Crossover and Coexistence of Quasiparticle Excitations in the Fractional Quantum Hall Regime at $\nu \leq 1/3$

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New low-lying excitations are observed by inelastic light scattering at filling factors $\nu = p/(\phi p \pm 1)$ of the fractional quantum Hall regime with $\phi = 4$. Coexisting with these modes throughout the range $\nu \leq 1/3$ are $\phi = 2$ excitations seen at $1/3$. Both $\phi = 2$ and $\phi = 4$ excitations have distinct behaviors with temperature and filling factor. The abrupt first appearance of the new modes in the low energy excitation spectrum at $\nu \lesssim 1/3$ suggests a marked change in the quantum ground state on crossing the $\phi = 2 \rightarrow \phi = 4$ boundary at $\nu = 1/3$.

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In the regime of the fractional quantum Hall (FQH) effect fundamental interactions within a 2D electron system cause condensation into quantum liquids. The fluids become incompressible at certain rational values of the Landau level (LL) filling factor $\nu = nhc/eB$, where $n$ is the areal density and B is the perpendicular magnetic field. When only the lowest electron LL is occupied ($\nu \leq 1$), the dominant FQH states are part of the sequences $\nu = p/(\phi p \pm 1)$, where $p$ is an integer that enumerates members of a particular sequence and $\phi$ is an even integer that labels different sequences. The states at $\nu = 1/(\phi \pm 1)$ are boundaries that separate major sequences of the FQH effect. The strongest such state occurs at $\nu = 1/3$, which can be formed with either $\phi = 2$ or $\phi = 4$. Magnetotransport measurements show that excitations at FQH states with $\nu \geq 1/3$ ($\phi = 2$) have characteristic energy scales larger than those of states with $\nu < 1/3$ ($\phi = 4$).

By associating strongly interacting electrons with an even number of vortices $\phi$ of the many-body wavefunction, the composite fermion (CF) framework posits the existence of quasiparticles that experience an effective magnetic field $B^* = \pm B/(\phi p \pm 1)$ that is reduced from $B$ due to Chern-Simons gauge fields that account for Coulomb interactions. Vortex attachment and gauge fields result in weakly interacting CFs (quasiparticles associated with a vortex) that populate quasi-LLs and exhibit an integer quantum Hall effect with effective filling factor $\nu^* = p$ at exactly the FQH filling factors $\nu = p/(\phi p \pm 1)$. The overlap of the FQH sequences at boundary states $\nu = 1/(\phi \pm 1)$ is present in the CF hierarchy: the $1/3$ state can be thought of as a $2\text{CF}$ and $4\text{CF}$ system, both at CF filling factor $\nu^* = 1$ but each with opposite effective magnetic field.

Because $2\text{CF}$ and $4\text{CF}$ excitations have different energy scales, new low-energy modes of $4\text{CF}$ collective excitations could emerge at $\nu \leq 1/3$. Resonant inelastic light scattering in the presence of weak residual disorder offers direct access to the low energy excitation spectrum of FQH liquids. In this Letter we report light scattering experiments that probe quasiparticle crossover between different $\phi$ sequences. Light scattering is here a powerful tool because it accesses low energy excitations both at and between the FQH states.

We investigate the crossover between FQH sequences with a boundary at $\nu = 1/3$. Starting at filling factors slightly below $1/3$, we find the emergence of new low lying excitations that reveal an interaction energy scale significantly below that of the liquid at $\nu \gtrsim 1/3$. The existence of these modes throughout the $\phi = 4$ regime as well as their low energy and sharp temperature dependence suggests they are excitations linked to $\phi = 4$ quasiparticles in the FQH effect at $\nu \leq 1/3$.

Remarkably, spin conserving quasiparticle-quasihole $2\text{CF}$ excitations seen at $\nu \geq 1/3$ are also found for $\nu < 1/3$. These $2\text{CF}$ modes remain strong throughout the $\phi = 4$ regime and shift continuously in energy with magnetic field. Both $2\text{CF}$ and $4\text{CF}$ excitations are found to coexist throughout the $\phi = 4$ regime, as illustrated in the inset to Fig. 8. These modes have distinct behaviors with temperature and magnetic field, confirming that they are related to excitations of different quasiparticles. Excitations in the quantum Hall regime are constructed from neutral pairs composed of quasiparticles excited to a higher energy level and quasiholes that appear in the ground state.

The simultaneous observation of $2\text{CF}$ and $4\text{CF}$ excitations is evidence that multiple quasiparticle flavors can be created in the ground and excited states.

