Optical Investigation of Spin-Wave Excitations in Fractional Quantum Hall States and of Interaction between Composite Fermions

I. V. Kukushkin,[1,2] J. H. Smet,[1] K. von Klitzing,[1] and K. Eberl[1]

[1]*Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany*

[2]*Institute of Solid State Physics, RAS, Chernogolovka, 142432 Russia*

(Received 3 January 2000)

We demonstrate that the temperature dependence of the electron spin polarization for the fractional states $\nu = 1/3$ and $\nu = 2/3$ displays activated behavior. This study enables the first measurement of the fractional quantum Hall spin-flip gaps. They are found to be systematically larger in comparison with the gaps simultaneously measured in transport. For $\nu = 1/3$ and $\nu = 1/2$, these spin-flip gaps allow the determination of the composite fermion interaction energy. This energy is investigated as a function of the finite width of the 2D channel.

PACS numbers: 73.40.Hm, 71.10.Pm, 78.66.Fd

The two-dimensional electron system, 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 energy [4]. A deviation of the magnetic field B from exact half filling results in the appearance of a nonzero 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 [7–9] support the validity of this theoretical concept and, moreover, demonstrate the semiclassical behavior of these quasiparticles. The CF concept was also successfully extended to the case of spin-flip excitations and the spectrum of spin-wave modes was calculated [10]. They were, however, never measured experimentally until now.

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 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, $k = 1/l_B$. Its energy approaches in the limit of large k the FQHE energy gap, i.e., the energy to create infinitely separated quasiparticle-quasielectron pairs [11,13]. The other branch of collective excitations, the SD mode, takes on the Zeeman energy at $k = 0$ (due to Larmor's theorem) and increases monotonically as a function of momentum until it approaches the exchange energy gap in the limit of infinite wave number [10,12]. Theoretically calculated dispersion laws indicate that the interaction between CFs is indeed about an order of magnitude weaker than the interelectron interaction [10,11,13].

In order to measure the interaction energy directly, one thus needs to study the dispersion law of the CD excitations or, alternatively, measure the FQHE spin-wave energy gap at infinite momentum. The 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. Here, we developed a new method based on the analysis of the temperature dependence of the degree of electron spin polarization in the 1/3 and 2/3 FQHE states as well as in the 1/2 CF state. This allows us to determine the interaction energy between CFs and to extract the FQHE spin-wave energy gap. We demonstrate that the Zeeman splitting of CFs is enhanced by a factor of 2.5 due to the interaction between CFs and this enhancement is very sensitive on the finite width of the 2D channel.

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/Vs] 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

 0031-9007/00/85(17)/3688(4)$15.00

heterointerface in the wide (1 μm) GaAs buffer layer [17]. In all samples the density n_s 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 to modify 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 gatable photon counting system with a spectral resolution of 0.03 meV. We have performed experiments as in Ref. [17], however, as a function of temperature. We measure the degree of the electron spin polarization, γ_e, 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%) measurement of γ_e. 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 γ_e 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 1(a) shows the temperature dependence of γ_e, measured at different B but fixed filling factor $\nu = 1/2$. Below and above the critical field $B_c = 9.3$ T [17], for which the CF system becomes fully spin polarized, γ_e 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 at $B = B_c$, $B > B_c$, and $B < B_c$ were predicted theoretically for noninteracting CFs [18], and it was demonstrated that the linear dependence at low temperatures and $B = B_c$ 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

