Transition from Free to Interacting Composite Fermions away from $\nu = 1/3$

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Spin excitations from a partially populated composite fermion level are studied above and below $\nu = 1/3$. In the range $2/7 < \nu < 2/5$, the experiments uncover significant departures from the noninteracting composite fermion picture that demonstrate the increasing impact of interactions as quasiparticle Landau levels are filled. The observed onset of a transition from free to interacting composite fermions could be linked to condensation into the higher order states suggested by transport experiments and numerical evaluations performed in the same filling factor range.

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In the composite fermion (CF) picture of the fractional quantum Hall effect (FQHE), fundamental interactions are taken into account at the mean-field level by mapping the system of strongly interacting electrons in a perpendicular magnetic field into a system of CFs moving in a reduced effective magnetic field [1]. The effective magnetic field experienced by CF quasiparticles is $B^* = B - B_{1/\phi}$, where ϕ is an even integer that labels different sequences of incompressible states and $B_{1/\phi}$ is the magnetic field corresponding to the filling factor $\nu = \frac{1}{\phi}$. In the CF framework, the reduction in magnetic field follows from the binding of ϕ flux quanta to electrons. The main sequence of FQHE states is at Landau level filling factor $\nu = p/(\phi p \pm 1)$, where p is the CF filling factor. Each FQHE sequence is then centered around an even-denominator fraction $\nu = 1/\phi$, where the effective field cancels and a compressible Fermi liquid is thought to form [2]. Underlying the CF paradigm is the formation of CF Landau levels with spacing that depends on the effective field B^* as

$$\omega_{\rm CF} = \frac{e|B^*|}{m^* c}, \tag{1}$$

where m^* is an effective CF mass.

In the CF framework, the complex strongly interacting many-body physics is transformed into the simple picture of noninteracting CFs at filling factors p. The sequence of lowest spin-split CF Landau levels is shown in Fig. 1 for quasiparticles with $\phi = 2$ (or ^{2}CFs) and $\phi = 4$ (or ^{4}CFs). The issue of the impact of residual CF interactions is of particular relevance to states that have $1 < p < 2$ in which there is partial population $p^* = p - 1$ of an excited Landau level (see Fig. 1). Residual CF interactions in the partially populated excited CF level are believed to be responsible for the formation of higher order FQHE states such as $\nu = 4/11$ and $\nu = 4/13$ that have $p^* = 1/3$ for ^{2}CFs and ^{4}CFs [3]. The experimental evidence for such higher order states brings into question the validity of the weakly interacting CF framework [4]. While these higher order fractions were actually predicted in the earlier hierarchical model [5,6], it was argued that the CF model may account for these new fractions when CF residual interactions are incorporated beyond the mean-field level [7–14].

Experimental evidence for the formation of a Landau level structure of CFs is found in light scattering measurements of spin-flip (SF) excitations in which the Landau level number and orientation of spin change simultaneously [15]. At filling factors away from $\nu = 1/3$, the lowest-lying SF excitations probe the level structure because the transitions in these excitations emanate from the partially populated CF level as shown in Fig. 1 [16,17]. Since SF excitations can be observed at fractional values of p, experiments that probe the lowest-lying SF modes are powerful tools in studies of CF interactions at filling factors away from the major FQHE states.

In this Letter, we report measurements of low-lying SF excitations by inelastic light scattering that reveal marked quasiparticle interactions when there is partial population of the $|1, \uparrow\rangle$ CF Landau level ($0 < p^* < 1$). The experiments indicate a sharp onset of CF interactions that occurs for $p^* \cong 1/5$. These results can be regarded as evidence that emergence of higher order FQHE states away from

