Inelastic Light Scattering by Gap Excitations of Fractional Quantum Hall States at $1/3 \leq \nu \leq 2/3$

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(Received 2 August 1999)

We report observations of collective gap excitations of the fractional quantum Hall (FQH) states at filling factors $\nu = p/(2p + 1)$ ($p =$ integer), for $1/3 \leq \nu \leq 2/3$, by inelastic light scattering. The collective gap energies at $\nu = 1/3$, $2/5$, and $3/7$ show a drastic decrease as the value $\nu = 1/2$ is approached. These energies and the one at $\nu = 3/5$ display the linear scaling with $(e^2/\epsilon l_0)/|2p + 1|$ that is characteristic of composite fermions in Chern-Simons gauge fields. In a narrow range of ν centered at $1/2$, where the FQH gaps collapse, we observe a new excitation mode which exists only at temperatures below 150 mK.

PACS numbers: 73.40.Hm, 73.20.Mf, 78.30.–j

The ground states of 2D electron systems in the regime of the fractional quantum Hall effect (FQHE) are described as incompressible quantum liquids with behaviors dictated by fundamental interactions [1,2]. Strong electron correlation in the lowest Landau level in the FQHE at filling factors $\nu = p/(2p + 1)$ ($p =$ integer) is often described in terms of composite fermions (CF). These are weakly interacting quasiparticles in which two flux quanta are attached to each electron [3]. CF quasiparticles move in effective perpendicular magnetic fields $B_{\mathrm{eff}} = B - B_{1/2}$, where B is the perpendicular component of applied field and $B_{1/2}$ is the field at $\nu = 1/2$. At $\nu = 1/2$ composite fermions experience vanishing B_{eff} and the low energy dynamics of CF quasiparticles resembles that of a liquid of electrons in zero magnetic field [4,5].

The incompressible FQH liquids have collective gap modes that are charge-density excitations associated with neutral quasiparticle-quasihole pairs [6–8]. The modes have wave vector dispersions determined by interactions between the quasiparticles. Characteristic features due to interactions are the rotons, or magnetorotons, at wave vectors $q \approx 1/l_0$, where $l_0 = \sqrt{\hbar c/eB}$ is the magnetic length. The energies of noninteracting quasiparticle-quasihole pairs are the $q \rightarrow \infty$ gap excitation energies, which are determined by thermally activated resistivity [9,10]. The scaling of activation gap energies with filling factor is consistent with a picture in which the FQHE arises from the low-energy dynamics of CF quasiparticles moving in a B_{eff}.

The composite fermion framework has been employed in extensive theoretical investigations of the FQH liquid. Analytical studies and numerical evaluations have explored the frequency and wave vector dependence of response functions and collective modes of the lowest Landau level FQHE [11–14]. These results offer detailed predictions for the energies and wave vector dispersions of collective gap excitations. Experimental studies of dispersive collective excitations could test predictions of CF and Chern-Simons formulations and uncover novel physics of the FQH liquid.

Inelastic light scattering (ILS) methods offer access to collective excitations of electrons in the FQH regime. Light scattering studies of gap modes of the incompressible liquid have been reported at $\nu = 1/3$ [15–17]. The initial work determined the gap energy in the long wavelength ($q \approx 0$) limit [15]. In subsequent studies a mode at lower energy was assigned to the critical point at the magnetoroton minimum in the mode dispersion [16,17]. ILS by rotons with relatively large wave vectors ($q \approx 10^6$ cm^{-1}) was explained by loss of translational symmetry due to residual disorder. Evidence of magnetoroton gap excitations is also found in absorption of ballistic acoustic phonons [18]. ILS by collective gap excitations of FQH states other than $\nu = 1/3$ remain largely unexplored.

In this Letter we report the first inelastic light scattering study of collective gap excitations of several FQH states at filling factors $\nu = p/(2p + 1)$, ($p =$ integer), within $1/3 \leq \nu \leq 2/3$. Nonzero scattering wave vectors $ql_0 \approx 0.1$ enable the acquisition of light scattering spectra at relatively low electron densities, $n \approx 5 \times 10^{10}$ cm^{-2}, even in the presence of intense luminescence. We note that the dynamical structure factor, the function that enters in conventional expressions for the scattering cross sections, is $S(q, \omega) \sim n(ql_0)^4$ for $q \rightarrow 0$, a rule that works in favor of lower density systems that have larger values of $l_0 \sim 1/\sqrt{n}$.

