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2. Quantum Hall effect

Magnetooptics of composite fermions

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Abstract. **The Fermi energy and the Zeeman splitting of composite fermions are measured from the temperature dependence of the electron spin polarization at $\nu = 1/2$. We demonstrate that the Zeeman splitting of composite fermions is enhanced by a factor of 2.5 due to the interaction between CFs. The latter is very sensitive on the finite width of the 2D channel. The spin polarization at $\nu = 1/3$ and $\nu = 2/3$ displays an activated behavior and the derived spin-wave gaps are compared with simultaneously measured transport values.**

The two-dimensional electron system (2DES), subjected to a strong perpendicular magnetic field, exhibits the spectacular correlation phenomenon of the fractional quantum Hall effect (FQHE) [1]. It is a characteristic property of the interaction between 2D electrons [2]. Recently, a conceptually different way of thinking about the interaction in the FQH-regime in terms of composite particles, made up of two flux quanta and one electron, has emerged [3]. At half filling of the lowest Landau level ($\nu = 1/2$), a metallic state of these so-called composite fermions (CF) forms and is characterized by a Fermi wave vector and a Fermi energy [4]. A deviation of the magnetic field from exact half filling results in the appearance of a non-zero effective magnetic field, that quantizes the CF motion and discretizes their energy spectrum into Landau levels. In this model, the FQHE is a manifestation of the Landau quantization of CFs and a rich variety of experimental observations can be understood straightforwardly in terms of nearly independent CFs [5, 6]. Recent experiments [8 – 10] support the validity of this theoretical concept and, moreover, demonstrate the semiclassical behavior of these quasi-particles. The CF concept was also successfully extended to the case of spin-flip excitations, and the spectrum of spin wave modes was calculated [7].

The attractiveness of the CF picture is based on the assertion that dressing the electrons with two flux quanta constitutes the main effect of the interaction between the 2D electrons. The remaining interaction between CFs is weak, so that in many instances the system can be considered as a nearly ideal Fermi gas of composite particles [3]. The residual interaction between CFs does, however, exist and plays an essential role in the dispersion of the neutral excitations at FQHE states [11]. No interaction between CFs would imply no dispersion of the neutral excitations, yet it is well known [11, 12] that the dispersion of the CF exciton is a rather complicated function of the excitonic momentum. Two types of intra-Landau-level neutral excitations for FQHE states below $\nu = 1$ have been recognized. They are neutral charge density (CD) excitations and neutral spin density (SD) excitations, associated with changes of the charge and spin degrees of freedom, respectively. The collective CD mode has a finite gap at zero wave vector ($k = 0$) and displays a characteristic 'magnetoroton' minimum at the inverse magnetic length, $k = 1/l_B$. In the limit of large k, its energy approaches the FQHE energy gap, i.e. the energy to create infinitely separated quasi-particle – quasi-electron pairs [11, 13]. The other branch of collective excitations, the SD mode, takes on the Zeeman energy at zero wave vector (due to Larmor theorem) and increases monotonically as a function of momentum until it approaches the exchange energy gap in the limit of infinite wave vector [7, 12]. Dispersion laws calculated theoretically for the CFs, indicate that the interaction between CFs is indeed about an order of magnitude weaker than the electron – electron interaction [7, 11, 13].

Thus, in order to measure the interaction energy directly, one needs to study the dispersion law of the CD excitations or, alternatively, measure the spin-wave energy gap at infinite momentum. The number of experimental possibilities are very limited. Some results were obtained from inelastic light scattering [14, 15] and NMR [16] investigations, however, complementary measurements using alternative methods are highly desirable. In the present contribution we investigate the temperature dependence of the degree of electron spin polarization in the 1/2-CF state. This allows us to determine the exchange interaction. Analogous experiments at the 1/3- and 2/3-FQHE states permit the extraction of the spin wave energy gap. Their results equally illustrate the importance of exchange interaction of CFs.

