Evidence of Landau Levels and Interactions in Low-Lying Excitations of Composite Fermions at $1/3 \leq \nu \leq 2/5$

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Excitation modes in the range $2/5 \geq \nu \geq 1/3$ of the fractional quantum Hall regime are observed by resonant inelastic light scattering. Spectra of spin-reversed excitations suggest a structure of lowest spin-split Landau levels of composite fermions that is similar to that of electrons. Spin-flip energies determined from spectra reveal significant composite fermion interactions. The filling factor dependence of mode energies displays an abrupt change in the middle of the range when there is partial population of a composite fermion level.

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The states of the fractional quantum Hall effect (FQHE) display remarkable behaviors that arise from fundamental electron interactions in two dimensions. Composite fermion (CF) quasiparticles explain the states with filling factors $\nu = p/(2np \pm 1)$, where p is the CF filling factor [1,2]. In CF's electrons stay apart by binding $2n$ ($n = 1, 2, \ldots$) vortices of the many-body wave function. The odd-denominator FQHE states have integer p. Chern-Simons gauge fields account for electron interactions so that CF's experience effective magnetic fields $B^* = B - B_{1/2n} = \pm B/(2np \pm 1)$, where B is the perpendicular component of the external field [3,4]. Composite fermions have spin-split Landau levels characteristic of charged fermions with spin 1/2, as shown schematically in the insets to Figs. 2(b) and 3(a) for $\nu \lesssim 2/5$ and $\nu \gtrsim 1/3$. In this simplest of pictures, CF Landau levels resemble those of electrons. The spacing of the lowest same spin levels is represented as a cyclotron frequency [3,5–11]

$$\omega_c = \frac{eB^*}{cm_{\mathrm{CF}}}, \tag{1}$$

where m_{CF} is a CF effective mass. ω_c is understood as the energy of the large wave vector ($q \to \infty$) inter-Landau level excitation of CF's that represents a quasiparticle-quasihole pair at large separation [3]. In the main sequence of the FQHE there are p fully occupied CF Landau levels. Equation (1) is employed to extract values of m_{CF} from the field dependence of activated magnetotransport [6] and from optically detected microwave absorption [12]. The existence of a ladder of spin-split Landau levels of CF's has been deduced from the angular dependence of magnetotransport at $5/3 \geqslant \nu \geqslant 4/3$ [13].

Spin-reversed quasiparticle-quasihole pairs have spin-flip energies that are strongly affected by residual CF interactions [14–17]. States such as 2/5, with two CF Landau levels fully populated, are spin-polarized because the spin-flip energies at relatively large fields are larger than the CF cyclotron frequency. Residual interactions among composite fermions are of great current interest. While couplings between CF's are understood as relatively weak, residual interactions are invoked to interpret FQHE states at filling factors in the range $2/5 > \nu > 1/3$ with partial population of CF Landau level [18–20].

Resonant inelastic light scattering methods access the low-lying excitations of electron liquids of the FQHE [21–23]. Recent light scattering experiments at filling factors 1/3 and 2/5 have determined the energies of rotons at $q \sim 1/l_0$, where $l_0 = (\hbar c/eB)^{1/2}$ is the magnetic length, and of large wave vector ($q \to \infty$) excitations of CF's [24]. The observed splittings between rotons and $q \to \infty$ modes are due to exciton-like bindings in neutral quasiparticle-quasihole pairs [25–27]. These results, quantitatively explained within CF theory [24,28], suggest that the structure of CF Landau levels and residual interactions could be explored by light scattering measurements of collective excitations.

We report resonant inelastic light scattering measurements of low-lying excitations of the electron liquids in the full range of filling factors $2/5 \geq \nu \geq 1/3$, where the main FQHE states are linked to CF's that bind two vortices ($n = 1$). Low-lying excitations are observed at all the magnetic fields within the range. The experiments enable the study of quasiparticles in states with partial population of one CF Landau level ($2 \geq p \geq 1$). They probe the structure of spin-split CF levels and the impact of residual interactions among quasiparticles.