Collective gap modes of incompressible states with marked temperature and magnetic field dependence are observed at fractional fillings $\nu = 1/3$, $2/5$, $3/7$, $2/3$, and $3/5$. The gap energies at $\nu = 1/3$, $2/5$, and $3/7$ decrease drastically as the filling factor $\nu = 1/2$ is approached, and suggest a collapse of the collective excitation gap before ν reaches $1/2$. In this relatively small range of ν, where the gap of the liquid has collapsed, we uncover a new collective mode that has a marked temperature dependence for $T \leq 150$ mK. The mode energy has a dependence on total magnetic field that suggests a link to the spin degree of freedom of CF quasiparticles.

We studied the high quality 2D electron system in single GaAs quantum wells (SQW) of widths $d = 330$ Å. We present results obtained in a sample that has $n = 5.4 \times 10^{10}$ cm^{-2}. The low temperature mobility of $\mu = 7.2 \times 10^6$ cm^2/V s is remarkably high considering its low density. 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 were as low as 45 mK. Light scattering spectra were excited with the emission of an external cavity tunable semiconductor diode laser. The power density was kept below 10^{-4} W/cm^2 to prevent heating of the electron gas. Incident photon energies ω_L were tuned close to the fundamental optical gap of the GaAs SQW to resonantly enhance the light scattering intensities. The backscattering geometry shown in Fig. 1(a) was used. For $\theta = 30°$ and a laser wavelength of $\lambda_L \approx 815$ nm the light scattering vector is $q = (4\pi/\lambda_L)\sin\theta \approx 8 \times 10^4$ cm^{-1}, which gives $ql_0 \lesssim 0.1$.

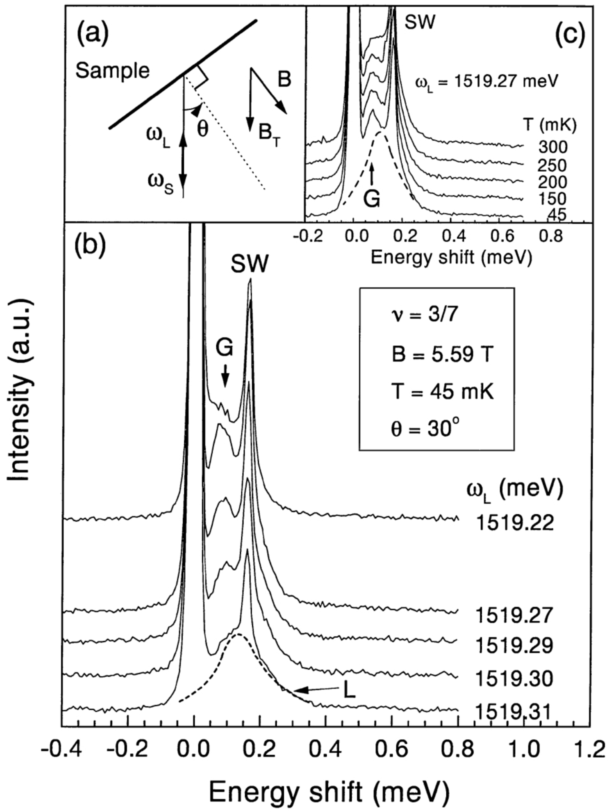

FIG. 1. (a) Schematic representation of the experimental geometry. (b) Resonant inelastic light scattering spectra at $\nu = 3/7$. SW and G denote the long wavelength spin wave and the collective gap excitations, respectively. The spin wave excitation is at the Zeeman energy $E_Z = g\mu_B B_T$, where $g = 0.43 \pm 0.01$. The dashed line, which is an approximate guide to the eye, indicates the luminescence background. (c) Temperature dependence of the light scattering spectra at $\nu = 3/7$.

Figure 1(b) shows resonant ILS spectra at $\nu = 3/7$ and temperature $T = 45$ mK. ω_L is varied to tune the resonance enhancement and to distinguish light scattering peaks from luminescence bands [15]. Sharp peaks (FWHM ≤ 0.06 meV) labeled G and SW are due to ILS by excitations of the 2D electron system. Peak G, at 0.08 meV, occurs only in a small interval $\Delta B \leq 0.1$ T centered at the magnetic field of $\nu = 3/7$, and has the marked temperature dependence shown in Fig. 1(c). Such pronounced temperature and magnetic field dependences associate this peak with a collective excitation of the FQH state. The sharp peak labeled SW is observed over a very wide range of magnetic field. Its energy is proportional to the total magnetic field B_T and is close to the Zeeman energy E_Z of electrons in GaAs. For this reason we assign it to the long wavelength ($q \approx 0$) spin wave (SW) excitation [6]. The broader bands, FWHM ≈ 0.2 meV, near or under light scattering peaks, are luminescence due to optical transitions of the GaAs SQW. The luminescence spectrum in this range of photon energies is shown as a dashed line, and in ILS plots the luminescence band shifts as ω_L is changed.