To this end, we studied several low-density ($n_s = 0.2 – 1.5 \times 10^{11}$ cm^{-2}) and high-quality (electron mobility $\mu = 0.9 – 4 \times 10^6$ cm^2 V^{-1} s^{-1}) GaAs/Al$_x$Ga$_{1-x}$As single heterojunctions with a δ-doped layer of Be-acceptors ($n_A = 2 \times 10^9$ cm^{-2}) located 30 nm from the heterointerface in the wide (1 μm) GaAs buffer layer [17]. In all samples the 2D electron concentration could be varied by a top gate. Moreover, a substrate bias voltage allowed the efficient tuning of the electric field at the heterointerface and thus modifying of the width and intersubband splitting of the 2D channel. 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 repetition rate of $10^4 – 10^6$Hz. Luminescence spectra were recorded by a

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gatable photon counting system with a spectral resolution of 0.03 meV. We measured the degree of the electron spin polarization from an analysis of the degree of circular polarization of the time-resolved radiative recombination of 2D electrons with photoexcited holes bound to the Be-acceptors. The crux of this method is the full control over the photoexcited hole contribution to the circular polarization of the luminescence. This was achieved by the time-resolved technique to ensure the complete relaxation of the hole system down to the bath temperature [17]. To analyze the circular polarization of the luminescence signal at low temperatures (down to 100 mK), an optical fiber system was used with a quarter wave plate and a linear polarizer placed in liquid helium just nearby the sample. This setup allows the detection of σ^-/σ^+ signal ratios up to 1000 (corresponding to a depolarization coefficient of 0.002). It guarantees a high accuracy (of about 1 percent) measurement of the electron spin polarization. The magnetoresistance was measured with the standard low-frequency (12 Hz), low-current lock-in technique. Temperatures were recorded with a calibrated RuO_2 thermometer. In some special cases, in order to measure the degree of electron spin polarization at very low temperatures more accurately, the temperature of the photoexcited holes (T_h) was effectively increased by a decrease of the delay time. In these cases the calibration of T_h was performed with the use of a completely occupied Landau level below the Fermi surface at fixed magnetic field and bath temperature as described in Ref. [17]. Other details of the experimental technique were published in Ref. [17].

Figure 1a shows the temperature dependence of the electron spin polarization (γ_e), measured at different magnetic fields but fixed filling factor $\nu = 1/2$. Below and above the critical magnetic field $B_c = 9.3T$ [17], for which the CF system becomes fully spin-polarized, the electron spin polarization saturates at low temperatures. In contrast, at $B = B_c$ a well defined linear dependence of γ_e on T is observed in the low T limit. Very similar behaviors and $B = B_c$, $B > B_c$ and $B < B_c$ were predicted theoretically for non-interacting CFs [18] and it was demonstrated that the linear dependence at low temperatures at $B = B_c$ results from the Fermi statistics (this linear term is expected to be stable for the case of weakly interacting particles). The slope of this dependence is determined by a single parameter, the Fermi energy of CFs: $\gamma_e(T) = 1 - (2T/E_F)\ln[(1+\sqrt{5})/2]$. The linear extrapolation of the low temperature portion of $\gamma_e(T)$ at $B = B_c$ yields a CF Fermi energy of 6.9 K. At $B = B_c$, the Fermi energy equals to the Zeeman energy, and one must conclude that the spin splitting of CFs is strongly (by a factor of 2.5) enhanced in comparison with the bare Zeeman energy (2.8 K at 9.3 T).