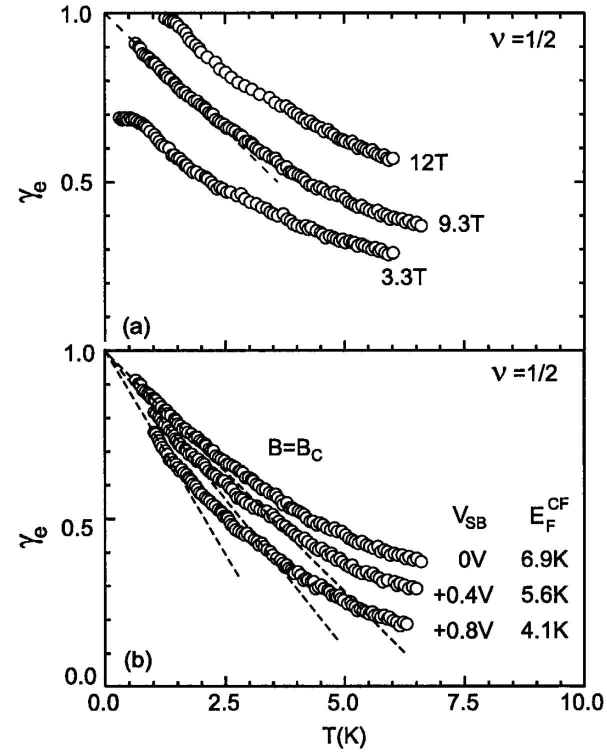

FIG. 1. (a) The T dependence of γ_e for $\nu = 1/2$ and $V_{SB} = 0$ V at different B fields. The dashed line corresponds to the linear extrapolation of the data taken at $B = B_c = 9.3$ T. From its slope the Fermi energy of the CF metal was determined. (b) Influence of the substrate voltage on the T dependence of γ_e at $\nu = 1/2$ and $B = B_c$.

$\gamma_e(T)$ at $B = B_c$ yields a CF Fermi energy of 6.9 K and a CF mass of $m_{CF} = 0.91 m_0$, in rather good agreement with the values measured in transport [5]. The discrepancy with the previously reported value in Ref. [17] stems from the incorrect, but common, assumption of noninteracting CFs. At $B = B_c$, E_F equals 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) as reported in Ref. [18].

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 1(b) depicts the temperature dependence of γ_e at $B = B_c$ for different V_{SB}. Figure 2(a) 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 V_{SB}. On the top axis calculated values for the channel width are indicated for several bias voltages. Figure 2(b) plots the Zeeman splitting (and E_F) as extracted from the T-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).

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 T dependence of γ_e at the 1/3 and 2/3 FQHE states. The analysis of our magneto-optical measurements is very similar to that used for activated magnetotransport investigations. Even so, the determined 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 delivers the inter-CF-Landau-level CD excitation gap (or CF magnetoplasmon, CFMP).

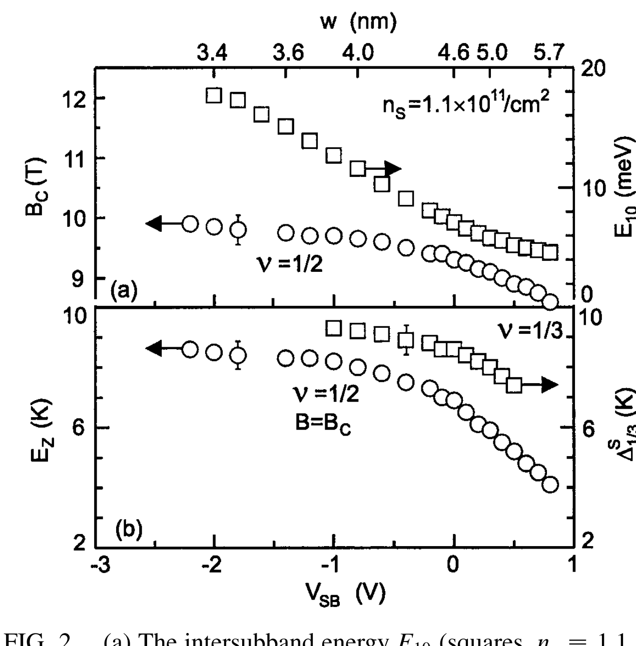

FIG. 2. (a) The intersubband energy E_{10} (squares, $n_s = 1.1 \times 10^{11}$ cm^{-2}) and critical magnetic field B_c (circles, $\nu = 1/2$) as a function of V_{SB}. The top axis gives the width of the wave function, w, obtained from a comparison of numerical simulations with the Fang-Howard function, for a few V_{SB} values. (b) The enhanced spin splitting of CFs (circles, $\nu = 1/2$, $B = B_c$) and the spin-flip gap at $\nu = 1/3$ (squares) as a function of V_{SB}.

