Spin Polarization of Composite Fermions: Measurements of the Fermi Energy

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(Received 30 November 1998)

From the degree of circular polarization of the time-resolved radiative recombination of 2D electrons with photoexcited holes bound to acceptors we have measured the magnetic field dependencies of the electron spin polarization for various fractional ($\nu = 2/3$, $3/5$, $4/7$, $2/5$, $3/7$, $4/9$, $8/5$, $4/3$, and $7/5$) and composite fermions ($\nu = 1/2$, $1/4$, and $3/2$) states. The Fermi energies of these composite fermion states are measured for the first time and the corresponding value of the composite fermion density of states mass at $\nu = 1/2$ is found to be about 4 times heavier than the previously reported values of the "activation" mass. [S0031-9007(99)09059-6]

PACS numbers: 71.10.Pm, 73.40.Hm

The existence of unusual new quasiparticles, composite fermions (CFs), assembled from several magnetic flux quanta and an electron, has been demonstrated in various experiments on two-dimensional (2D) electron systems in high magnetic fields [1–3]. These CFs were introduced theoretically [4,5] to explain the fractional quantum Hall effect (FQHE). According to this theory, at half filling of the Landau level ($\nu = 1/2$), two flux quanta are attached to an electron to form a CF, which moves in zero effective magnetic field, since external field is compensated by attached fluxes. The CF concentration is equal to that of 2D electrons and the system of these quasiparticles can be characterized by a Fermi wave vector and a Fermi energy. Any deviation of the magnetic field from exactly half filling of the Landau level results in the appearance of an effective magnetic field, which quantizes the CF motion and splits their energy into Landau levels. Every integer filling of the CF Landau levels corresponds to a specific FQHE state. The recent experiments [6–8] not only supported the validity of this theoretical concept but demonstrated also the semiclassical behavior of these strange quasiparticles. A well-defined Fermi wave vector was established [1,3], and its dependence on the CF concentration was experimentally determined [8].

However, there exists an apparent inconsistency inside this simple picture, describing the FQHE in terms of CFs. In the case of normal 2D electrons, their Fermi energy is equal to the cyclotron gap at filling factor $\nu = 2$. If this holds for CFs, their Fermi energy, E_F^{CF}, can be taken as the value of the energy gap measured for $\nu = 1/3$ (for this state, the CF filling factor is $\nu_{\mathrm{CF}} = 1$). Since for the magnetic field $B \approx 10$ T this gap is typically 8–12 K [2,9], E_F^{CF} can be estimated as 10 K (the same value can be also directly obtained from the published CF mass $m_{\mathrm{CF}} \approx 0.6 m_0$ [2,10] at $B \approx 10$ T). Because of the small value of the g factor of electrons in GaAs, the Zeeman energy (E_Z) at $B = 10$ T is only about 3 K, which means that $E_F^{\mathrm{CF}} \gg E_Z$ and, therefore, one may expect that the Fermi gas of CF is practically spin unpolarized at $B \approx 10$ T. In contrast, it follows from the above mentioned experiments, in which the CF wave vector was measured, that the system of CFs is completely spin polarized at $B \approx 10$ T. This apparent discrepancy was our main motivation to measure the spin polarization of CFs using a well-established optical method [11].

In the present Letter we investigate the magnetic field dependence of the spin polarization of a 2D system in the $\nu = 1/2$, $3/2$, and $1/4$ CF states. The CF Fermi energies for each of those states have been determined from the value of the magnetic field B_c at which a system of CFs becomes completely spin polarized ($E_F^{\mathrm{CF}} = E_Z$ at $B = B_c$). The CF density of states mass is found to be about 4 times heavier than the previously reported "activation" mass [2,10] and more close to the value obtained from the temperature dependence of CFs scattering [12]. Another experimental task solved in the present Letter concerns the phase transitions between differently spin polarized ground states of the FQHE. Several spin transitions between unpolarized, partly polarized, and fully polarized spin states, which are accompanied by threshold changes in the electron spin polarization, γ_e, are detected for the $\nu = 2/3$, $3/5$, $4/7$, $2/5$, $3/7$, $4/9$, $8/5$, $4/3$, and $7/5$ FQHE states and absolute values of γ_e are determined for these partly spin polarized FQHE ground states.

