Observation of Multiple Magnetorotons in the Fractional Quantum Hall Effect

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Magnetorotons in the dispersions of collective gap excitation modes of fractional quantum Hall liquids are measured in resonant inelastic light scattering experiments. Two deep magnetoroton minima are observed at $\nu = 2/5$, while a single deep minimum is resolved at $\nu = 1/3$. The observations are the first evidence of multiple roton minima in gap excitations of the quantum liquids. The results support Chern-Simons and composite fermion calculations that predict multiple roton minima for states with $\nu > 1/3$.

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The states of the fractional quantum Hall effect (FQHE) are incompressible quantum liquids with behaviors dictated by fundamental interactions [1,2]. Condensation of 2D electron systems into quantum liquids is manifested in distinctive low-lying collective excitation modes built from neutral quasiparticle-quasihole pairs in the same Landau level [3–5]. The energy (ω) vs wave vector (q) dispersion relations of the modes display characteristic features such as magnetoroton minima in the dispersions of charge-density gap excitations. The roton minima, caused by excitonic bindings in the neutral pairs, occur at wave vectors $q \approx 1/l_0$, where $l_0 = \sqrt{\hbar c/eB}$ is the magnetic length. Analytical studies and numerical calculations have explored the low-lying collective modes of FQH liquids within composite fermion (CF) and Chern-Simons (CS) frameworks [6–11]. Experiments that probe these collective modes offer crucial tests of theories of the quantum liquid.

Resonant inelastic light scattering by low-lying charge-density and spin-density collective modes has been reported at filling factor $\nu = 1/3$ [12–14]. These experiments measure long wavelength modes and peaks in the density of states (DOS) due to critical points in the dispersions at magnetoroton minima. In more recent work we reported light scattering by modes at fractional Landau level fillings of $\nu = p/(2p + 1)$, (p = integer), within $1/3 \leq \nu \leq 2/3$ [15,16].

In this Letter we report resonant inelastic light scattering measurements of the low-lying charge-density excitations at filling factors $\nu = 2/5$ and $1/3$. The spectra are interpreted within a framework in which collective excitation modes are described by energy vs wave vector dispersion relations. The major consequence of weak residual disorder in the quantum Hall states is the activation of modes with wave vectors $ql_0 \gtrsim 1$ that are larger than the light scattering wave vector k [17,18]. Peaks in the spectra are assigned either to long wavelength modes, with $k = q$, or to peaks in the DOS such as those arising from the critical points at magnetorotons in the mode dispersions.

We find that spectra at $\nu = 2/5$ display significant differences from those at $\nu = 1/3$. At $\nu = 1/3$ there is a single deep magnetoroton minimum and at $\nu = 2/5$ we identify an additional roton minimum. There are also marked differences in the spectral line shapes of modes with $q \approx 0$ that are explained as another manifestation of the multiple roton structure at $\nu = 2/5$. To the best of our knowledge, these results are the first experimental evidence of multiple rotons in the dispersions of collective excitations of FQH states with $\nu > 1/3$.

The evidence of two rotons in the mode dispersion of the state with $\nu = 2/5$ supports key predictions of CS and CF theories of the FQH liquids [9,19–21]. The difference in roton structures of collective excitations in the states at $\nu = 2/5$ and $1/3$ can be visualized within the picture in which the FQHE is described as the integer QHE of composite fermions. In this picture, collective excitations of $\nu = 1/3$ and $\nu = 2/5$ states are conceived as excitations of *spinless* $\nu = 1$ and $\nu = 2$ integer quantum Hall states of CF's, respectively. The existence of roton minima in the dispersion of collective excitations can be understood from the insight on the structures of the wave functions in Landau levels. Magnetoroton minima are due to the attractive Coulomb interaction in a quasiparticle-quasihole pair of separation $x = ql_0^2$ [3,22]. This interaction is maximized when the overlap of the wave functions of ground and excited states is largest. The existence of multiple rotons naturally comes from multiple nodes in wave functions of higher Landau levels. We note that the dispersion of inter-Landau level excitations at $\nu = 1$, like the collective mode dispersion at $\nu = 1/3$, has a single roton [3]. On the other hand, the roton structure at $\nu = 2/5$ could be similar to that of inter-Landau level excitations at $\nu = 4$ (or *spinless* $\nu = 2$), which displays multiple roton minima [23].