At filling factors close to 2/5 we observe modes due to spin-flip (SF) transitions $1\uparrow \to 0\downarrow$ in which there are simultaneous changes in spin and CF Landau level quantum numbers, as shown in the inset to Fig. 2(b). Such SF inter-Landau level collective modes of composite fermions were recently evaluated for the state at $\nu = 2/5$ [10]. Spin-flip excitations observed at filling factors close to 1/3 when the $1\uparrow$ level begins to populate confirm the scheme of spin-split Landau levels in the inset to Fig. 3(a) and yield a spin-flip energy that reveals significant interactions between quasiparticles.

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The observations of SF modes offer direct insights on the CF Landau level structure and residual CF interactions. At filling factors 1/3 and 2/5 the measured spectra are consistent with the electron-like Landau level structure shown in the insets to Figs. 2(b) and 3(a). For filling factors $\nu \lesssim 2/5$ the SF mode energy has a linear dependence on the effective magnetic field that is consistent with Eq. (1). For larger fields the mode energy becomes independent of field. A remarkable change in the spectra of low-lying excitations occurs in the middle of the magnetic field range between 1/3 and 2/5. The change in character is relatively abrupt, occurring over a narrow magnetic field interval of $\Delta\nu \lesssim 0.03$. Such changes in the middle of the filling factor range are regarded as manifestations of residual quasiparticle interactions in partially populated CF levels.

The high quality 2D electron system is in a single GaAs quantum well (SQW) of width $d = 330$ Å. The electron density is $\rho = 5.6 \times 10^{10}$ cm^{-2} and the mobility is $\mu \gtrsim 7 \times 10^6$ cm^2/V sec at $T \cong 300$ mK. The sample was mounted on the cold finger of a ^{3}He/^{4}He dilution refrigerator that is inserted in the cold bore of a superconducting magnet with windows for optical access. Cold finger temperatures are variable and as low as 50 mK. The resonant inelastic light spectra were excited with a diode laser with photon energies ω_L close to the fundamental optical gap of the GaAs SQW. The power density was kept below 10^{-4} W/cm^2. The spectra were acquired with a double Czerny-Turner spectrometer operating in additive mode and a CCD camera with 15 μm pixels. The combined resolution with a 30 μm slit is 0.016 meV. We measured depolarized spectra with orthogonal incident and scattered light polarizations and polarized spectra in which polarizations are parallel. Excitation modes with changes in the spin degree of freedom tend to be stronger in depolarized spectra, while modes in the charge degree of freedom tend to be stronger in polarized spectra. A backscattering geometry shown in the inset to Fig. 1(b) was used with $\theta \sim 30°$. The perpendicular component of magnetic field is $B = B_T \cos\theta$, where B_T is the total field. The light scattering wave vector is $k = (2\omega_L/c)\sin\theta \approx 10^5$ cm^{-1} and $kl_0 \lesssim 0.1$.

In Fig. 1 we show the interplay between luminescence and inelastic light scattering. Resonant light scattering spectra with photon energies at the fundamental gap are compared with luminescence spectra excited with higher photon energy. At $\nu = 1/3$ the light scattering spectrum in Fig. 1(a) displays four peaks. SW is the long wavelength spin wave at the Zeeman energy E_Z. The other peaks at $E_G(R)$, $E_G(\infty)$, and $E_G(0)$ are charge-density modes (CM) at the roton, at $q \to \infty$ and $q \to 0$, respectively [24]. Figure 1(b) shows spectra taken at $\nu = 0.386$ where the SW mode is dominant. These results reveal that luminescence intensities have minor impact in resonant light scattering spectra when photon energies overlap the fundamental gap.