We studied several low-density [$n_s = (0.36–2.4) \times 10^{11}$ cm^{-2}] and high-quality [electron mobility $\mu = (0.9–3) \times 10^6$ cm^2/V s] GaAs/$\mathrm{Al}_x\mathrm{Ga}_{1-x}$As single heterojunctions with a δ-doped monolayer of Be acceptors ($n_A = 2 \times 10^9$ cm^{-2}) located in the wide (1 μm) GaAs buffer layer at a distance of 30 nm from the interface [13]. In all samples a variation of 2D-electron concentration was possible by the use of a top gate. For photoexcitation, we used pulses from a tunable Ti-sapphire laser (the wavelength was close to 780 nm) with a duration of 20 ns, a peak power of 10^{-4}–10^{-2} W/cm^2, and a frequency of 10^4–10^6 Hz. Luminescence spectra were detected by a gatable photon counting system with a spectral resolution of 0.03 meV. To analyze the circular polarization of

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the luminescence signal at low temperatures (down to 300 mK), we used an optical fiber system with a quarter wave plate and a linear polarizer placed in liquid helium just nearby the sample. Measurements were performed in the temperature range of 0.3–1.8 K. Other details of the experimental technique will be published elsewhere [14].

The spin polarization of the ground state of the 2D-electron system is defined by a competition between the Zeeman and Coulomb (E_C) energies. This was well established both theoretically [15,16] and experimentally [17–19] for the ground states of different FQHE states in the extreme quantum limit. It was found that some electronic states (such as $\nu = 1$, $1/3$, and $1/5$) are fully spin polarized even for vanishing Zeeman energy, whereas other fractional states show spin transitions from unpolarized to a fully (or partly) spin polarized state depending on the ratio E_Z/E_C [16]. In our previous work [11], we demonstrated unambiguously that such spin transitions can be directly detected from the degree of circular polarization γ_L of time-resolved radiative recombination of 2D electrons with photoexcited holes bound to acceptors [$\gamma_L = (I_- - I_+)/(I_- + I_+)$, where I_- and I_+ are integral intensities of the luminescence measured in the σ^- and σ^+ polarizations, respectively]. There are two independent reasons for the luminescence to be circularly polarized. One reason is the spin polarization of the hole system due to the Zeeman effect, which depends on the magnetic field and the temperature of the photoexcited holes (i.e., on the population of the different spin-split levels). The other reason is the spin polarization of the 2D electrons, which depends on filling factor, temperature, and magnetic field. It is possible to derive the contribution of the holes to the circular polarization of the luminescence separately by investigating the emission from fully occupied electron Landau levels (at $\nu = 2, 4, 6, \ldots$ and also well below the Fermi surface), because in this case both spin up and down states of electrons are completely occupied and the circular polarization of the luminescence is determined only by the spin polarization of the holes [11]. It has been demonstrated experimentally (and in agreement with calculations [11]), that the spin polarization of the hole system is defined by the ratio B/T, so that it can be excluded from the polarization of the luminescence for a fixed value of B/T and a direct correspondence between γ_L and γ_e can be established.