We studied the high quality 2D electron system in single GaAs quantum wells (SQW) of widths $d = 250$–330 Å. Electron densities are in the range of $n = 2.4 \times 10^{10}$–1.2×10^{11} cm^{-2}. The low temperature and low field electron mobilities are $\mu \gtrsim 5 \times 10^6$ cm^2/V sec. Sample design was optimized for optical experiments. This design results in large parallel conductivity at fields of $\nu < 1$ that prevents measurement of activated magnetoresistivity. Samples were 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 obtained with photon energies ω_L close to the fundamental optical gap of the GaAs SQW's. The power density was kept below 10^{-4} W/cm^2. A conventional backscattering configuration was used at an angle of incidence θ [15]. The perpendicular component of magnetic field is $B = B_T \cos\theta$, where B_T is the total field. For $\theta = 30°$ and a laser wavelength of $\lambda_L \approx 815$ nm, the light scattering wave vector is $k = (2\omega_L/c)\sin\theta \approx 10^5$ cm^{-1} and $kl_0 \lesssim 0.1$.

Figures 1(a) and 2(a) show spectra at $\nu = 1/3$ and $\nu = 2/5$. The marked dependences of the intensities on ω_L are characteristic of resonant light scattering measurements. The peaks labeled SW are due to long wavelength spin wave excitations of the spin polarized 2D electron system [12–16]. There are three other peaks at $\nu = 1/3$ and four at $\nu = 2/5$. These peaks are interpreted as collective excitations of the FQH states because they show characteristic temperature and filling factor dependencies of the quantum fluids. Inelastic light scattering due to collective excitations in FQH states is observed only under extreme resonance enhancements of widths as small as 100 μeV. The resonance enhancements depend on the energies of the modes, implying that all the collective modes may not be measured in a single spectrum.

In Fig. 1(a) the sharp peak at the highest energy (0.92 meV) is the charge-density gap mode of the $\nu = 1/3$ state at long wavelengths [12–16]. The two bands at the lower energy are assigned to peaks in the DOS of charge-density excitations. Specific assignments of these bands are readily made by comparing the experimental results with the calculated dispersions shown in Fig. 1(b). The solid curve was scaled down, from the ideal 2D result [10], by a constant to facilitate the assignment of the observed modes. Solid squares indicate results of calculations that incorporate the effects of finite thickness of the 2D electron system [24]. The band at the lowest energy (0.46 meV) is assigned to the critical point at the deep magnetoron minimum in the dispersion of gap excitations. The band at 0.68 meV is interpreted as a peak in the DOS of modes with large wave vectors because for $ql_0 \gtrsim 2$ the dispersion is flat. These results suggest the existence of just *one* deep magnetoroton minimum at $\nu = 1/3$.

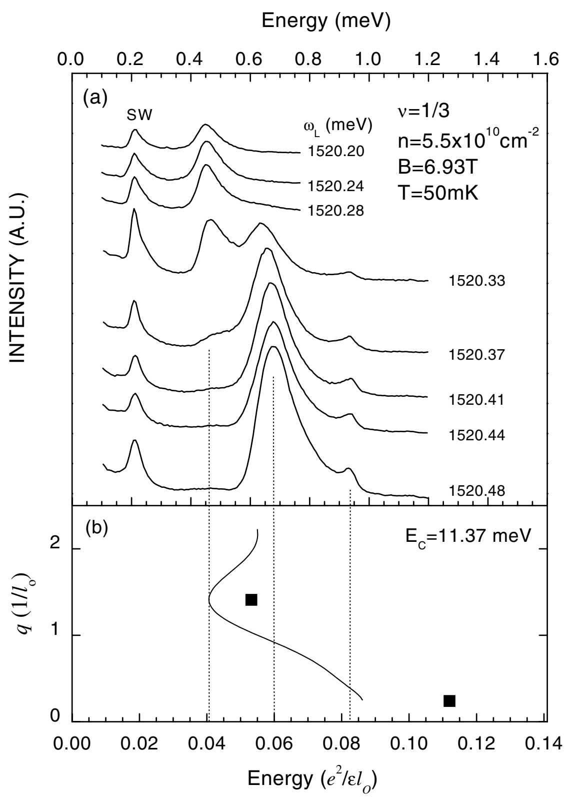

FIG. 1. (a) Resonant inelastic light scattering spectra at $\nu = 1/3$. SW denotes the long wavelength spin wave excitation at the Zeeman energy $E_Z = g\mu_B B_T$, where $g = 0.43 \pm 0.01$. Dotted lines indicate collective excitations of the FQH state. (b) The dispersion of collective excitations at $\nu = 1/3$. The solid curve was scaled down from the ideal 2D result [10] by a constant to help in assigning the observed modes. Solid squares indicate results of calculations that incorporate the effect of finite thickness [24].