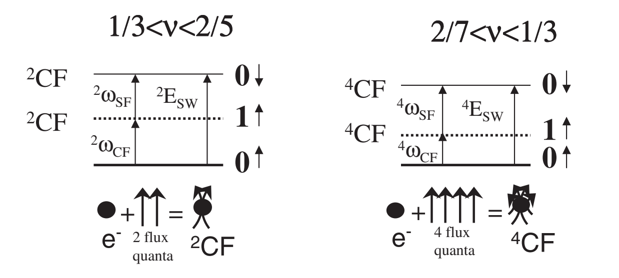

FIG. 1. Composite Fermion level structure for $\nu > 1/3$ (^{2}CF or $\phi = 2$ flux attachment, left) and $\nu < 1/3$ (^{4}CF or $\phi = 4$ flux attachment, right) with the corresponding spin excitations: the spin-flip (SF) and the spin-wave (SW). The dotted lines represent the partially populated levels.

filling factor $\nu = 1/3$ is linked to a transition from "free" to interacting behavior at a relatively low occupation of the $|1,\uparrow\rangle$ CF level.

The sensitivity of low-lying SF modes to interactions among CF quasiparticles occurs because, in a "single-particle," or free, CF paradigm (no impact of CF interactions), the mode linewidths are expected to be independent of p^* and their light scattering intensities should be proportional to p^*. We find that, at low values of $p^* < 0.2 = 1/5$, the SF mode remains sharp (width $\gamma \leq 0.06$ meV) and its light scattering intensity indeed is linear in p^* for both $\nu > 1/3$ and $\nu < 1/3$. When $p^* > 1/5$, however, the light scattering spectra reveal marked departures from the free CF behavior. The SF mode of ^{2}CFs displays significant broadening, with γ reaching 0.1 meV for $p^* > 1/2$, and the light scattering intensities of SF modes of ^{2}CFs and ^{4}CFs saturate when $p^* \rightarrow 1/2$.

The broadening of the light scattering peak of SF modes for $p^* > 1/5$ suggests a small energy scale for ^{2}CFs interactions that is in the range of 0.1 meV. It is conceivable that the broadening is linked to lower-lying collective excitations that exist when there is partial population of the $|1,\uparrow\rangle$ ^{2}CF level. In this scenario, the energy range for such excitations would be comparable to the enhanced broadening of SF excitations. Currently, there is no evaluation of SF excitations as a function of p^*, but the observed broadening energies are in the range of predictions for the energy scale of residual CF interactions [11,13].

The inelastic light scattering measurements were performed on a high quality GaAs single quantum well of width 330 Å. The electron density is $n = 5.5 \times 10^{10}$ cm^{-2} and its low temperature mobility is $\mu = 7.2 \times 10^6$ cm^2/V s. The sample was mounted on the cold finger of a ^{3}He/^{4}He dilution refrigerator, with windows for optical access, that is inserted in the cold bore of a superconducting magnet. Cold finger temperatures can reach as low as $T = 23$ mK. The backscattering geometry was used at an angle θ with the normal of the sample surface as shown in the inset in Fig. 2. The magnetic field perpendicular to the sample is $B = B_T \cos\theta$ and B_T is the total field. The results reported here have been obtained with $\theta = 50° \pm 2°$. Resonant inelastic light scattering spectra were obtained by tuning the incident photon energy of a Ti:sapphire laser close to the fundamental optical gap of GaAs to enhance the light scattering cross section. The power density was kept below 10^{-5} W/cm^2 to prevent heating of the electron gas. The scattered signal was dispersed by a triple grating spectrometer working in additive mode and analyzed by a CCD camera with 26 μm wide pixels. With a slit width of 30 μm, the combined resolution of the system is about 0.02 meV.

Figure 2 shows that two low-lying spin excitations are observed. In addition to the SF mentioned above, there is the spin-wave excitation (SW) in which only the spin orientation changes ($\delta S_z = \pm 1$) (see Fig. 1). By virtue of the Larmor theorem, at long wavelengths the spin wave is at the "bare" Zeeman energy $E_z = g\mu_B B_T$, where μ_B is the Bohr magneton and g is the Landé factor of GaAs. On the other hand, the energies and line shapes of SF excitations incorporate quasiparticle interactions that offer probes of composite fermion physics [15–20]. At $\nu = 1/3$, the only low-energy spin excitation observed is the long wavelength SW mode at E_z. When the electron fluid becomes compressible, for *both* $\nu > 1/3$ and $\nu < 1/3$, the SF peak appears on the lower energy side of the SW mode. The narrow linewidth of SF excitations on both sides of $\nu = 1/3$ (full width at half maximum or $\gamma < 0.06$ meV) suggests that $|1,\uparrow\rangle$ Landau levels of ^{2}CFs and ^{4}CFs are sharp.