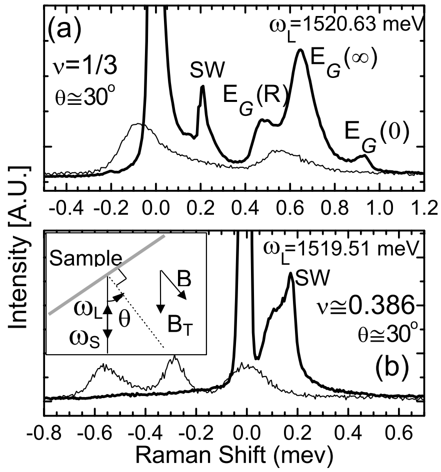

FIG. 1. Depolarized inelastic light scattering spectra (thick lines) and luminescence spectra (thin lines). The intensity of the luminescence has been rescaled to adjust a background intensity. (a) $\nu = 1/3$. (b) $\nu \sim 0.386$. The inset shows the scattering geometry, where ω_S is the scattered photon energy.

Figure 2(a) shows light scattering spectra of low-lying excitations ($\omega \lesssim 0.3$ meV) measured at $\nu \lesssim 2/5$. The spectrum at $\nu = 2/5$ shows an asymmetric peak (SW) at $E_Z = g\mu_B B_T$, where μ_B is the Bohr magneton and $g \cong 0.44$ is the Lande factor. SW is the mode in which there are

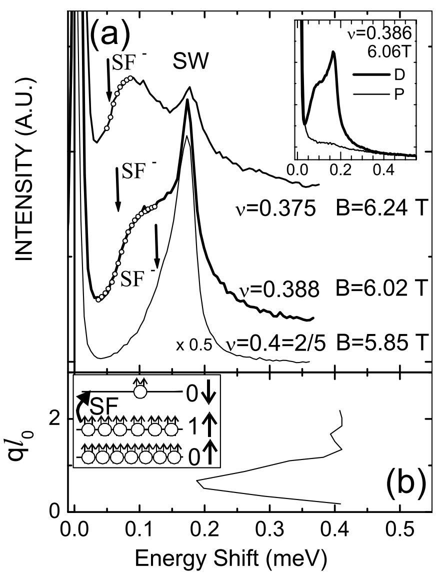

FIG. 2. (a) Inelastic light scattering spectra at filling factor $\nu \lesssim 2/5$. The dots superimposed on the measured spectra are fits based on a broadened step density of states at the roton minimum in the SF mode dispersion (the spectra at $\nu = 2/5$ has been scaled down by a factor of 2). The inset compares polarized (P) and depolarized (D) spectra. (b) Dispersion of SF modes at $\nu = 2/5$ calculated by Mandal *et al.* [10]. The inset shows the scheme of spin-split Landau levels at $\nu = 2/5$. Landau levels are labeled by quantum numbers and arrows that indicate orientation of spin. Composite fermions are shown as circles with two arrows that represent the two vortices attached to each electron.

changes only in the spin quantum number. Spectra at slightly higher fields, showing better resolved structures, reveal that the asymmetry of the SW peak at 2/5 is due to a different excitation mode that is labeled SF^-. This mode being below E_Z can involve only a change in spin because the charge-density modes occur at energies above E_Z [10]. The inset to Fig. 2(a) shows that SW and SF^- modes have the same polarization selection rules. This also indicates that the mode at energy below the SW involves a change in the spin degree of freedom. Figure 2(b) shows a calculated dispersion of SF excitations at $\nu = 2/5$ [10]. The calculation displays a deep roton minimum at energy close to E_Z. This comparison with theory suggests that the mode below E_Z is the roton of the SF mode. Observations of roton minima are explained by the breakdown of wave vector conservation [22,24].

Figure 3(a) displays spectra obtained at $\nu \gtrsim 1/3$ showing the long wavelength SW mode at E_Z and a narrow peak labeled SF^+ that occurs slightly below. The ordering of lowest CF energy levels in the inset is consistent with Knight shift results showing that spin polarization in the range of our experiments is larger than 0.94 [29]. The SF^+ mode is absent at $\nu = 1/3$ and grows as the filling factor increases. This dependence suggests the mode is related to the population of the second CF Landau level $1\uparrow$ as shown in the inset to the figure. On this basis we assign the SF^+ peak to the SF excitation due to $1\uparrow \rightarrow 0\downarrow$ transitions.

The spectra in Figs. 2(a) and 3(a) confirm the presence of the SF excitations predicted by the electronlike level schemes shown in the insets. These results offer strong evidence that the lowest CF levels are similar to those of electrons. It is significant that spectra of SF excitations can be measured over the whole filling factor range and that there is a markedly different filling factor dependence of SF modes near 2/5 and 1/3.

