Drastic Enhancement of Composite Fermion Mass near Landau Level Filling $\nu = \frac{1}{2}$

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We have determined the effective mass of composite fermions in the vicinity of half Landau level filling and observe a mass enhancement by as much as 40% as the filling factor ν approaches $\nu = \frac{1}{2}$. These measurements provide the first experimental data for the energetics of this novel fermion system as $\nu \rightarrow \frac{1}{2}$. The apparently divergent particle mass indicates that the system at exactly $\nu = \frac{1}{2}$ is not an ordinary Fermi liquid.

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According to recent theory [1–3] and supported by experiments [4–12], the electronic state in a two-dimensional electron system at half-filled Landau level, $\nu = \frac{1}{2}$, can be regarded as a degenerate system of new fermions in the absence of magnetic field, populating a Fermi sea up to the Fermi wave vector k_F. The new particles, termed composite fermions [13], result from the highly correlated motion of the carriers which effectively attaches flux quanta to each electron [1–3,13–18]. In this way, the external magnetic field at $\nu = \frac{1}{2}$ of exactly two flux quanta per electron becomes incorporated into the new particles, and these composites move in an apparently vanishing magnetic field. Since the density of the composite fermions remains unaltered compared to the constituent electrons, the Fermi wave vector k_F quite naturally takes on the value [1] $k_F = \sqrt{4\pi n}$. It differs from k_F for electrons at $B = 0$ only by a factor of $\sqrt{2}$, due to the lifting of the spin degeneracy at $\nu = \frac{1}{2}$. This value of k_F has been experimentally confirmed by three elegant techniques [8,9,12] exploiting dimensional resonances of the composite fermion orbit.

While these experiments directly establish the existence of the parameter k_F, validating the new theoretical concept at half filling, the energetics of the state at $\nu = \frac{1}{2}$ remain theoretically uncertain and experimentally unknown. Since the state originates purely from electron-electron interaction, the relevant energy scale is evidently $e^2/\varepsilon l_0$, with e being the electronic charge, ε the dielectric constant of the material, and $l_0 = (\hbar/eB)^{1/2}$ the magnetic length. However, more precise measures for, e.g., the value of the Fermi energy E_F, or the effective mass m^* of the composite particles, remain largely elusive. The most promising approach yet [1,13], to establish a composite fermion mass, draws from an assumed correspondence between regular electrons in a magnetic field and composite fermions in a residual magnetic field $B_{\text{eff}} = B - B_{1/2}$, where $B_{1/2}$ is the magnetic field at exactly $\nu = \frac{1}{2}$. As the magnetic field B deviates from $B_{1/2}$, the effective magnetic field B_{eff} quantizes the composites into Landau levels in analogy to Landau quantization of regular electrons. The well-known Shubnikov–de Haas (SdH) oscillation of electrons, symmetric around $B = 0$, reappear as SdH oscillations of composite fermions, symmetric around $B_{1/2}$ at $\nu = \frac{1}{2}$. Most remarkably, these oscillations coincide with the positions of the fractional quantum Hall effect (FQHE) series [19] at $\nu = p/(2p \pm 1)$ between $\nu = \frac{1}{3}$ and $\nu = \frac{2}{3}$. Consequently, these FQHE states may be regarded as arising from the Landau quantization of composite fermions; a striking inter-relationship proposed theoretically early on [13].

Pursuing the analogy further, the energy gap Δ of each of these FQHE states is taken to reflect the cyclotron energy of the composite fermions at this particular B_{eff} from which the particle mass m_{cf}^* can be deduced. The merit of such a view has found strong support in recent activation energy measurements [6] of the FQHE states around $\nu = \frac{1}{2}$. The resultant gap energies for several members of the FQHE series at $\nu = p/(2p \pm 1)$ follows an approximately linear dependence on $|B_{\text{eff}}|$, consistent with a roughly constant m_{cf}^* of about 10 times the electron mass in GaAs m_{GaAs}^*. More recent experiments [10,11] in the same regime demonstrate surprisingly that a simple Shubnikov–de Haas formalism can be successfully employed to analyze the magnetoresistance oscillations due to the FQHE around $\nu = \frac{1}{2}$. This single particle formalism proves to be internally consistent when applied to the FQHE oscillations and allows one to extract mass values and scattering times for composite fermions. All these experimental data have strengthened our confidence in the usefulness of the composite fermion concept around half Landau level filling. At the same time, it is important to realize that all such energetics have been evaluated far away from $\nu = \frac{1}{2}$, and it remains uncertain to what degree the apparent composite fermion mass at $\nu = \frac{1}{3}, \frac{2}{5}$, or $\frac{3}{7}$ reflects the particle mass at $\nu = \frac{1}{2}$.