Figure 3 displays the evolution of the spectra of SF and SW modes for $\nu > 1/3$ as a function of p^*. These spin excitations are linked to (^{2}CF) quasiparticles. It is immediately apparent from these spectra that the SF mode line shape and energy are strong functions of p^*. We constructed reasonably good fits to the spectra with two-Gaussian functions, as shown in Fig. 3. A similar procedure was carried out for ^{4}CF when $\nu < 1/3$ (not shown in

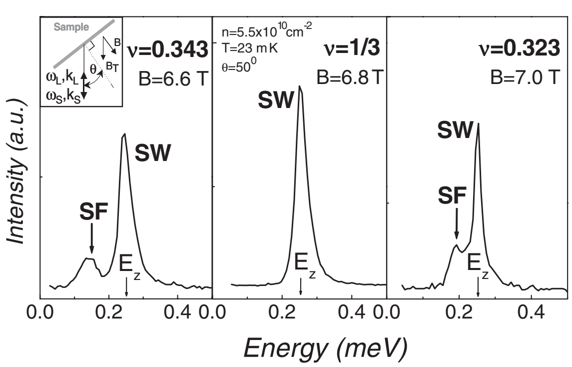

FIG. 2. Light scattering spectra of the low-lying spin excitations at three different filling factors: $\nu = 0.343$, $\nu = 1/3$, and $\nu = 0.323$. The scattering geometry is shown in the inset.

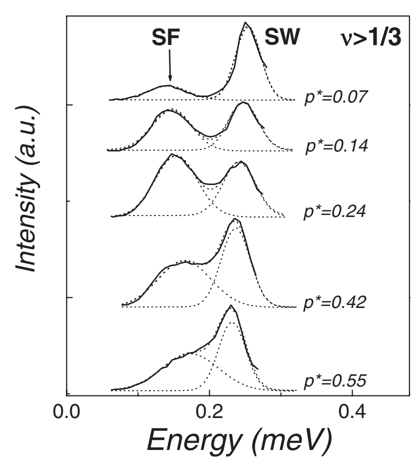

FIG. 3. Evolution of the light scattering spectrum with p^* for $\nu > 1/3$. The dotted line shows the analysis with a two-Gaussian fit of the spin-flip (SF) and spin-wave (SW) peaks.

Fig. 3). The linewidth γ and the integrated intensity of the SF mode that are obtained by this analysis are shown in Fig. 4.

The dependence of the integrated SF intensity and γ on p^* in Fig. 4 reveals two distinct regimes. At low p^*, the integrated intensity grows linearly with p^* and the linewidth remains constant around 0.06 ± 0.01 meV. These features are consistent with a picture of free CFs that applies to both ^{2}CF and ^{4}CF sides. For $p^* > 0.2$, however, the saturation of the integrated intensity seems to indicate the onset of a breakdown of the free CF picture.

The observed p^* dependence of the SF linewidths is consistent with the scenario of an onset of a regime dominated by CF interactions for $p^* > 0.2$. The linewidth of the SF light scattering peak of ^{2}CF, shown in Fig. 4, increases when $p^* > 0.2$ up to 0.1 meV for $p^* = 0.55$. The enhanced SF linewidwth could be regarded as a key manifestation of the onset of CF interactions. In contrast, the SF peak remains sharp for ^{4}CF, likely due to the expected weaker residual interactions among ^{4}CFs.