Figure 4(a) plots the energies of the low-lying spin modes. The SF peaks are quite different at the two filling factor limits, with a marked change in character roughly in the middle of the range. Near 2/5 the observed SF^- mode is interpreted as the roton minimum in the wave vector dispersion. The position of the minimum is obtained by fitting the spectral intensity below E_Z with a roton density of states represented as a convolution of a step function with a Lorentzian function. The mode energy collapses rapidly from 0.11 meV until it stabilizes at a very low value of 0.055 meV. This mode disappears for fields $\nu \lesssim 0.353$. Near 1/3 the very sharp SF^+ mode at energy close to E_Z has no dependence on magnetic field and disappears for fields $\nu \gtrsim 0.363$.

Figure 4(b) shows the magnetic field dependence of the energies of the lowest charge-density excitations. These modes arise from transitions $0\uparrow \rightarrow 1\uparrow$ labeled CM in the inset to Fig. 3(a), in which there is no change in the spin degree of freedom. Near 1/3 the excitation shown is the roton of the wave vector dispersion, and near 2/5 it is the lowest of the two rotons [24]. The large wave vector charge-density modes, at $E(\infty)$, also seen in the spectra, show similar behavior. The abrupt changes in the energies of spin-flip and charge-density modes are in stark contrast with the field dependence of the SW peak that is exactly defined by the Zeeman energy E_Z over the whole range.

The soft SF^- mode collapses to a low energy that is significantly smaller than E_Z within a small magnetic

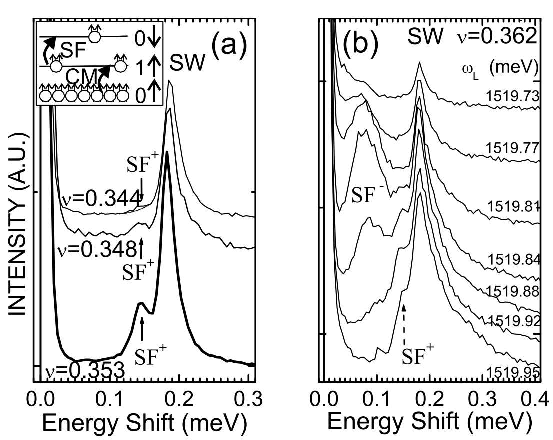

FIG. 3. (a) Inelastic light scattering spectra at filling factors $\nu \gtrsim 1/3$. Light polarizations are as in Fig. 2. Vertical arrows show the peak assigned to the spin-flip mode. The inset shows the three lowest CF levels near 1/3 and the transitions in SF modes and in charge density modes (CM). (b) Resonant inelastic light scattering spectra at $\nu = 0.362$. Incident photon energies are given in meV. These spectra display the coexistence of SF^+ and SF^- modes that occurs roughly in the middle of the filling factor range.

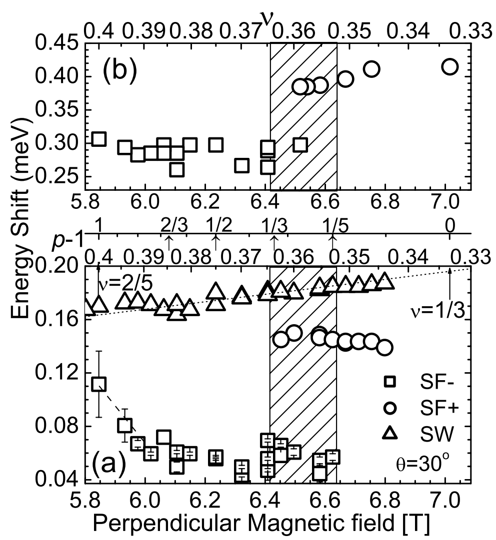

FIG. 4. Energies of low-lying modes as a function of perpendicular field B. (a) Spin modes. The dashed line is the E_{SF} given by the variation of the CF cyclotron frequency as discussed in the text. The dotted line is a fit of the SW energy with E_Z as described in the text. $p - 1$ is the population of the second Landau level. (b) Rotons of charge density modes. The shaded area corresponds to the region where distinct modes originating from 2/5 and 1/3 coexist.