At present, we have no measurement of a mass value at $\nu = \frac{1}{2}$, nor does there exist a simple experimental procedure which could be applied to the systems and provide such data. Therefore, we have made a considerable effort to perform measurements of the composite fermion

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mass as close to $\nu = \frac{1}{2}$ as today's sample quality permits. Our data reveal a drastic enhancement of the composite fermion mass, by as much as 40% compared to the high-field value, as we approach $\nu = \frac{1}{2}$, with a tendency to diverge further in closer proximity. This observation indicates that the state at $\nu = \frac{1}{2}$, indeed, is not an ordinary Fermi system [1].

Our sample is a GaAs-AlGaAs heterostructure of electron density $2.25 \times 10^{11}\ \mathrm{cm}^{-2}$ and mobility $12.8 \times 10^{6}\ \mathrm{cm}^2/\mathrm{V\,s}$. The distance between electrons and the Si-doping layer is $d_s = 800$ Å. Eight indium contacts are diffused symmetrically around the edges of the 5 mm × 5 mm specimen. The electron density and mobility were established after a brief illumination by a light-emitting diode at low temperature. A standard low-frequency (3–11 Hz) lock-in technique was employed. The electric transport measurements were performed using a combination of superconducting and Bitter magnets with fields up to 30 T. Low temperatures from 30 mK to 0.6 K were provided by a ^{3}He-^{4}He mixture dilution refrigerator. The sample was immersed into the coolant next to a calibrated RuO_2 resistor of known corrections for magnetoresistance. Care was taken to avoid electrical heating of the 2D electrons.

Figure 1 shows a magnetoresistance trace at base temperature around $\nu = \frac{1}{2}$. The very high quality of the specimen is reflected in the appearance of FQHE features at filling factor ν as high as $\frac{8}{17}$ and $\frac{8}{15}$. This allows us to deduce effective masses reliably from fractions as high as $\frac{7}{15}$ and $\frac{7}{13}$, within ~1.3 T of $\nu = \frac{1}{2}$. Our evaluation of the effective mass followed a simple SdH formalism, successfully applied earlier [10,11] to FQHE oscillations further removed from $\nu = \frac{1}{2}$. According to this formalism [20], the amplitude ΔR of the SdH

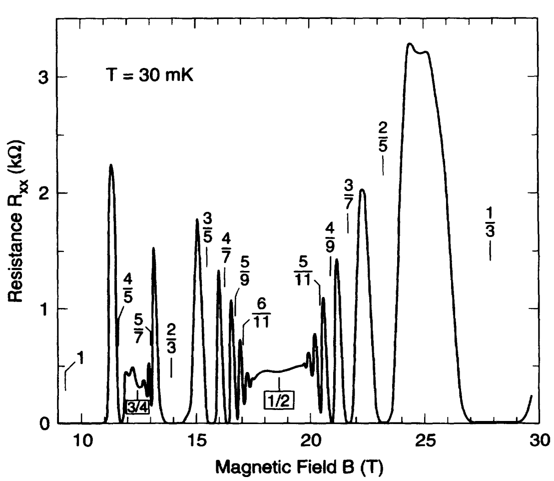

FIG. 1. Overview of the magneto-oscillations due to the fractional quantum Hall effect in the vicinity of half Landau level filling, in a high-quality two-dimensional electron system at $T = 30$ mK.