Interaction phenomena are quite sensitive to the width of the 2D channel. They are gradually suppressed upon increasing the channel width. In order to vary this width, we applied a substrate-bias voltage (V_{SB}), while maintaining a fixed carrier concentration through a simultaneous change of the top gate bias. The intersubband splitting E_{10} provides a measure for the finite width w of the 2D channel and can be obtained directly from luminescence spectra at small delays after the laser pulse, when recombination from both subbands is observable. Alternatively, numerical simulations in the Hartree approximation of the eigenvalues and wave functions of the ground and first excited subband can serve this purpose. The effective width w can be estimated from a fit of the calculated wave function to the Fang–Howard function $\psi(z) = z\exp(-bz/2)$, with $w = 1/b$ [19]. Figure 1b depicts the temperature dependence of the electron spin polarization at $B = B_c$ for different V_{SB}. Figure 2a shows the intersubband splitting and the critical magnetic field B_c as a function of V_{SB} at a fixed density of $n_s = 1.1 \times 10^{11}$ cm^{-2}. The latter depends only weakly on the substrate bias. On the top axis, calculated values of the channel width are indicated for several bias voltages. Figure 2b plots the Zeeman splitting (and Fermi energy) as extracted from the temperature-dependent data. Positive (negative) substrate bias voltages correspond to a decrease (increase) of E_{10} and to an increase (decrease) of the channel width. The enhanced spin splitting of CFs is considerably suppressed for positive V_{SB}, which means that the exchange interaction between CFs drops drastically for wide channels ($w > 6$ nm).

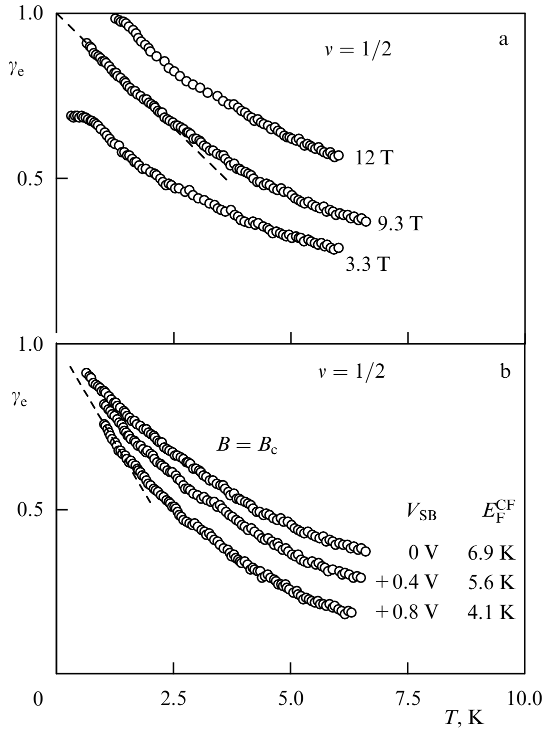

Figure 1. (a) Temperature dependence of the electron spin polarization measured for $\nu = 1/2$ and $V_{SB} = 0$ at different magnetic fields. The dashed line corresponds to the linear extrapolation of the experimental data taken at $B = B_c = 9.3$ T. From its slope the Fermi energy of CF metal was determined. (b) Influence of the substrate-bias voltage on temperature dependence of the electron spin polarization at $\nu = 1/2$ and $B = B_c$.

Since the concept of CFs is quite successful (both in numerical calculations and in experiment) in explaining many properties of the FQHE states, we can proceed in a similar manner and estimate the interaction energy between CFs from the temperature dependence of the electron spin polarization at the 1/3- and 2/3-FQHE states. The analysis of our magnetooptical measurements is very similar to that used for activated magnetotransport investigations. Even so, the determined energy gap is quite different since it is selectively sensitive to the spin degree of freedom. It therefore provides information about the intra-CF-Landau-level SD excitation (or CF spin waves, CFSW), whereas magnetotransport data deliver the inter-CF-Landau-level CD excitation gap (or CF magnetoplasmon, CFMP).

In Figure 3a we show the temperature dependence of γ_e, measured at different magnetic fields, for the $\nu = 1/3$ FQHE state. The presence of a gap in the CFSW mode makes an