Typical luminescence spectra, recorded for both σ^- and σ^+ polarizations and the calibration curves, obtained for different temperatures for a given magnetic field are shown in Fig. 1. For a fixed value of B/T, the spin polarization of the holes is also fixed and it determines the interval of variation of γ_L. For $B/T = 3$ T/K this interval corresponds to the ($\gamma_e = 0$) low boundary of the ratio $I_-/I_+ = 9.1$ and to the high ($\gamma_e = 1$) boundary $I_-/I_+ = 15.3$. Within this interval, the ratio I_-/I_+ is an almost linear function of γ_e. It was established that γ_e increases slightly with decreasing temperature but saturates at low temperatures (see Fig. 1b). The value of γ_e found from the

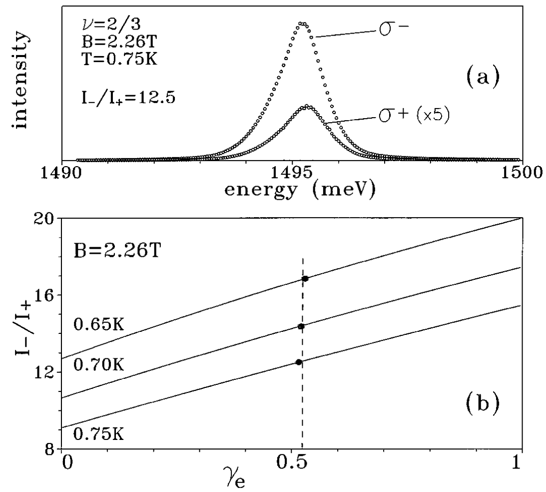

FIG. 1. (a) Typical luminescence spectra measured in the σ^- and σ^+ polarizations for $\nu = 2/3$, $B = 2.26$ T, $T = 0.75$ K and (b) calibration dependence [11] of the ratio I_-/I_+ on the electron spin polarization γ_e, obtained for $B/T = 3.01$ ($T = 0.75$ K), $B/T = 3.23$ ($T = 0.70$ K), $B/T = 3.48$ ($T = 0.65$ K). I_- and I_+ are the integrated intensities of the luminescence, measured in the σ^- and σ^+ polarizations, respectively.

extrapolation of $\gamma_e(T)$ to $T \rightarrow 0$ was taken as the correct one. The magnetic field dependence of the electron spin polarization $\gamma_e(B)$ measured for two different concentrations of 2D electrons is plotted in Fig. 2. It shows pronounced minima and maxima at several FQHE states. Both of the fundamental sequences of fractional states $n/(2n + 1)$ ($\nu = 2/5, 3/7, 4/9$) and $n/(2n - 1)$ ($\nu = 2/3, 3/5, 4/7$) are present in these data. In addition, the

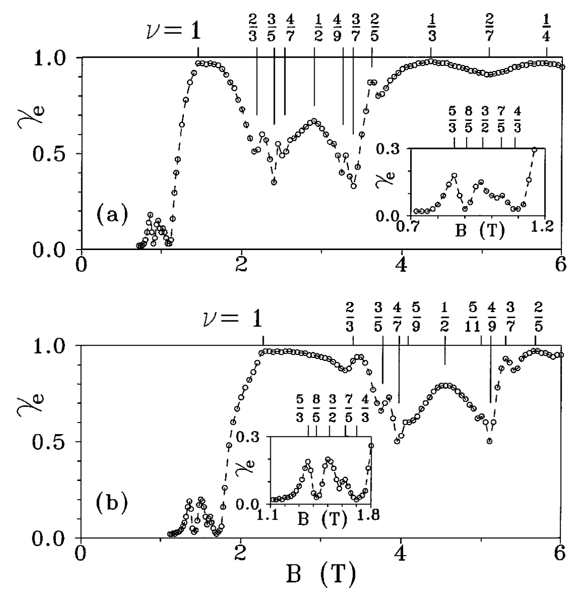

FIG. 2. Magnetic field dependence of the electron spin polarization γ_e measured for two different 2D-electron concentrations: (a) $n_S = 3.5 \times 10^{10}$ cm^{-2} and (b) $n_S = 5.5 \times 10^{10}$ cm^{-2}. Insets show the details around $\nu = 3/2$.

series of fractions 5/3, 8/5, 7/5, and 4/3 around $\nu = 3/2$ is clearly visible in $\gamma_e(B)$ shown in the insets in Fig. 2. However, it was rather inconvenient to analyze the magnetic field dependence of γ_e at a fixed electron density since, depending on n_s, the features at fractional filling factors sometimes show up as minima or as maxima, or even disappear. Instead, much more clear behavior was detected for a fixed filling factor value, when the dependence $\gamma_e(B)$ was analyzed at a given ν.

