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 ϕ 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 [1–6] as well as calculations [7–11] 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 ϕ of the many-body wave function, 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 [12–14]. Vortex attachment and gauge fields result in weakly interacting $^{\phi}$CFs (quasiparticles associated with ϕ vortices) 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}CF and ^{4}CF system, both at CF filling factor $\nu^* = 1$ but each with opposite effective magnetic field.

Because ^{2}CF and ^{4}CF excitations have different energy scales, new low-energy modes of ^{4}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 [15–17]. In this Letter we report light scattering experiments that probe quasiparticle crossover between different ϕ sequences. Light scattering is here a powerful tool because it accesses low-energy excitations both at and between the FQH states [18].

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 $\phi = 4$ quasipartices in the FQH effect at $\nu \leq 1/3$.

Remarkably, spin-conserving quasiparticle-quasihole ^{2}CF excitations seen at $\nu \geq 1/3$ are also found for $\nu < 1/3$. These ^{2}CF modes remain strong throughout the $\phi = 4$ regime and shift continuously in energy with magnetic field. Both ^{2}CF and ^{4}CF excitations are found to coexist throughout the $\phi = 4$ regime, as illustrated in the inset of Fig. 3 below. 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 [7,19,20]. The simultaneous observation of ^{2}CF and ^{4}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 $1/3 \gtrsim \nu \gtrsim 2/7$. 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 [15,16]. 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 of the 2D electron system when crossing the boundary at 1/3.

The evidence that the new ground states that emerge at $\nu \lesssim 1/3$ incorporate both $\phi = 2$ and $\phi = 4$ quasiparticle excitations represent key findings that were not anticipated and should be accounted for by theory. One of our most intriguing results is the observation of the new low-lying $\phi = 4$ excitations at filling factor $\nu \rightarrow 1/3$. To the best of our knowledge, the issue of the filling factor at which $\phi = 4$ excitations are expected to emerge between 1/3 and 2/7 has not been discussed in the literature. Interpretation of the present results would shed new light on the reach of theories of quasiparticle excitations in the FQH regime.

The 2D electron system studied here is formed in a GaAs single quantum well with width $w = 330$ Å. The electron density is $n = 5.4 \times 10^{10}$ cm^{-2} and the low temperature mobility is $\mu = 7.2 \times 10^6$ cm^2/V s. The sample is mounted in a backscattering geometry, making an angle θ between the incident photons and the normal to the sample surface, as illustrated in the inset of Fig. 1(a). The magnetic field perpendicular to the sample is $B = B_T \cos\theta$, where B_T is the total applied field. The wave vector transferred from the photons to the 2D system is $k = (2\omega_L/c)\sin\theta$.

Light scattering measurements at a base temperature of 50 mK are performed in a dilution refrigerator through windows for direct optical access, and the power density is kept below 10^{-4} W/cm^2 to avoid heating the electron system. The energy of the incident photons ω_L is in resonance with the excitonic optical transitions of the 2D electron system in the FQH regime [21,22]. These resonance enhancements, which occur only for the excitations of the 2D system, and the marked dependence on temperature and filling factor identify the observed excitations as arising from the electron fluids in the GaAs quantum well.

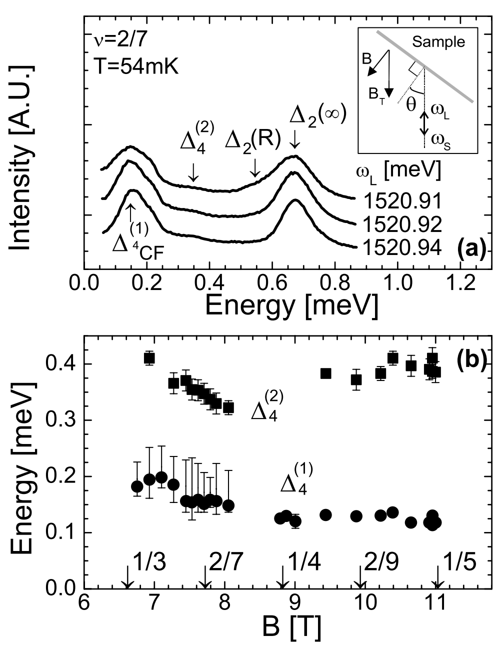

FIG. 1. (a) Light scattering spectra at $\nu = 2/7$ and $T = 54$ mK for several ω_L. Various labeled excitations, discussed in the text, are resonant at different energies. The inset shows the backscattering geometry. (b) Magnetic field dependence of the peak energy of $\Delta_4^{(1)}$ (solid circles) and $\Delta_4^{(2)}$ (solid squares). Filling factors are labeled at the bottom.