The $\phi = 4$ modes are seen at filling factors that asymptotically approach $1/3$ from below and remain with similar spectral intensity throughout the range $1/3 \lesssim \nu \lesssim 2/7$. These low-lying modes are first detected at the filling factor $\nu \lesssim 1/3$ that coincides with the disappearance of the long wavelength modes of the $1/3$ state. The appearance of the new low energy modes and the coexistence with remaining $\phi = 2$ modes at $\nu \lesssim 1/3$ mark a dramatic transition in quantum ground state properties.
GaAs single quantum well with width \( w \) of distinct coexisting intriguing possibilities for the new ground state is that \( \nu = 2 \) and \( \phi = 2 \). Electron density is \( n = \nu \). Various labelled excitations, discussed in the text, are resonant at different energies. The inset shows the backscattering geometry. (b) Magnetic field dependence of the peak energy of \( \Delta^1 \) (solid circles) and \( \Delta^2 \) (solid squares). Filling factors are labelled at the bottom.

The 2D electron system studied here is formed in a GaAs single quantum well with width \( w = 330 \text{ Å} \). The electron density is \( n = 5.4 \times 10^{10} \text{ cm}^{-2} \) and the low-temperature mobility is \( \mu = 7.2 \times 10^{6} \text{ cm}^2/\text{Vs} \). Light scattering measurements at a base temperature of 50mK are performed in a dilution refrigerator through windows for direct optical access. The energy of the incident photons \( \omega_L \) is tuned close to the fundamental optical gap of the GaAs well and the power density is kept below \( 10^{-4} \text{ W/cm}^2 \). The sample is mounted in a backscattering geometry, making an angle \( \theta \) between the incident photons and the normal to the sample surface, as illustrated in the inset of Fig. 1a. The magnetic field perpendicular to the sample is \( B = B_{\text{T}} \cos \theta \), where \( B_{\text{T}} \) is the total applied field. The wavevector transferred from the photons to the 2D system is \( k = (2\omega_L/c) \sin \theta \).

Figure 1a shows low-energy spectra at various \( \omega_L \) for \( \nu = 2/7 \). New excitations labelled \( \Delta^1 \) and \( \Delta^2 \) are at energies below and above the Zeeman energy \( E_Z = g \mu_B B_{\text{T}} \), where \( g = 0.44 \) is the Lande g-factor for electrons in GaAs and \( \mu_B \) is the Bohr magneton. Two higher energy modes seen at \( \nu \leq 1/3 \) and labelled \( \Delta_2(R) \) and \( \Delta_2(\infty) \) are discussed below. The excitations \( \Delta^1 \) and \( \Delta^2 \) exist both at and between the FQH states for \( \nu < 1/3 \) but are not seen at \( \nu \geq 1/3 \). The mode \( \Delta^1 \) is strongest in the range \( 1/3 > \nu > 2/7 \), where its intensity does not qualitatively change with \( \nu \). Figure 1b shows the field dependence of the peak energies. Remarkably, the lower energy \( \Delta^1 \) modes do not have a strong dependence on magnetic field, shifting to lower energy as the effective filling factor decreases between 1/3 and 2/7 and then remaining relatively constant for \( 1/5 \leq \nu \leq 1/4 \). The energies of \( \Delta^2 \) excitations have a stronger dependence on magnetic field, decreasing as \( \nu \rightarrow 1/4 \) from both sides.

FIG. 1: (a) Light scattering spectra at \( \nu = 2/7 \) and \( T = 54 \text{ mK} \) for several \( \omega_L \). Various labelled excitations, discussed in the text, are resonant at different energies. The inset shows the backscattering geometry. (b) Magnetic field dependence of the peak energy of \( \Delta^1 \) (solid circles) and \( \Delta^2 \) (solid squares). Filling factors are labelled at the bottom.

FIG. 2: (a) Spectra at \( \nu < 1/3 \) and \( T \sim 50 \text{ mK} \). Up-arrows mark \( \Delta_2(R) \) and \( \Delta_2(\infty) \) excitations while the down-arrow indicates the \( \Delta_2(0) \) mode at \( \nu = 1/3 \). (b) Magnetic field dependence of \( \Delta_2(R) \) (open circles) and \( \Delta_2(\infty) \) (open triangles). The solid line is a fit of \( \Delta_2(\infty) \) that includes a finite width correction, as described in the text. Filling factors are labelled at the bottom.
find that these two excitations exist throughout the $\phi = 4$ regime of $1/3 > \nu \geq 1/5$. Fig. 2b shows the magnetic field dependence of excitations $\Delta_2(R)$ and $\Delta_2(\infty)$ that exist throughout the range $1/3 \geq \nu \geq 1/5$. Because these excitations evolve continuously from $\Delta_2(R)$ and $\Delta_2(\infty)$ at $\nu = 1/3$, these modes are interpreted as $2CF$ excitations that continue to exist in the $\phi = 4$ regime.

$\Delta_1^{(1)}$ and $\Delta_1^{(2)}$ excitations have the marked temperature dependence shown in Fig. 3 at $\nu = 2/7$. We see that both modes begin to weaken above $T = 300\,\text{mK}$ and are significantly lower in intensity at higher $T$. The modes associated with $\Delta_2$ transitions, at $\Delta_2(R)$ and at $\Delta_2(\infty)$ have markedly weaker temperature dependence. Similar results are found throughout the $\phi = 4$ regime.