In Fig. 3a we plot the magnetic field dependence of the electron spin polarization measured for several FQHE states from the sequence $\nu = n/(2n - 1)$. In order to obtain it, we investigated six different samples with top gates, which has allowed us to vary the electron concentration, so that a rather broad interval of magnetic fields was accessible for each fraction. Data measured for different samples are shown by different symbols (for $\nu = 2/3$) and illustrate the consistency of the obtained results. Well-defined spin transitions between various differently spin-polarized ground states, governed by the magnetic field, are clearly visible from Fig. 3a for all studied fractions. For $\nu = 2/3$ only one transition (if one neglects the weakly developed feature around $B = 2.3$ T) from spin unpolarized to a completely spin polarized state was observed at $B \approx 2$ T. In contrast, the magnetic field dependence of γ_e obtained for other FQHE states, such as 3/5 and 4/7, definitely indicates a broad region of stability of the partly polarized spin states (γ_e is close to 1/3 for $\nu = 3/5$ and it is about 1/2 for $\nu = 4/7$), and additional transitions between unpolarized, partially polarized, and completely spin polarized ground states were detected (for $\nu = 4/7$ such transitions take place at $B \approx 1.8$ T and $B \approx 4.8$ T). Interestingly, a similar sequence of spin transitions with nearly identical absolute values of γ_e was observed also for FQHE states from the other sequence, $\nu = n/(2n + 1)$ (see Fig. 3b). A correspondence between 2/3, 3/5, and 3/7 states from one side and 2/5, 3/7, and 4/9 states from the other side is apparent from a comparison of Figs. 3a and 3b. Such a similarity is consistent with the model of composite fermions and can be illustrated by a well-known single-particle model for Landau levels of CFs [2]. According to this model the cyclotron energy of CFs is proportional to $\sqrt{B}$, whereas the Zeeman splitting is a linear function of B and therefore spin transitions (as well as γ_e) are defined by the crossing of the Landau levels corresponding to different spin numbers [2,20].

