the external magnetic field for the electron case and the effective magnetic field $B_{\rm eff}=B-B_{1/2}$ for the composites. The peak positions have been corrected for the small density differences between the samples. The solid (dashed) lines show the calculated electron (fermion) peak positions. The slopes of the lines differ by $\sqrt{2}$.

at $\nu=\frac{3}{2}$ although the $s=1$ doublet remains unresolved.

While our experiments were performed in a static geometry, related geometrical resonances are also expected in SAW experiments when the wave vector of the surface phonons becomes commensurate with the classical cyclotron orbit [20]. Such resonances have been observed by Willett *et al.* [31].

In summary, we have observed dimensional resonances of new particles at $\nu=\frac{1}{2}$ filling factor of a Landau level. The resonances scale by exactly a factor of $\sqrt{2}$ between traditional electron resonances and those of the new composite particles as expected from their spin polarization. The observation of the resonances and their appropriate scaling demonstrates the semiclassical motion of composite fermions and suggests that in transport experiments around $\nu=\frac{1}{2}$, these new particles, in many aspects, behave like ordinary electrons. It is remarkable that the complex electron-electron interaction in the presence of a magnetic field can be described in such simple, semiclassical terms.

We would like to thank R. L. Willett for discussions and assistance with the *e*-beam lithography during earlier phases of the experiment.

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