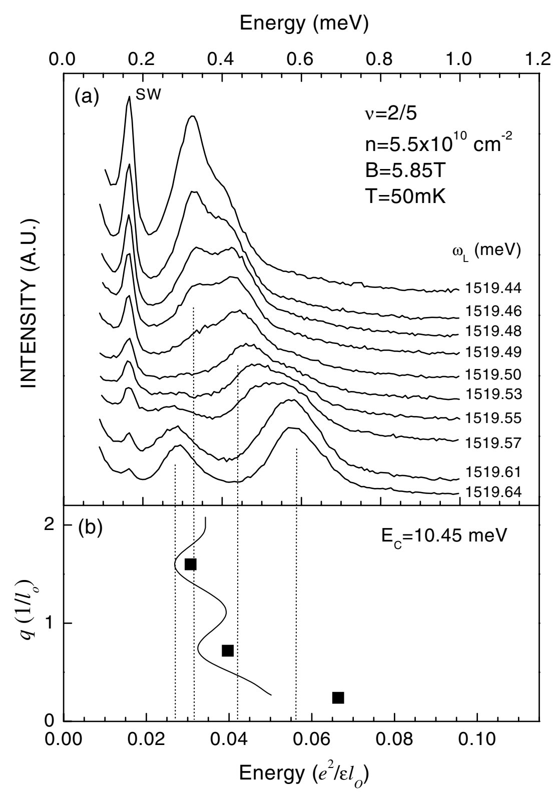

FIG. 2. (a) Resonant inelastic light scattering spectra at $\nu = 2/5$. Dotted lines denote collective excitations in the FQH state. (b) The dispersion of collective excitations at $\nu = 2/5$. The solid curve was scaled down from the ideal 2D result [10] by a constant, as in Fig. 1(b). Solid squares indicate results of calculations that incorporate the effect of finite thickness [24].

In Fig. 2(a) the highest energy band is also interpreted as the long wavelength gap mode of the $\nu = 2/5$ state. The three bands at lower energies are assigned to *three* critical points in the dispersion of the modes. A comparison of spectra in Figs. 1(a) and 2(a) indicates that at $\nu = 2/5$ there are additional critical points at wave vectors $ql_0 \gtrsim 1$. The result implies that in the dispersion of gap excitations at $\nu = 2/5$ there is one more magnetoroton minimum. Specific assignments are made here also with calculated dispersions shown in Fig. 2(b). Two lower energy modes at 0.28 and 0.33 meV are assigned to two roton minima in the dispersion. The mode at 0.44 meV could be interpreted as the local maximun between two rotons or the $q \to \infty$ mode. We could not make a more specific assignment because observations of critical points of the DOS determine mode energies but do not reveal mode wave vectors.

We note that the magnetoroton modes are not always stronger than spectral features assigned to other modes, while current theory predicts that spectral weight is largest for modes close to rotons [25]. Resonant inelastic light scattering involves complex interactions in the quantum liquids. It is likely that measured light scattering intensities may not be deduced in a simple way from spectral weights of dynamic structure factors.

The dispersions of collective gap excitations are key predictions of theories of quantum liquids in the FQHE. The results in Figs. 1 and 2 show that inelastic light scattering experiments provide comprehensive characterizations of collective gap modes that are crucial tests of these theories. The calculations in Figs. 1(b) and 2(b), marked as solid squares, are carried out within a CF framework with rigorous treatment of the finite widths and geometries of SQW samples [10,24]. The evaluations that incorporate the finite width of the 2D layer show good agreement (typically better than 20%) with experiments. Such agreement is significant because the uncertainty in the evaluation of the finite width corrections can be as large as 20% [10,26].

The spectra in Figs. 1(a) and 2(a) reveal marked differences between long wavelength ($q \approx 0$) modes at $\nu = 1/3$ and $2/5$. The band of the $q \approx 0$ mode at $\nu = 1/3$ is rather sharp (FWHM < 0.05 meV). On the other hand, the band of the long wavelength mode at $\nu = 2/5$ displays a much broader line shape with a FWHM of about 0.2 meV. The difference suggests a link to the different magnetoroton structures in the dispersions of the gap modes.

At $\nu = 1/3$ the energy of the $q \approx 0$ mode (0.92 meV) is exactly twice the energy of the magnetoroton minimum (0.46 meV). This observation supports the early conjecture of Girvin and co-workers that the lowest long wavelength charge-density mode is a two-roton bound state [5]. A two-roton bound state occurs in numerical studies of finite systems [25], and was recently confirmed by CF calculations [11]. Our measurements suggest that the binding energy of the two-roton state could be relatively small, probably less than the width of the roton band in Fig. 1(a). The two-roton character of the long wavelength modes is further supported by the results in Fig. 3, where measured $q \approx 0$ mode energies are twice the roton energies for densities in the range of $n = 2.4 \times 10^{10}$–1.2×10^{11} cm^{-2} [27]. Numerical studies show that the $q \approx 0$ mode energy of single quasiparticle-quasihole pair excitation, as shown in Fig. 1(b), is substantially higher than twice the roton energy [10].