oscillations normalized to R_0, the resistance at vanishing field ($B_{\mathrm{eff}} = 0$ at $\nu = \frac{1}{2}$), follows the expression

$$\frac{\Delta R}{4R_0} = D_T \exp(-\pi/\omega_c\tau), \quad D_T = \frac{A_T}{\sinh A_T},$$
$$A_T = 2\pi^2 kT/\hbar\omega_c, \quad \omega_c = e|B_{\mathrm{eff}}|/m^*_{\mathrm{cf}}, \tag{1}$$
$$B_{\mathrm{eff}} = B - B_{1/2}.$$

Data were taken at 14 different temperatures between 30 mK and 0.6 K. The temperature dependent amplitude ΔR was evaluated at the minima of the FQHE and at the intermediate maxima and plotted in a standard fashion [10,11] as $\ln(\Delta R/4R_0T)$ versus T. The effective mass was determined by fitting Eq. (1) to the data using m^*_{cf} as a fitting parameter. In all cases Eq. (1) reproduced the data extraordinarily well. The SdH analysis could not be extended to effective fields beyond $\nu = \frac{3}{7}$ and $\nu = \frac{3}{5}$. In our high mobility samples and for such large $|B_{\mathrm{eff}}|$, the maxima between fractions are severely distorted (probably due to developing new even-denominator states), making a determination of the oscillation amplitude unreliable. Since we are focusing on the regime in the vicinity of $\nu = \frac{1}{2}$, the lack of such higher $|B_{\mathrm{eff}}|$ data has no impact on our conclusions.

A summary of our so-derived effective masses m^*_{cf} in units of the free electron mass m_0 is shown in the top of Fig. 2. Consistent with earlier measurements [6,10,11], m^*_{cf} deviates considerably from the electron mass of the GaAs host material of $m^*_{\mathrm{GaAs}} \approx 0.7m_0$. In fact, $m^*_{\mathrm{cf}} \approx m_0$ and is, thereby, larger than in previous reports [10,11]. The relatively larger mass is a simple consequence of the comparably higher electron density n, which requires a higher magnetic field to reach $\nu = \frac{1}{2}$. Since B_{eff} scales as B and the Coulomb energy scales as $\sqrt{B}$, their ratio, which in its simplest form reflects the carrier mass, scales as $\sqrt{B}$ and, hence, as $\sqrt{n}$.

The essential feature of Fig. 2 is the rapid mass increase as ν approaches $\nu = \frac{1}{2}$ from both sides, equivalent to $|B_{\mathrm{eff}}| \to 0$. Its value rises by 40% from $\nu = \frac{4}{9}$ to $\nu = \frac{7}{15}$, much beyond the experimental uncertainty in m^*_{cf} of about 10%. Hints for variations of the composite fermion mass were apparent in earlier data, taken on a much lower density sample [10]. However, these variations did not exceed the inherent experimental uncertainties and a mass enhancement could not be deduced. The experiments by Leadley *et al.* [11] could not detect this mass enhancement around $\nu = \frac{1}{2}$, since their analysis was limited to the high-field regime beyond $\nu = \frac{5}{9}$ and $\nu = \frac{5}{11}$. The present specimen does not only reveal an increase of the composite's mass but also suggests a divergent behavior as $\nu \to \frac{1}{2}$. This behavior is extraordinary for a degenerate fermion system. Since the mass enhancement represents our central finding, we carefully examine our data collection and data reduction procedure in order to exclude a possible artificial origin.