The picture we propose to interpret these results assumes that states of CF change with interactions in the same way as states of electrons. In a free CF picture, such as the one in Fig. 1, the partially populated $|1,\uparrow\rangle$ level is expected to be infinitely sharp and CF quasiparticles are long-lived. This picture is expected to hold at low p^*. As p^* increases, CF quasiparticles acquire a finite lifetime due to interactions, and the $|1,\uparrow\rangle$ level is expected to broaden significantly as sketched in the inset in Fig. 4. In this regime, the width of the SF mode is expected to increase as seen in our data for $p^* > 0.2$. The $|1,\uparrow\rangle$ level may eventually split into well-defined higher order CF Landau levels, which, in turn, can give birth to higher order FQHE states such as the one observed at $\nu = 4/11$ by Pan *et al.* [3].

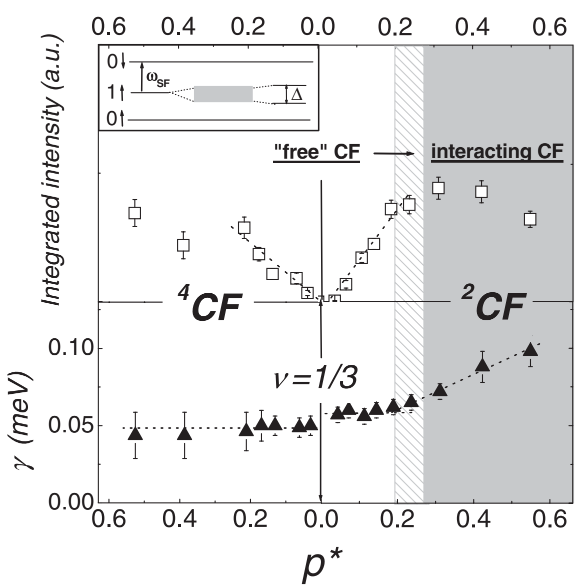

FIG. 4. Evolution of the integrated light scattering intensity (open squares) and the spectral linewidth γ (solid triangles) of the spin-flip (SF) excitation as a function of partial filling factor p^*. The left panel shows the data for $\nu < 1/3$ or ^{4}CF, while the right panel shows data for $\nu > 1/3$ or ^{2}CF. The dotted lines are guides to the eyes. A CF Landau level scheme is drawn in the inset. It depicts a simple picture of the transition from a free to an interacting CF regime.

An estimate of the CF level broadening can be obtained from the evaluations of the gap Δ of the incompressible state at $\nu = 4/11$. Recent calculations that incorporate corrections to account for the width of the quantum well give a value of roughly 0.1 meV [11]. This value is consistent with the linewidths observed and supports the interpretation that the width of the SF peak indeed increases due to the increasing impact of the CF interactions for $p^* > 0.2$.

Additional insights can be obtained from the filling factor dependence of the SF mode energy. Up to now, we have implicitly considered that the level ordering is the one depicted in Figs. 1 and 4. This ordering assumes full spin polarization in the full range $1/3 < \nu < 2/5$. While this assumption has been debated [7,8,13,14], transport experiments with tilted magnetic fields indicate that at least the state at $\nu = 4/11$ is fully spin polarized for $B_T > 10$ T.

In the following, we show that the filling factor dependence of the SF peak energy clarifies this issue. If we neglect excitonic interactions between the excited CF quasiparticle and the quasihole, one can write a simple expression for the SF mode energy [8,15]

$$\hbar\omega_{\rm SF} = E_z^* - \hbar\omega_{\rm CF}, \qquad (2)$$

where $E_z^* = E_z + E^{\uparrow\downarrow}$ and $E^{\uparrow\downarrow}$ is the spin-reversal many-body energy for composite fermions [21]. $E^{\uparrow\downarrow}$ depends strongly on the spin polarization of the system and should vanish in the absence of spin polarization. Therefore, any loss of spin polarization should drastically decrease the spin-reversal many-body energy and drive the SF peak energy towards zero energy [22].