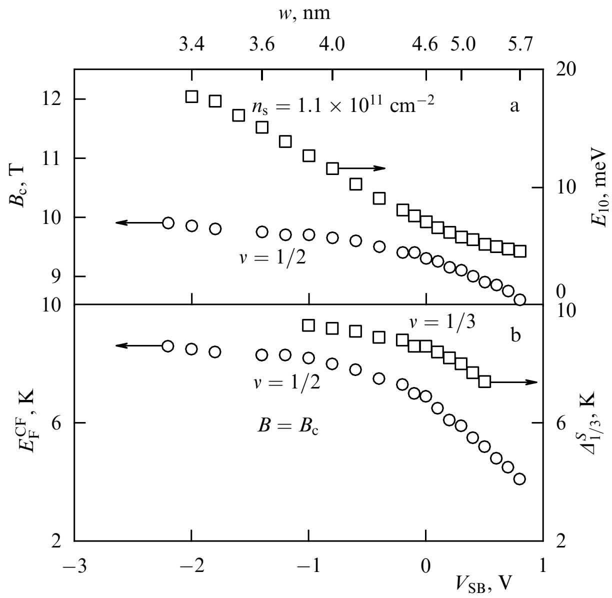

Figure 2. (a) The dependences of the intersubband energy E_{10} (squares, $n_s = 1.1 \times 10^{11}$ cm^{-2}) and the critical magnetic field B_c (circles, $\nu = 1/2$)) on the substrate-bias voltage V_{SB}. On the top axis the width of wavefunction w, a obtained from a comparison of numerical simulations with the Fang–Howard function is indicated for several values of V_{SB}. (b) The enhanced spin splitting of CFs (circles, $\nu = 1/2$, $B = B_c$) and of the spin-flip gap at $\nu = 1/3$ (squares) as a function of the substrate-bias voltage V_{SB}.

Arrhenius-type of analysis, as shown in Fig. 3b, reasonable. At low temperatures, the deviation of γ_e from 1 as a function of temperature is well described by a single exponential dependence:

$$\gamma_e = 1 - 2 \times \exp\left(-\frac{\Delta}{2k_B T}\right).$$

Such a dependence is expected theoretically as described in Ref. [20]. Two possible values for Δ were discussed in this article, because of the presence of two different gaps: Zeeman gap (Δ_Z) and CFSW gap ($\Delta^{SW}_{1/3}$). In the former case the activated gap Δ equals $2\Delta_Z$ [20], whereas for the latter case Δ equals $\Delta^{SW}_{1/3}$. The infinite density of states associated with spin wave transitions at large wave vectors makes it plausible that $\Delta^{SW}_{1/3}$ determines the activated behavior. Indeed, the measured values of Δ are considerably larger than $2\Delta_Z$ and exhibit a nonlinear magnetic field dependence. A comparison of the measured CFSW gap with gaps derived from activated transport under the same conditions revealed that the gap derived from $\gamma_e(T)$ is systematically larger than the transport gaps as shown in Fig. 3b, c. We therefore can conclude that in transport measurements, a different smaller gap, the CFMP gap, is measured. The dependence of the CFSW gap measured for the 1/3-FQHE state on V_{SB} (and thus the channel width) is illustrated in Fig. 2b. The interaction energies between CFs, measured for $\nu = 1/2$ and $\nu = 1/3$, as well as their dependence on the channel width are in good agreement with each other.

The $\nu = 2/3$ FQHE state is known for its spin transition at $B = B^C_{2/3} = 2.1$ T [17] from an unpolarized to a completely spin-polarized ground state. Because of the close relationship between the exchange interaction energy of CFs and the spin polarization of the system, the spin transition at $B = B^C_{2/3}$ may serve as an excellent illustration of the CF interaction. The temperature dependence of the electron spin polarization at