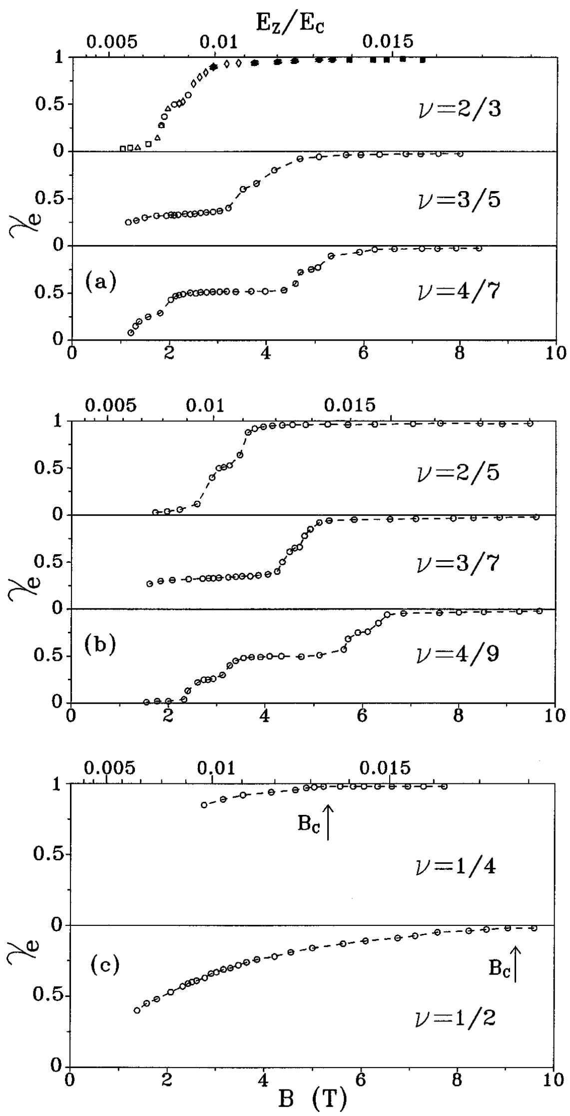

FIG. 3. Magnetic field dependence of the electron spin polarization γ_e measured for different FQHE and CF states (a) sequence $n/(2n - 1)$, (b) sequence $n/(2n + 1)$, and (c) $\nu = 1/2$ and 1/4. The results shown for $\nu = 2/3$ by different symbols correspond to the data obtained for different gated samples.

Figure 3c shows the magnetic field dependence of the electron spin polarization measured for the CF state at $\nu = 1/2$. First of all, it is clear from the measured dependence that the system of CFs becomes fully spin polarized at $B_c = 9.3 \pm 0.5$ T. It means that at $B = B_c$ the CF Fermi energy is equal to the Zeeman splitting, which is equal to 2.8 K at 9.3 T (the CF g factor is the same as that of electrons $g_{\mathrm{CF}} = g_e = -0.44$). Note that the Zeeman energy of the CFs can be enhanced by interaction between them; however, this effect is expected for odd CF filling factors (for example, the 1/3 FQHE state), but not for the $\nu = 1/2$ state. Moreover, the experimentally measured g factor of CFs was found to be very close to that of the electrons in GaAs, and this fact means that the interaction between CFs is rather weak [2]. If we assume a parabolic dispersion law for the CFs at $\nu = 1/2$, then the value of their density of state mass m_{DS} (or "polarization" mass [20]) can be estimated from the values of their E_F^{CF} and density ($n_{\mathrm{CF}} = n_S = 1.26 \times 10^{11}$ cm^{-2} for $B = 9.3$ T and $\nu = 1/2$), which yields $m_{\mathrm{DS}} = 2.27 m_0$ (m_0 is the free electron mass in vacuum). The obtained mass is several times heavier than the previously reported values, measured from the activation energies. However, these masses have a different meaning [20]. Indeed, the filling factor dependence of the ground state energy has a cusp at fractional ν and the activation energy is sensitive to the strength of this cusp (slopes), but not to the absolute value of the minimum, corresponding to the ground state energy. In contrast, the competition between differently spin-polarized ground states, driven by the Zeeman energy, is sensitive only to the energy of this minimum and, therefore, the density of states mass describes the energy splitting between the states with different γ_e. Since there is no energy gap (cusp) at $\nu = 1/2$ the only relevant CF parameters are their Fermi energy and the density of state mass. It is important that if one assumed that CFs are 2D particles with a parabolic dispersion law (at effective magnetic field $B = 0$ at $\nu = 1/2$), then the magnetic field dependence of γ_e should be a linear function of the parameter E_Z/E_F ($\gamma_e = E_Z/2E_F$), so that $\gamma_e \propto B^{1/2}$ (due to $E_F \propto n_s \propto B$ and the expected increase in the CF mass, as $\sqrt{B}$ [20]). The dependence $\gamma_e(\sqrt{B})$ measured for $\nu = 1/2$ was found to be a slightly sublinear function of $\sqrt{B}$, which is mainly due to the temperature smearing of the Fermi surface. The dependence of $\gamma_e(B)$ measured for $\nu = 1/4$ is shown in Fig. 3c. From the value of $B_c = 5.2 \pm 0.2$ T we derived that for $\nu = 1/4$ and $n_S = 0.32 \times 10^{11}$ cm^{-2}, $m_{DS} = 1.13 m_0$. Note that the values of the CF mass obtained for $\nu = 1/2$ and $1/4$ are simply $2\nu m_0/g_e$, which follows from equating the Zeeman and Fermi energies.