In Fig. 3(a) we show $\gamma_e(T)$, measured at different magnetic fields, for the $\nu = 1/3$ FQHE state. The presence of a gap in the CFSW mode makes an Arrhenius type of analysis, as shown in Fig. 3(b), reasonable. At low T, the deviation of γ_e from 1 as a function of temperature is well described by a single exponential dependence: $\gamma_e = 1-2 \times \exp(-\Delta/2k_BT)$. 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 $\Delta_{1/3}^{SW}$. In the former case the activated gap Δ equals $2\Delta_Z$ [20], whereas for the latter case Δ equals $\Delta_{1/3}^{SW}$. The infinite density of states associated with spin-wave transitions at large wave-vectors makes it plausible that $\Delta_{1/3}^{SW}$ determines the activated behavior. Indeed, the measured values of Δ are considerably larger than $2\Delta_Z$ and exhibit

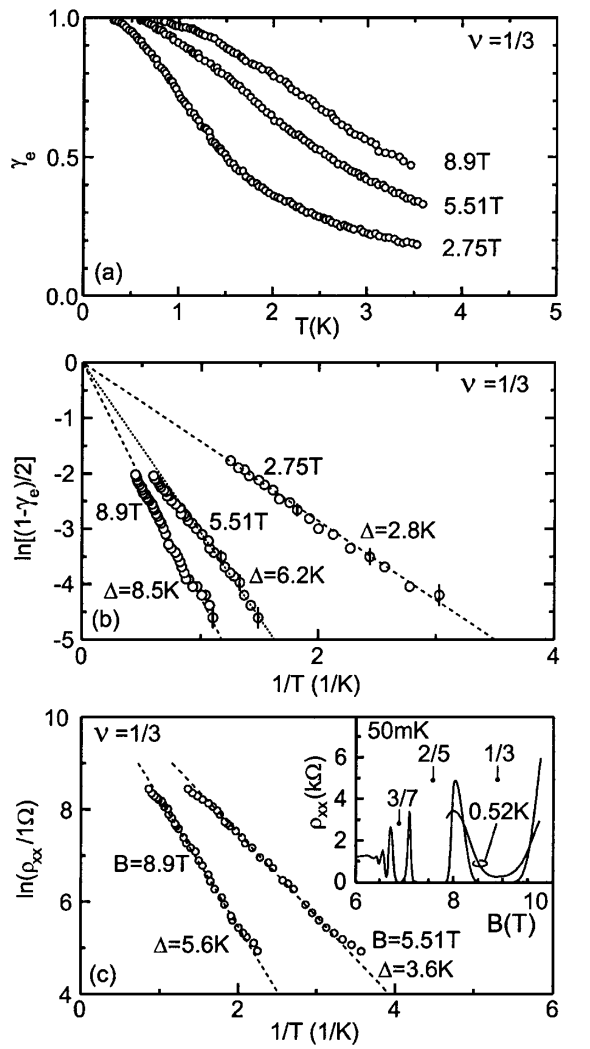

FIG. 3. The T dependence of γ_e (a) and Arrhenius plots (b) $\ln[(1 - \gamma_e)/2]$ vs $1/T$ measured at $\nu = 1/3$ and $V_{SB} = 0$ V for different B fields. (c) Activation behavior of ρ_{xx} at $B = 5.51$ and 8.9 T. The inset depicts $\rho_{xx}(B)$ near $\nu = 1/3$ at two different temperatures.