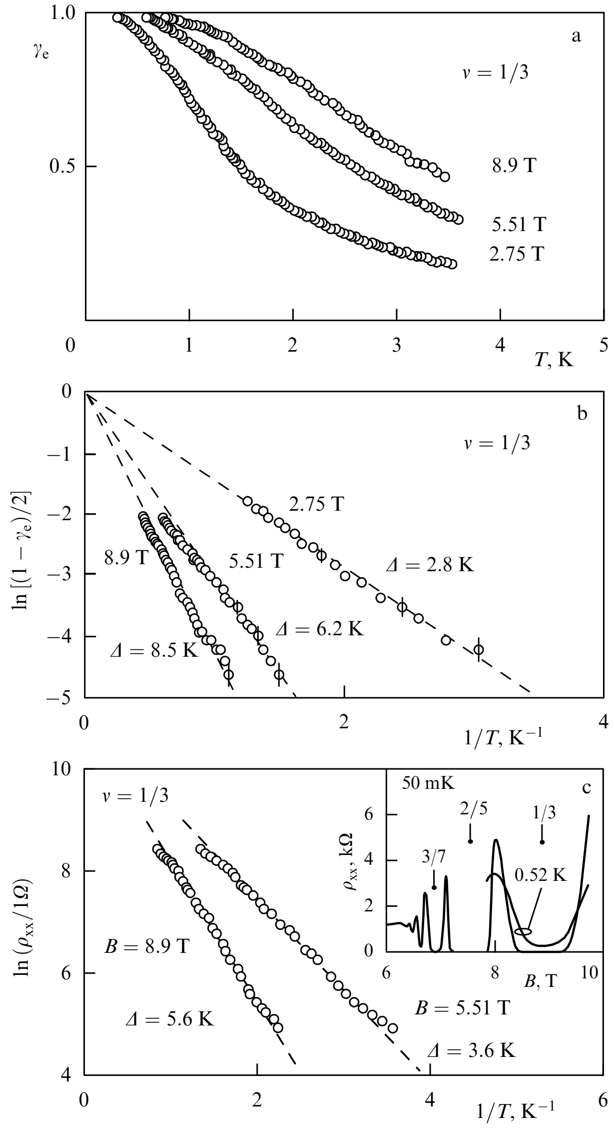

Figure 3. Temperature dependence of the electron spin polarization (a) and Arrhenius plots (b) $\ln[(1-\gamma_e)/2]$ vs. 1/T measured at $\nu = 1/3$ and $V_{SB} = 0$ for different magnetic fields. (c) Activation behavior of ρ_{xx} measured at $B = 5.51$ T and $B = 8.9$ T. The inset depicts the magnetic field dependence of ρ_{xx} near $\nu = 1/3$ at two different temperatures.

$\nu = 2/3$ for different magnetic fields both below and above $B = B^C_{2/3}$ is shown in Fig. 4a. The behavior of $\gamma_e(T)$ at low temperatures is qualitatively different for $B > B^C_{2/3}$ (circles) and $B < B^C_{2/3}$ (squares), even though the temperature dependence in both cases is well described by a single exponential at low temperatures: $\gamma_e = 1 - \exp(-\Delta/2k_B T)$ (for $B > B^C_{2/3}$) and $\gamma_e = \exp(-\Delta/2k_B T)$ (for $B < B^C_{2/3}$). These equations can be easily obtained with the aid of a CF spin-split Landau level chart as shown in the inset to Fig. 4c for $B > B^C_{2/3}$ and $B < B^C_{2/3}$. A best fit to data in an Arrhenius plot with a line passing through the origin yields the CFSW energy gaps $\Delta^S_{2/3}$ of Fig. 4b. The magnetic field dependence of the $\Delta^S_{2/3}$ in the vicinity of $B^C_{2/3}$ is presented in Fig. 4c. An abrupt enhancement of the CFSW gap at $B > B^C_{2/3}$ is obvious and demonstrates once more the importance of the exchange interaction between CFs.