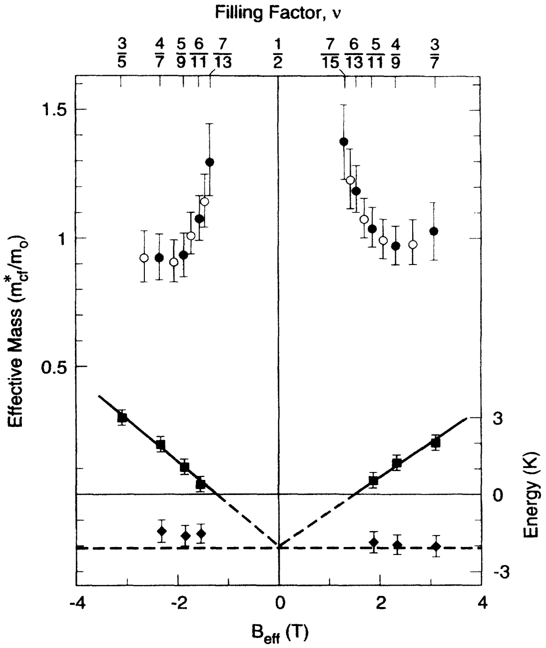

FIG. 2. Effective composite fermion mass as determined from the temperature dependence of the Shubnikov–de Haas oscillations (top and left), and energy gap (■) as determined from activation energy measurements (bottom and right) on higher-order fractional quantum Hall states in the vicinity of $\nu = \frac{1}{2}$. The data points (◆) at negative energies represent the broadening factor Γ derived from mass and energy gap data. The lines indicate the roughly linear dependence of the energy gap, its extrapolation to $B_{\rm eff} = 0$, and the level of agreement of this extrapolated value of Γ, with the value derived from the gap and mass data.

Density fluctuation across the specimen as well as a fixed density gradient could affect the amplitude of the magneto-oscillations. Each partial density generates a slightly shifted oscillatory pattern and all partial patterns add up to the observed SdH oscillations. Different from regular electron SdH oscillations in which the $B = 0$ origin remains unique for all partial electron densities, for composite fermions, the origin itself ($B_{\rm eff} = 0$) fluctuates with carrier density. Such a varying shift of the origin affects high-frequency SdH oscillations closer to $\nu = \frac{1}{2}$ more severely than low-frequency oscillations further away from $\nu = \frac{1}{2}$ and could be the origin of an apparent mass enhancement. We have performed extensive computer modeling of such inhomogeneities, summing the contribution from various density distributions and finally evaluating the resultant model oscillations in complete analogy to the procedure applied to our experimental data. In all cases of density fluctuations, the derived mass *decreased* rather than increased on approaching $\nu = \frac{1}{2}$. Furthermore, the decrease never exceeded 6% for a density fluctuation of 1%, which we can confidently regard as an upper limit to the density fluctuation present in our specimens.

As a further check of the influence of density fluctuation, as well as disorder on SdH amplitudes in general, we performed standard electron SdH measurements on a different sample with electron density $n = 1.1 \times 10^{11}$ cm^2, whose electron mobility was intentionally reduced to $\mu \approx 1 \times 10^5$ cm^2/V s by introducing scatterers into the 2D plane. This procedure rendered the scattering rate of the electron sample very similar to the scattering rate derived for the composite fermions in the present sample [21]. Over the whole range of data collection from $\nu = 8$ to $\nu = 22$ the electron mass determined by the SdH formalism was constant to within 3% around the known $m_{\rm GaAs}$. From all this we conclude that density fluctuation and simple smearing effects of the SdH amplitude due to disorder cannot explain the mass enhancement of composite fermions observed in the top of Fig. 2.

Finally, we performed standard activation energy measurements on the sequence of FQHE states around $\nu = \frac{1}{2}$ to complement the SdH data. The results of these measurements on the states accessible within the temperature range of our equipment are shown in the bottom section of Fig. 2. As expected, the energy gaps of the FQHE states rapidly collapse as $\nu \rightarrow \frac{1}{2}$, following the previously observed [6], roughly linear dependence on $B_{\rm eff}$ and extrapolating towards an approximately common, negative intercept at $B_{\rm eff} = 0$. The linear dependences translate into effective masses $m_{\rm cf}^* \approx 1.0 m_0$ for $B_{\rm eff} > 0$ and $m_{\rm cf}^* \approx 0.82 m_0$ for $B_{\rm eff} < 0$ consistent with the range of masses measured by the SdH effect and shown in the top of Fig. 2. An explicit dependence of $m_{\rm cf}^*$ on $B_{\rm eff}$ cannot be deduced with any reliability from the activation energy measurements. Within the above conceptual framework, the level broadening Γ subtracts off the true energy gap Δ to yield the experimental energy gap $\Delta' = \Delta - \Gamma$. The level broadening, in turn, is not accessible at an arbitrary $B_{\rm eff}$ and needs to be surmised from the not very reliable extrapolation towards $B_{\rm eff} = 0$. However, we may use the SdH masses to derive Δ and employ the activation data Δ' to deduce $\Gamma(B_{\rm eff})$. The results are plotted as diamonds at the bottom of Fig. 2. We find $\Gamma(B_{\rm eff}) \approx 2$ K, approximately independent of $B_{\rm eff}$ and similar to the intercept of the extrapolation towards $B_{\rm eff} = 0$. It is very reassuring that SdH data and activation energy data on the FQHE oscillation show this level of internal consistency over the magnetic field range at which both are experimentally accessible.