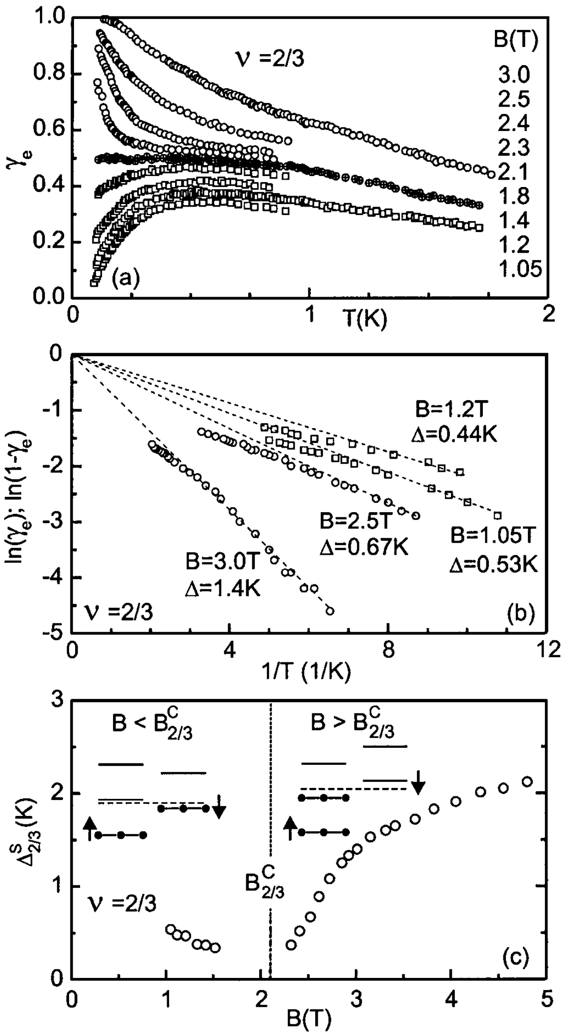

FIG. 4. (a) The temperature dependence of γ_e at $\nu = 2/3$ and $V_{SB} = 0$ V for different magnetic field values in the vicinity of the spin-transition $B^C_{2/3} = 2.1$ T. (b) Arrhenius plots $\ln(\gamma_e)$ vs 1/T (for $B < B^C_{2/3}$, squares) and $\ln(1 - \gamma_e)$ vs 1/T (for $B > B^C_{2/3}$,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

a nonlinear B 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 Figs. 3(b) and 3(c). We therefore can conclude that in transport 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. 2(b). The interaction energies between CFs, measured for $\nu = 1/2$ and 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 T dependence of γ_e at $\nu = 2/3$ for different B both below and above $B = B^C_{2/3}$ is shown in Fig. 4(a). 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 T: $\gamma_e = 1 - \exp(-\Delta/2k_BT)$ (for $B > B^C_{2/3}$) and $\gamma_e = \exp(-\Delta/2k_BT)$ (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 of Fig. 4(c) for $B > B^C_{2/3}$ and $B < B^C_{2/3}$. A best fit to the data in an Arrhenius plot with a line passing through the origin yields the CFSW energy gaps $\Delta^S_{2/3}$ of Fig. 4(b). The B dependence of the $\Delta^S_{2/3}$ in the vicinity of $B^C_{2/3}$ is presented in Fig. 4(c). 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.

Financial support from the Volkswagen Stiftung, INTAS, the Russian Fund of Fundamental Research, and the Bundesministerium für Bildung und Forschung (01BM919/5) is gratefully acknowledged.

[1] D. C. Tsui *et al.,* Phys. Rev. Lett. **48**, 1559 (1982).
[2] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).
[3] J. K. Jain, Phys. Rev. Lett. **63**, 199 (1989).
[4] B. I. Halperin *et al.,* Phys. Rev. B **47**, 7312 (1993).
[5] R. R. Du *et al.,* Phys. Rev. Lett. **70**, 2944 (1993); **75**, 3926 (1995).
[6] R. L. Willett *et al.,* Phys. Rev. Lett. **71**, 3846 (1993).
[7] V. J. Goldman *et al.,* Phys. Rev. Lett. **72**, 2065 (1994).
[8] J. H. Smet *et al.,* Phys. Rev. Lett. **77**, 2272 (1996).
[9] R. L. Willett *et al.,* Surf. Sci. **361/362**, 38 (1996).
[10] T. Nakajima and H. Aoki, Phys. Rev. Lett. **73**, 3568 (1994).
[11] J. K. Jain and R. K. Kamilla, in *Composite Fermions,* edited by O. Heinonen (World Scientific, Singapore, 1998), p. 1.
[12] G. Murthy, Phys. Rev. B **60**, 13 702 (1999).
[13] S. M. Girvin *et al.,* Phys. Rev. Lett. **54**, 581 (1985).
[14] A. Pinczuk *et al.,* Phys. Rev. Lett. **70**, 3983 (1993); **68**, 3623 (1992).
[15] H. D. M. Davies *et al.,* Phys. Rev. Lett. **78**, 4095 (1997).
[16] P. Khandelwal *et al.,* Phys. Rev. Lett. **81**, 673 (1998).
[17] I. V. Kukushkin *et al.,* Phys. Rev. B **40**, 7788 (1989); **55**, 10 607 (1997); **60**, 2554 (1999); Phys. Rev. Lett. **82**, 3665 (1999).
[18] I. V. Kukushkin *et al.,* JETP Lett. **70**, 722 (1999).
[19] F. C. Zhang and S. Das Sarma, Phys. Rev. B **33**, 2903 (1986).
[20] A. H. MacDonald and J. J. Palacios, Phys. Rev. B **58**, R10 171 (1998).