Figure 1(a) shows low-energy spectra at various ω_L for $\nu = 2/7$. New excitations labeled $\Delta_4^{(1)}$ and $\Delta_4^{(2)}$ are at energies below and above the Zeeman energy $E_Z = g\mu_B B_T$, where $g = 0.44$ is the Landé g factor for electrons in GaAs and μ_B is the Bohr magneton. Two higher energy modes seen at $\nu \leq 1/3$ and labeled $\Delta_2(R)$ and $\Delta_2(\infty)$ are discussed below. The excitations $\Delta_4^{(1)}$ and $\Delta_4^{(2)}$ exist both at and between the FQH states for $\nu < 1/3$ but are not seen at $\nu \geq 1/3$. The mode $\Delta_4^{(1)}$ is strongest in the range $1/3 > \nu \gtrsim 2/7$, where its intensity does not qualitatively change with ν. Figure 1(b) shows the field dependence of the peak energies. Remarkably, the lower energy $\Delta_4^{(1)}$ 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 $1/5 \leq \nu \lesssim 1/4$. The energies of $\Delta_4^{(2)}$ excitations have a stronger dependence on magnetic field, decreasing as $\nu \rightarrow 1/4$ from both sides.

Three modes at $\nu = 1/3$ shown in Fig. 2(a) are identified with spin-conserving ^{2}CF excitations. The mode labeled $\Delta_2(0)$ is assigned to the wave vector conserving [$q = k \lesssim 1/10l_0$, where $l_0 = (\hbar c/eB)^{1/2}$ is the magnetic length] excitation and is seen only in a small range of ν around 1/3. At $\nu = 1/3$, breakdown of wave vector conservation activates excitations from the roton [$\Delta_2(R)$] and large-q [$\Delta_2(\infty)$] critical points of the dispersion of spin-conserving excitations [16,17,23]. These excitations have been seen for a wider range in ν and were found to disappear between $2/5 > \nu > 1/3$ [16,18]. Surprisingly, as shown in Figs. 1(a) and 2(a), we find that these two excitations exist throughout the $\phi = 4$ regime of $1/3 > \nu \geq 1/5$. Figure 2(b) 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 ^{2}CF excitations that continue to exist in the $\phi = 4$ regime.

$\Delta_4^{(1)}$ and $\Delta_4^{(2)}$ excitations have the marked temperature dependence shown in Fig. 3 at $\nu = 2/7$. We see that both modes begin to weaken above $T = 300$ mK and are significantly lower in intensity at higher T. The modes associated with Δ_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.

The new low-lying modes labeled Δ_4 exist only in the range $1/3 \gtrsim \nu \geq 1/5$. The filling factor dependence

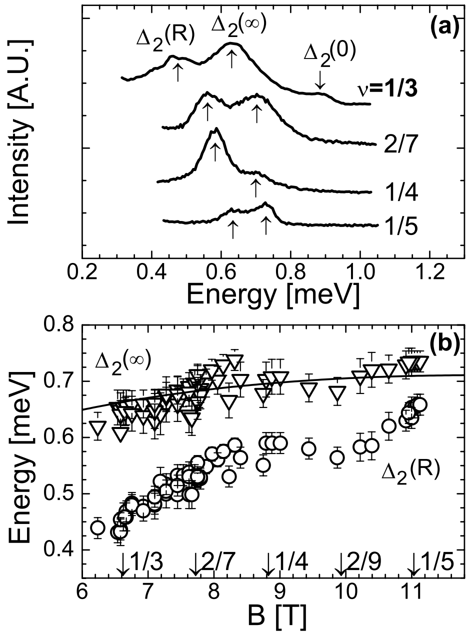

FIG. 2. (a) Spectra at $\nu < 1/3$ and $T \sim 50$ mK. Up arrows mark $\Delta_2(R)$ and $\Delta_2(\infty)$ excitations, while the down arrow indicates the $\Delta_2(0)$ mode at $\nu = 1/3$. (b) Magnetic field dependence of $\Delta_2(R)$ (open circles) and $\Delta_2(\infty)$ (open triangles). The solid line is a fit of $\Delta_2(\infty)$ that includes a finite width correction, as described in the text. Filling factors are labeled at the bottom.

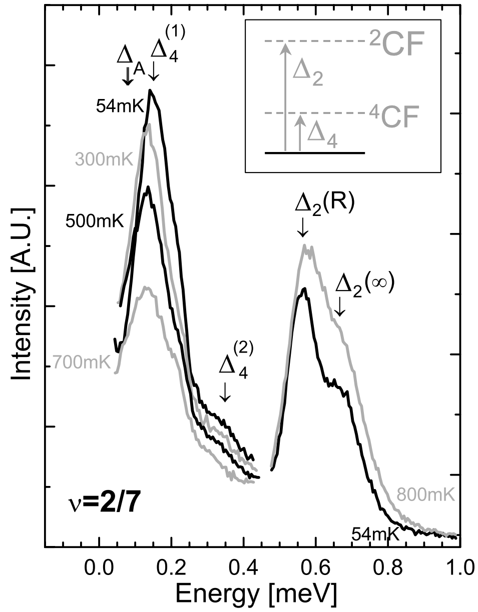

FIG. 3. Temperature dependence of ^{2}CF [$\Delta_2(R)$ and $\Delta_2(\infty)$] and ^{4}CF ($\Delta_4^{(1)}$ and $\Delta_4^{(2)}$) modes at $\nu = 2/7$ and the activation gap Δ_A [3,6], scaled as described in the text. The inset is a schematic of the energy level structure corresponding to the transitions to which the modes are assigned.