Current theory is not very specific about the character of the $q \approx 0$ mode at $\nu = 2/5$. In the data of Fig. 2(a) the $q \approx 0$ mode energy occurs in the range of twice the roton energies. This suggests that the $q \approx 0$ mode here could also be related to excitations built of two-roton states. However, the existence of multiple rotons adds more possible combinations of multiple roton states for $q \approx 0$ excitation, which may account for the broader linewidth at $\nu = 2/5$. This is an aspect of collective excitations of states with $\nu > 1/3$ that requires further experimental and theoretical study.

We also consider trends in the energies of the charge-density excitation gap of the quantum liquids in FQH states. Figure 4 summarizes results for states with $\nu = 1/3$, $2/5$, and $3/7$. In this figure we include the single excitation mode observed at $\nu = 3/7$ (at a very low energy 0.08 meV) [16]. Given the very low energy of this mode, we tentatively assign it to a magnetoroton mode of the $3/7$ state. However, we also note the possibility that this mode could be associated with the roton of spin excitations of CF's as suggested in a recent theoretical study [28]. If the mode at $\nu = 3/7$ is a roton in the charge-density excitation gap, this figure reveals that the lowest collective excitation gaps represented by roton excitations decrease quite rapidly as the filling factor approaches $1/2$. This is consistent with the fact that we could not observe any collective excitation mode in the fractional states in the range

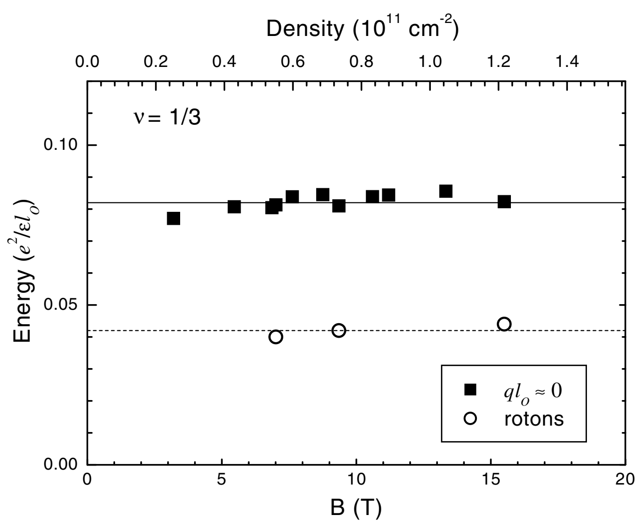

FIG. 3. Collective gap excitations at $\nu = 1/3$ from samples with various densities (n) within $2.4 \times 10^{10} \leq n \leq 1.2 \times 10^{11}$ cm^{-2}. Collective gap excitation energies are measured in terms of the Coulomb energy, $E_C = e^2/\epsilon l_0$.

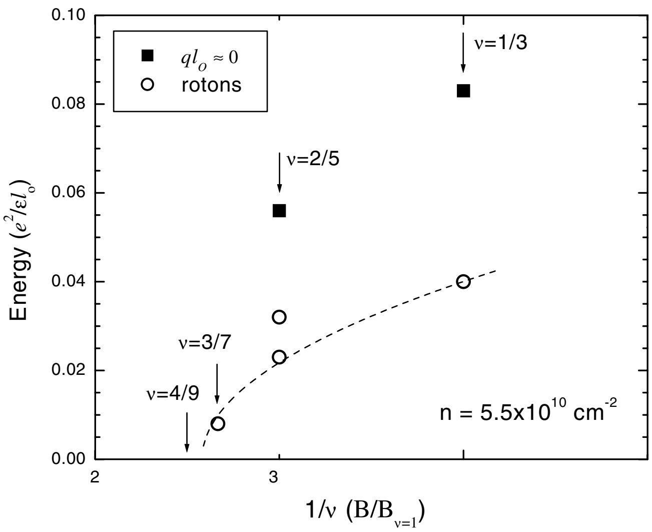

FIG. 4. Magnetoroton energies at FQH states $\nu = 1/3$, $2/5$, and $3/7$. The dashed line is a guide for the eye.

$4/9 \leq \nu \leq 1/2$. Such rapid collapse of the gap in the vicinity of $\nu = 1/2$ is consistent with the results of activation gap measurements [29,30] and theoretical predictions [31]. The collapse of the gap is also linked to broadening of electronic states by disorder and/or to finite thickness effects [29–31].

In summary, we measured the energies of critical points in dispersions of collective gap excitations of the FQH states at $\nu = 1/3$ and $2/5$. These experiments are enabled by the breakdown of wave vector conservation in resonant inelastic light scattering processes due to weak residual disorder. Our measurements provide evidence of two magnetoroton minima in the dispersion of gap modes at $\nu = 2/5$ and of a single minimum at $\nu = 1/3$. The experiments confirm key predictions of Chern-Simons and composite fermion theories. Measured energies of critical points and of long wavelength excitations also show good agreement with current theoretical evaluations of the FQH state collective excitations based on the composite fermion framework.

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