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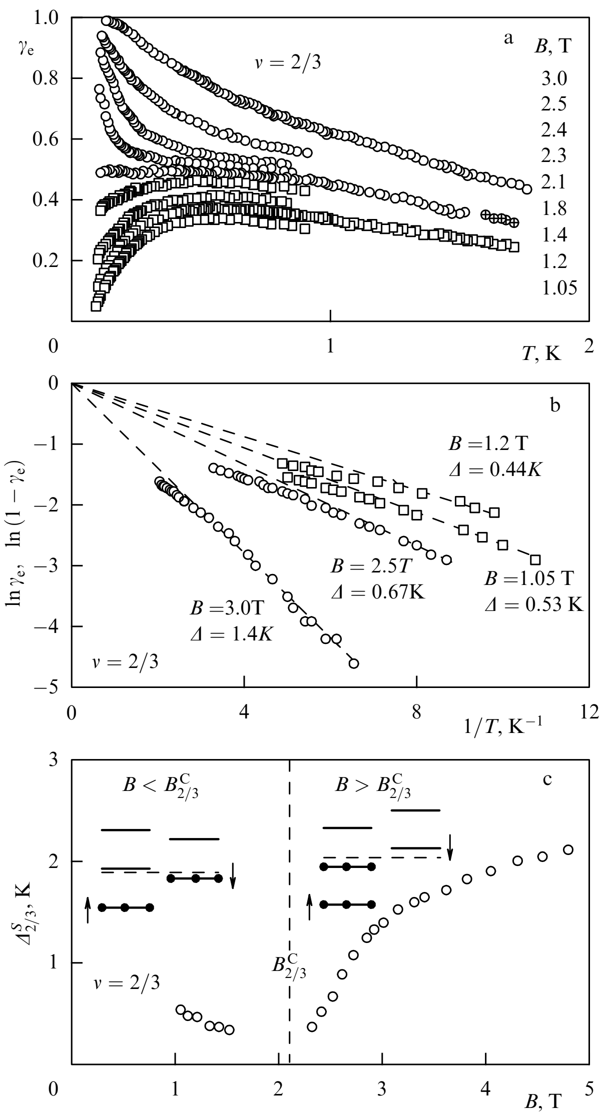

Figure 4. (a) Temperature dependence of the electron spin polarization at $\nu = 2/3$ and $V_{SB} = 0$ for different magnetic field values in the vicinity of the spin transition $B^C_{2/3} = 2.1T$. (b) Arrhenius plots $\ln(\gamma_e)$ vs. 1/T (for $B < B^C_{2/3}$, squares) and $\ln(1-\gamma_e)$ vs. 1/T (for $B > B^C_{2/3}$, circles) at several magnetic fields. (c) Magnetic field dependence of the spin-flip activation energy for $\nu = 2/3$ around $B^C_{2/3}$. In the insets the CF spin-split Landau level diagrams are presented.

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Magnetocapacitance studies of two-dimensional electron systems with long-range potential fluctuations

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Abstract. We report on magnetocapacitance study of the quantum Hall effect (QHE) states. Capacitance minima width was found to be independent of magnetic field and to be the same for even, odd and fractional QHE states when measured as a function of the average electron density. This result indicates that the width of capacitance minima in the samples investigated are governed by long-range carrier density fluctuations. At low temperatures, the amplitudes of the minima decrease linearly with the temperature increase. All our experimental results for the integer QHE states are quantitatively explained by introducing unbroadened magnetic levels and dispersion of the electron density along the sample. The energy gaps at even filling factors obtained from fitting the experimental data are found to be close to the known cyclotron gaps. At odd fillings $\nu = 1, 3$, and 5, the energy gaps appear to be enhanced in comparison with the Zeeman splitting, with the enhancement decreasing with filling factor.

The capacitance minima are argued to originate from the motion of incompressible regions along a sample caused by the gate voltage variation. We derive the condition for the appearance and motion of such regions for the case of gated samples with long-range fluctuations of density of charged donors.

The appearance of narrow magnetocapacitance peaks when a dc current is passed through the sample is reported. We hypothesize that these peaks are due to the current percolation along incompressible regions.

1. Introduction

The method of capacitance spectroscopy, which implies precise measurement of electric capacitance C of a parallel-plate capacitor formed from a two-dimensional electron system (2DES) and a parallel metal film (FET gate), is one of a few experimental methods for detecting thermodynamic characteristics of 2DES. It can also be used to investigate distribution of current under the conditions corresponding to the quantum Hall effect.

In this paper we will consider details of the application of the method for studies of 2DES with long-range potential fluctuations in the quantum Hall regime. An example of electron systems of this type is the most perfect semiconducting heterostructures with selective doping. We will show that

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