The filling factor dependence of the SF mode energy is shown in Fig. 5 for $0.31 < \nu < 0.38$. The SF mode energies have a monotonic dependence on the filling factor for both $\nu > 1/3$ and $\nu < 1/3$. These behaviors clearly indicate that there is no significant loss of spin polarization in this filling factor range.

It is significant that the SF mode energies show opposite trends with ν (or B): While $^2\omega_{\rm SF}$ increases with ν, $^4\omega_{\rm SF}$ decreases. The CF framework captures the opposite trends of the SF mode energies with ν. Indeed, according to Eq. (2) and neglecting the weak $\sqrt{B}$ dependence of the spin-reversal many-body energy, the splitting between the Zeeman energy and $\omega_{\rm SF}$ should scale as $|B^*|$. B^*, the reduced effective field experienced by CF quasiparticles, is written as $B - B_{1/2}$ and $B - B_{1/4}$ for ^{2}CF and ^{4}CF, respectively. The evolution of the splitting as a function of $|B^*|$ is shown in the inset in Fig. 5. These results are remarkably consistent with key predictions of the CF

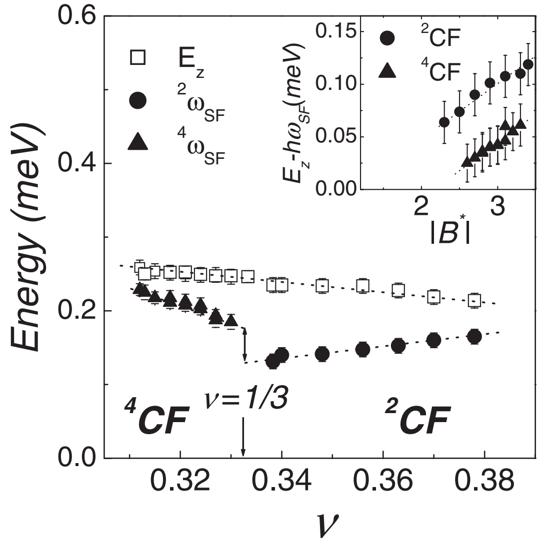

FIG. 5. Filling factor dependence of ω_{SF} (black solid circles and up-triangles for $^2\omega_{SF}$ and $^4\omega_{SF}$, respectively) and E_z (open squares) for $0.31 < \nu < 0.38$. The dotted lines are guides to the eyes. The inset shows the splitting between E_z and ω_{SF} plotted as a function of the reduced effective field B^* of CF theory (see text).

framework in that the mode energy is proportional to $|B^*|$ for both SF excitations.

A sharp discontinuity in the SF mode energy occurs at $\nu = 1/3$. This observation finds a natural explanation within the CF framework because, when crossing the $\nu = 1/3$ boundary, there is an abrupt change in character of the quasiparticles in the ground state of the quantum fluid. The discontinuity of the SF energy at exactly $\nu = 1/3$ is thus regarded as a manifestation of the different energy scales associated with ^{2}CF and ^{4}CF quasiparticles. Indeed, the energies of SF excitations are linked to the CF cyclotron frequency ω_{CF} and the spin-reversal many-body energy $E^{\uparrow\downarrow}$. These energies are expected to be markedly smaller for ^{4}CF quasiparticles, as found in the recent light scattering observations of ^{4}CF spin-conserving excitations [23]. We note that a similar discontinuity has been reported recently in luminescence experiments around $\nu = 1/3$ [24].

In summary, we have observed CF SF excitations away from $\nu = 1/3$ and use them as a tool to study CF interactions away from major fractions. The evolution of the line shape of the SF peak excitation reveals a striking transition from a weakly interacting to a strongly interacting CF regime. The breakdown of the weakly interacting CF picture is expected to result in the formation of higher order fractional quantum Hall states that do not belong to the primary CF sequence. The results of light scattering experiments in conjunction with CF theories that go beyond the mean-field noninteracting limit should reveal intriguing new physics of composite quasiparticles in the regime of the FQHE.

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