We now turn to the determination of the scattering time which provides yet further evidence for the enhancement of the composite fermion mass as $\nu \rightarrow \frac{1}{2}$. Figure 3(a) shows the standard Dingle plot of the SdH data [22]. Such a semilogarithmic plot of $\Delta R / 4 R_0 D_T$ of Eq. (1) versus $1/|B_{\rm eff}|$ is expected to follow a single trace for all temperatures. Furthermore, the slope of this trace is a direct measure for the scattering time τ. All data of Fig. 3(a) indeed follow a singular trace, however, they strongly deviate from a linear relationship. Linearity is nearly regained if the mass enhancement of Fig. 3 is taken into

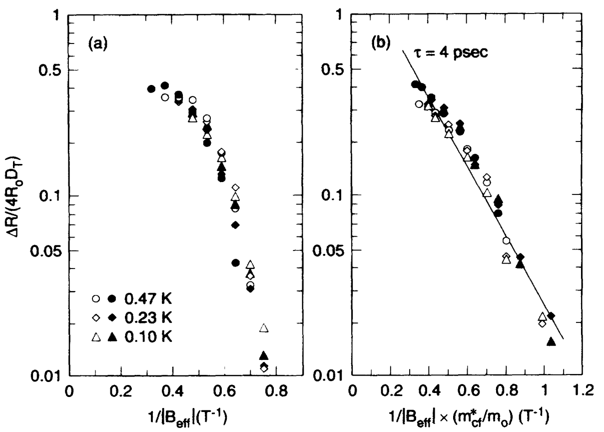

FIG. 3. Standard (a) and modified (b) Dingle plot to derive the carrier scattering time τ for composite fermions in the vicinity of $\nu = \frac{1}{2}$. Open (closed) symbols represent negative (positive) B_{eff}. When the considerable variation of the effective mass is taken into account (b) in defining the horizontal axis $[(1/|B_{\mathrm{eff}}|)m_{\mathrm{cf}}^*/m_0$ instead of $1/|B_{\mathrm{eff}}|]$ and in D_T of the vertical axis $[m_{\mathrm{cf}}^*(B_{\mathrm{eff}})$ instead of $m_{\mathrm{cf}}^* = 1.0m_0]$ the expected linear relationship on a semilogarithmic plot emerges.

account by modifying the horizontal axis from $1/|B_{\mathrm{eff}}|$ to $(1/|B_{\mathrm{eff}}|)m_{\mathrm{cf}}^*/m_0$ and including the varying mass into D_T on the vertical axis. The necessity to include the mass variation in order to achieve a satisfactory Dingle plot is further indication for a strongly B_{eff}-dependent composite fermion mass. A Dingle plot of the data from the low-mobility electron specimen, mentioned earlier, follows the anticipated linear relationship without any such modifications, yielding $\tau = 2.5$ ps for the electron scattering time. For the composite fermions, the data of Fig. 3(b) reflect a scattering time of $\tau \approx 4.0$ ps equivalent to a broadening $\Gamma = \hbar/\tau$ of 1.9 K. This value is in good agreement with the values of Γ derived in Fig. 2. All these observations and their internal and mutual consistency provide convincing evidence for a large increase of the effective mass of composite fermions as the filling factor approaches $\nu = \frac{1}{2}$.