Because they exist only in the range $1/3 > \nu \geq 1/5$, it is natural to associate the modes labelled $\Delta_4$ with excitations of $\phi = 4$ quasiparticles. Since the energy of the modes does not increase with magnetic field, which would be characteristic of spin excitations, these modes are identified as spin conserving excitations due to the $4CF$ transitions shown in the inset to Fig. 3. Activation gaps $\Delta_4$ for $\phi = 4$ FQH states at $2/7$ and $1/5$ are marked, scaled by the Coulomb energy to match the density of our sample, are roughly $0.08m\text{eV} \sim 900\,\text{mK}$. As shown in Fig. 3, $\Delta_4$ at $\nu = 2/7$ is slightly lower than the peak energy of $\Delta_1^{(1)}$ but is within the width of the peak and is consistent with the temperature dependence.

Similar differences are found between the $\Delta_2(\infty)$ energy and the activation gap at $1/3$.

The low-lying excitations of the $\phi = 4$ regime emerge rather abruptly when $\nu \approx 1/3$ at the filling factor where $\Delta_3(0)$ disappears. As seen in Fig. 3b, the $\Delta_4$ modes are already clearly seen at $\nu = 1/3 - 0.006$. Figure 4 shows the spectrum obtained after removal of the overlapping tail of the laser in the spectrum in Fig. 3a. The corrected spectrum displays a low energy onset at $0.07\,\text{meV}$ and a cut-off at higher energies. For the $4CF$ hierarchy, the $1/3$ state is the reverse $B^*$ analog of $1/5$. The spectrum in Fig. 4b, could be interpreted with the calculated spin conserving $\Delta_4$ modes of the $1/5$ state. To account for mode softening from the finite well width, we scale the calculated $1/5$ dispersion for spin-conserving excitations by a constant factor of 0.6. This is consistent with the correction used for $2CF$ modes at $1/3$. As shown in Fig. 4c, the scaled dispersion is in good agreement with the measurement. The high energy cut-off is consistent with the large-q value of the dispersion ($\Delta_4(\infty)$), and the low energy onset is interpreted as the roton of the dispersion ($\Delta_4(R)$). The roton may determine the scale of the $4CF$ temperature dependence.

The scaling of $\Delta_2(R)$ and $\Delta_2(\infty)$ with $B$ seen in Fig. 2b, goes approximately as $e^2/\ell_0$, which is consistent with the $\Delta_2(0)$ and $\Delta_2(R)$ scaling with density. Better agreement is obtained for $\Delta_2(\infty) = 0.95e^2/\ell_0(1 - L/\ell_0)$.
where $0.95\epsilon^2/\epsilon_0$ is the value of the activation gap without including finite width effects. A best fit of $L = 37\lambda = 0.11w$ shown in Fig. 2a. The second term can be understood as the scaling of the finite width correction with magnetic field, which in a simple approximation goes as the ratio of a length related to the transverse extent of the 2D electron wavefunction to $l_0$. This is consistent with calculations of the 1/3 activation gap that include the effects of finite width. In simple $2CF$ theory, the energy level spacing at the FQH states with $\nu^* = p$ is given by

$$\omega_{CF} = \epsilon_2B_1|m^*c = (C/2p \pm 1)e^2/\epsilon_0$$

where $C$ is a constant. Such a scaling is consistent with that of the $\Delta_2(\infty)$ mode if the condition $p = 1$ is kept for all $\nu \leq 1/3$.

At $\nu < 1/3$, the separation between $\Delta_2(R)$ and $\Delta_2(\infty)$ decreases with $B$. This energy difference can be thought of as a binding energy between the excited quasiparticle and quasihole, arising from residual $CF$ interactions. This effect would be strongest at integer effective $2CF$ filling factor, where screening would be weakest. The decrease in separation energy away from $\nu = 1/3$ is interpreted as a manifestation of increasing $2CF$ screening of residual $CF$ interactions, although it may also include differences in the scaling of the finite width correction at the roton.

In summary, new low-lying excitations emerge in the FQH regime of $\nu \leq 1/3$ when the quasiparticles change character from $\phi = 2$ to $\phi = 4$. The excitations of $4CF$ quasiparticles are seen both at and between the FQH excitations. Coexisting with these modes throughout the $\phi = 4$ regime are spin-conserving $2CF$ excitations seen at $\nu = 1/3$. The abrupt appearance of the new low-energy modes and the continued existence of $\Delta_2(R)$ and $\Delta_2(\infty)$ indicate a significant change in the quantum ground state properties. The possible coexistence of $\phi = 2$ and $\phi = 4$ liquids for $\nu < 1/3$ is a topic for further study.

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