In Fig. 4a we plot the magnetic field dependence of $\gamma_e(B)$ measured for several FQHE states from the sequences $2 - [n/(2n \pm 1)]$ ($\nu = 8/5$, $7/5$, and $4/3$) and also for $\nu = 3/2$ (the dashed line $\gamma_e = 1/3$ shown in this figure corresponds to the complete spin polarization of the CFs at $\nu = 3/2$). It is clear from these figures that various spin transitions are also available for these FQHE states; however, in contrast to the fractional states at $\nu < 1$, these transitions are shifted to much higher magnetic fields. In Fig. 4b we plot the phase diagram. It illustrates at which magnetic fields (and at what value of $E_Z/E_C \propto \sqrt{B}$) the spin transition to a fully polarized state takes place for different fractions (open circles) and also for various CF states $\nu = 1/2$ and $1/4$ (filled circles). The importance of the parameter E_Z/E_C for the considered problem was already mentioned (also demonstrated in recent theory [20]) and it explains the choice of the coordinates in Fig. 4b. The dashed lines on this figure correspond to linear dependence plotted through the experimental points and also through the points at $\nu = 1$, $1/3$, and $1/5$ since at these filling factors the 2D-electron system is expected to be fully spin polarized even for vanishing Zeeman energy. Empty squares correspond to the extrapolation of these lines to $\nu = 1/2$ and $3/2$ (note that for $\nu = 1/2$ the result obtained from the extrapolation is in a good agreement with the directly measured value). The threshold value of E_Z/E_C obtained for $\nu = 3/2$ from the extrapolation procedure corresponds to $B_c = 17.5 \pm 0.5$ T, which yields $m_{CF} = 2.27 m_0$ at $n_S = 6.3 \times 10^{11}$ cm^{-2} (for $\nu = 3/2$, $n_{CF} = n_s/3 = 2.1 \times 10^{11}$ cm^{-2}).

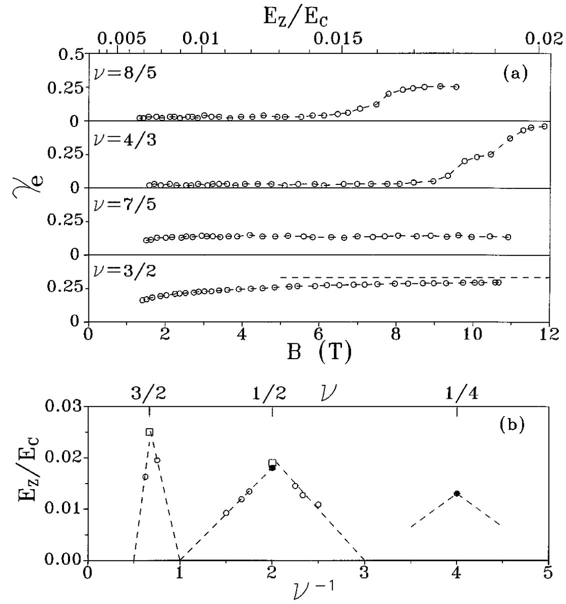

FIG. 4. (a) Magnetic field dependence of the electron spin polarization γ_e measured for the $\nu = 8/5$, $4/3$, and $7/5$ FQHE states and for the $\nu = 3/2$ CF state. (b) Phase diagram $E_Z/E_C(\nu^{-1})$ illustrating at which magnetic fields the spin transition into fully polarized states takes place for different fractions (open circles) and also for various CF states $\nu = 3/2$, $1/2$, and $1/4$ (filled circles). Other details are explained in the text.

We thank T. Chakraborty, V. Falko, and J. Smet for very useful discussions. This work was supported by Volkswagen Stiftung and Russian Fund of Fundamental Research.

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