field interval $\Delta B < 0.2$ T. In this narrow range of filling factor the change in mode energy could be approximated by $\Delta\omega_c = e\Delta B/cm_{CF}$, which ignores changes in interactions among CF's. $\Delta\omega_c$ is obtained with a determination of m_{CF} from the energy $E_G(\infty)$ which represents quasiparticle-quasihole pairs at large separation. $E_G(\infty)$ is interpreted as the CF cyclotron energy given by Eq. (1). The result $E_G(\infty) = \hbar\omega_c = 0.64$ meV, reported at $\nu = 1/3$ by Kang *et al.* [24] for the same sample, yields a CF mass of $m_{CF} = 0.4m_0$, where m_0 is the electron rest mass. The dashed line in Fig. 4(a), which is a good representation of the softening, is obtained with $m_{CF} = 0.4m_0$ in $\hbar\Delta\omega_c$.

In spin-polarized states the spin-reversal energy $E^{\uparrow\downarrow}$ of CF quasiparticles is a measure of residual interactions. To obtain it from our measurements we consider the SF^+ energy in the limit $\nu \rightarrow 1/3$ when there is vanishing population of the $1\uparrow$ level ($p \rightarrow 1$). In this limit coupling between the excited quasiparticle and its quasihole is negligible and the SF transition energy approaches the value

$$E_{SF} \rightarrow E_Z + E^{\uparrow\downarrow} - \hbar\omega_{CF}. \quad (2)$$

Equation (2) and the determinations of $E_{SF} = 0.14$ meV, $\hbar\omega_{CF} = E_G(\infty) = 0.64$ meV, and $E_Z = 0.185$ meV yield $E^{\uparrow\downarrow} = 0.595$ meV. This determination of $E^{\uparrow\downarrow}$ is consistent with recent CF evaluations [10,17].

The direct access to low-lying collective modes between major states of the FQHE offers venues to explore new behaviors of the liquids. These states with partially populated CF levels may experience further condensation under the impact of CF interactions, as suggested by recent experimental and theoretical results [18–20]. It is intriguing that the SF^- mode reaches its lowest energy for filling factors $\nu \lesssim 0.385$ where, as indicated in Fig. 4(a), the filling of the $1\uparrow$ level is $p - 1 = 2/3$. Here, the departure of the SF^- energy from the prediction of Eq. (1) suggests an onset of new interaction effects in the partially populated $1\uparrow$ level. The independence of the SF^+ energy on magnetic field that extends to filling factors very close to 1/3 could also manifest the impact of residual CF interactions when there is low population of the $1\uparrow$ CF Landau level.

Figure 4 highlights the abrupt changes in the energies of spin-flip and charge-density modes that occur roughly in the middle of the filling factor range. These results seem to indicate the existence of two types of excitations arising either from 1/3 or from 2/5 states. However, such a picture can be regarded only as incomplete at best. Figure 3(b) shows spectra of SF modes when SF^+ and SF^- modes coexist. These spectra have a strong dependence on temperature. The intensity of the higher energy mode SF^+ is seen to increase markedly with a simultaneous decrease in the intensity of the SF^- mode as the temperature is increased above 200 mK. Observations of mode coexistence and its temperature dependence offer venues to further studies of the impact of CF interactions.

To conclude, resonant inelastic light scattering experiments access low-lying excitations of electron liquids in the full range of filling factors between states of the main sequence of the FQHE. Near 2/5 and 1/3 we found evidence of lowest spin-split CF Landau levels of charged fermions with spin 1/2 that are similar to those of electrons. Spin-reversal energies determined from the spectra reveal sizable composite fermion interactions. Current evaluations of spin-reversed quasiparticle excitations are in excellent quantitative agreement with our results. Interpretations of low-lying excitation modes at filling factors in the middle of the range between 1/3 and 2/5 require further experimental and theoretical exploration.

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