confirms their assignment as excitations of the 2D electron system, and it is natural to associate the modes 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 ^{4}CF transitions shown in the inset of Fig. 3. The labeled Δ_4 energies show a relatively weak dependence on magnetic field that is similar to determinations from activated transport. Activation gaps Δ_A for $\phi = 4$ FQH states at $2/7$ and $1/5$ [1–3,5,6], scaled by the Coulomb energy to match the density of our sample, are roughly 0.08 meV $\sim$ 900 mK. As shown in Fig. 3, Δ_A at $\nu = 2/7$ is slightly lower than the peak energy of $\Delta_4^{(1)}$ 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 $1/3$ [17,24].

The low-lying excitations of the $\phi = 4$ regime emerge rather abruptly when $\nu \lesssim 1/3$ at the filling factor where $\Delta_2(0)$ disappears. As seen in Fig. 4(a), the Δ_4 modes are already clearly seen at $\nu = 1/3 - 0.006$. Figure 4(b) shows the spectrum obtained after removal of the overlapping tail of the laser in the spectrum of Fig. 4(a). The corrected spectrum displays a low-energy onset at 0.07 meV and a cutoff at higher energies. For the ^{4}CF hierarchy, the $1/3$ state is the reverse B^* analog of $1/5$. The spectrum in Fig. 4(b) could be interpreted with the calculated spin-conserving Δ_4 modes of the $1/5$ state [9,10]. 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 ^{2}CF modes at $1/3$ [17]. As shown in Fig. 4(c), the scaled dispersion is in good agreement with the measurement. The high-energy cutoff 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 ^{4}CF temperature dependence.

The scaling of $\Delta_2(R)$ and $\Delta_2(\infty)$ with B seen in Fig. 2(b) goes approximately as $e^2/\epsilon l_0$, which is consistent with the $\Delta_2(0)$ and $\Delta_2(R)$ scaling with density [17]. Better agreement is obtained for $\Delta_2(\infty) = 0.95e^2/\epsilon l_0(1 - L/l_0)$, where $0.95e^2/\epsilon l_0$ is the value of the activation gap without including finite width effects [8,25–27], with a best fit of $L = 37$ Å $= 0.11w$ shown in Fig. 2(b). 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 wave function to l_0. This is consistent with calculations of the $1/3$ activation gap that include the effects of finite width [25,28]. In simple ^{2}CF theory, the energy level spacing at the FQH states with $\nu^* = p$ is given by $\omega_{\mathrm{CF}} = e|B^*|/m^*c = (C/2p \pm 1)e^2/\epsilon l_0$ [3,14], 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

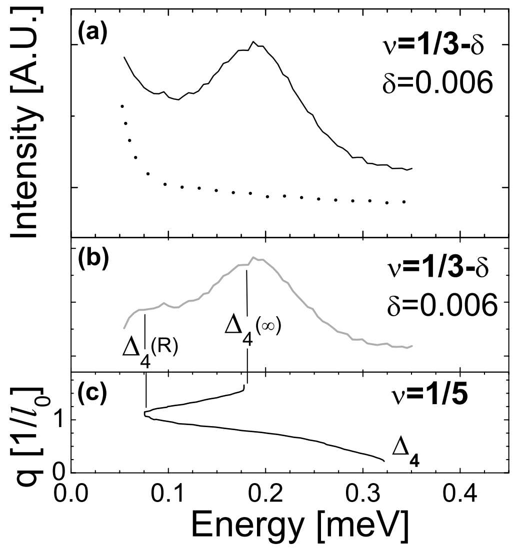

FIG. 4. (a) Spectra at $\nu = 1/3 - 0.006$ and $T \sim 50$ mK (solid line). Also shown is the laser tail from the negative energy side (dotted spectrum). (b) The obtained difference between the spectrum and the laser tail shown in (a). (c) Dispersions of spin-conserving excitations of ^{4}CFs at 1/5 [10], scaled to the density and magnetic field in (a) and multiplied by 0.6 to account for the effects of finite layer width, as discussed in the text.

of as a binding energy between the excited quasiparticle and quasihole [19], arising from residual CF interactions. This effect would be strongest at integer effective ^{2}CF filling factor, where screening would be weakest. The decrease in separation energy away from $\nu = 1/3$ is interpreted as a manifestation of increasing ^{2}CF screening of residual CF interactions, although it may also include differences in the scaling of the finite width correction at the roton [26].

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 ^{4}CF quasiparticles are seen both at and between the FQH effect filling factors. Coexisting with these modes throughout the $\phi = 4$ regime are spin-conserving ^{2}CF 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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