At present there does not exist a satisfactory theory for the B_{eff} dependence of the composite fermion mass. From theoretical arguments [1] one may expect dependences as $m_{\mathrm{cf}}^* \sim a + b|B_{\mathrm{eff}}|^{-1/2}$ or $m_{\mathrm{cf}}^* \sim a + b\ln|B_{\mathrm{eff}}|$ for short range interactions and Coulomb interactions, respectively. The constants a and b are appropriately chosen, and the relationships are expected to hold in the vicinity of $\nu = \frac{1}{2}$. Our data are not compatible with either of these dependences. The best fit to the results of Fig. 2 in terms of a power law is achieved by choosing

$$m_{\mathrm{cf}}^* = \begin{cases} 0.84m_0 + 1.49m_0(B_{\mathrm{eff}}/\mathrm{T})^{-4} & \text{for } B_{\mathrm{eff}} < 0, \\ 0.92m_0 + 1.43m_0(B_{\mathrm{eff}}/\mathrm{T})^{-4} & \text{for } B_{\mathrm{eff}} > 0. \end{cases}$$

Such a relationship suggests a divergence of the composite fermion mass which is much stronger than expected on theoretical grounds [1].

In conclusion, the effective mass of composite fermions in the vicinity of a half-filled Landau level appears to be strongly magnetic field dependent, seemingly diverging as the filling factor approaches $\nu = \frac{1}{2}$. This observation underpins the unusual energetics of these novel particles in the FQHE and projects their extraordinary properties at exactly $\nu = \frac{1}{2}$.

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[1] B. I. Halperin, P. A. Lee, and N. Read, Phys. Rev. B **47**, 7312 (1993).
[2] V. Kalmeyer and S. C. Zhang, Phys. Rev. B **46**, 9889 (1992).
[3] E. Rezayi and N. Read, Phys. Rev. Lett. **72**, 900 (1994).
[4] H. W. Jiang, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **40**, 12 013 (1989).
[5] R. L. Willett, M. A. Paalanen, R. R. Ruel, K. W. West, L. N. Pfeiffer, and D. J. Bishop, Phys. Rev. Lett. **65**, 112 (1990).
[6] R. R. Du, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **70**, 2944 (1993).
[7] R. L. Willett, R. R. Ruel, M. A. Paalanen, K. W. West, and L. N. Pfeiffer, Phys. Rev. **47**, 7344 (1993).
[8] R. L. Willett, R. R. Ruel, K. W. West, and L. N. Pfeiffer, Phys. Rev. Lett. **71**, 3846 (1993).
[9] W. Kang, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **71**, 3850 (1993).
[10] R. R. Du, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Solid State Commun. **90**, 71 (1994).
[11] D. R. Leadley, R. J. Nicholas, C. T. Foxon, and J. J. Harris, Phys. Rev. Lett. **72**, 1906 (1994).
[12] V. J. Goldman, B. Su, and J. K. Jain, Phys. Rev. Lett. **72**, 2065 (1994).
[13] J. K. Jain, Phys. Rev. Lett. **63**, 199 (1989); Phys. Rev. B **40**, 8079 (1989); **41**, 7653 (1990).
[14] S. M. Girvin and A. H. MacDonald, Phys. Rev. Lett. **58**, 1252 (1987).
[15] R. B. Laughlin, Phys. Rev. Lett. **60**, 2677 (1988).
[16] S. C. Zhang, H. Hanson, and S. A. Kivelson, Phys. Rev. Lett. **62**, 82 (1989).
[17] N. Read, Phys. Rev. Lett. **62**, 86 (1989).
[18] A. Lopez and E. Fradkin, Phys. Rev. B **44**, 5246 (1991).
[19] D. C. Tsui, H. L. Stormer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
[20] E. N. Adams and T. D. Holstein, J. Phys. Chem. Solids **10**, 254 (1959).
[21] The scattering rates were determined by a Dingle plot described in the following paragraphs.
[22] R. B. Dingle, Proc. R. Soc. London Sect. A **211**, 517 (1952).