Figure 2 shows ILS spectra of low-energy collective excitations measured at several FQH states. In addition to a spectrum at $\nu = 3/7$, we show spectra at $\nu = 1/3$, $2/5$, $3/5$, and $2/3$. While light scattering intensities of the mode measured at $\nu = 1/3$ persist to temperatures close to 1 K, intensities measured at $\nu = 2/5$, $3/7$, $3/5$, and $2/3$ have more dramatic temperature dependences qualitatively similar to that shown in Fig. 1(c). Such dramatic temperature dependences are typical of FQHE states with $|p| > 1$ [9,10]. The narrow widths (FWHM ≤ 0.06 meV) of the excitation modes indicate that wave vector is conserved in these spectra, and that we observe long wavelength modes ($ql_0 < 0.1$). ILS spectra measured with breakdown of wave vector conservation, such as those due to magnetorotons, typically have broader spectral shapes (FWHM ≥ 0.15 meV) [16].

The modes shown in Figs. 1 and 2 are seen only in narrow ranges of magnetic field centered at the field of the respective FQH states. The pronounced dependences on B and T identify the modes as gap excitations of the incompressible states. The energies of these long wavelength gap modes are plotted as a function of magnetic field in Fig. 3. The energies at $\nu = 1/3$, $2/5$, and $3/7$ decrease drastically as the magnetic field B approaches $\nu = 1/2$. These results suggest that incompressible FQH states with filling factors very close to $1/2$ may be unstable. Trends towards instabilities of the FQHE states before reaching the compressible state at $\nu = 1/2$ are also found in measurements of activation gaps [9,10]. At $\nu = 1/3$, the measured $q \approx 0$ gap energy in the unit of Coulomb energy ($E_c = e^2/\epsilon l_0$, ϵ is the dielectric constant) is about twice the activation gap energies from Ref. [9]. At higher fractions, the ratio of the $q \approx 0$ gap to the activation gap from Ref. [9] gets smaller, suggesting that $q \approx 0$ gaps measured from our

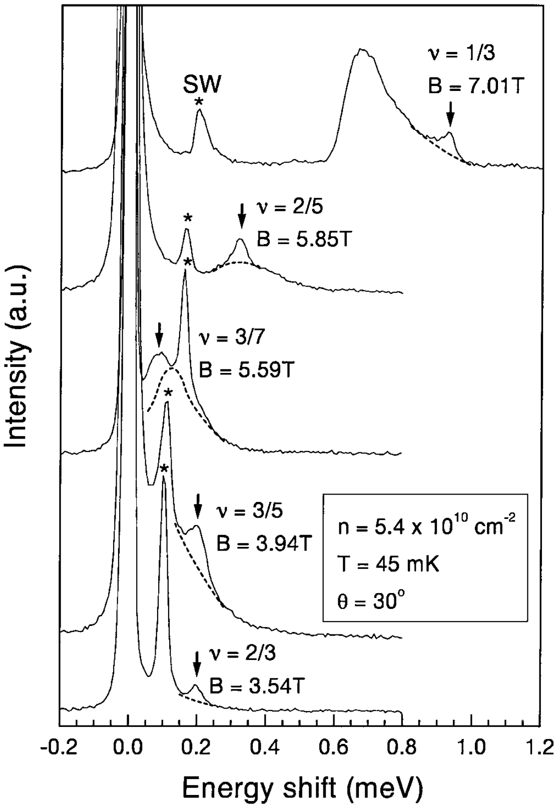

FIG. 2. Collective gap excitations in the FQH states with various fractional filling factors within $1/3 \leq \nu \leq 2/3$. Arrows (↓) indicate the gap excitation and SW (*) the long wavelength spin wave excitation. The spectra shown are arbitrarily scaled, and the intensity of a given peak depends strongly on resonance conditions as shown in Fig. 1(b).

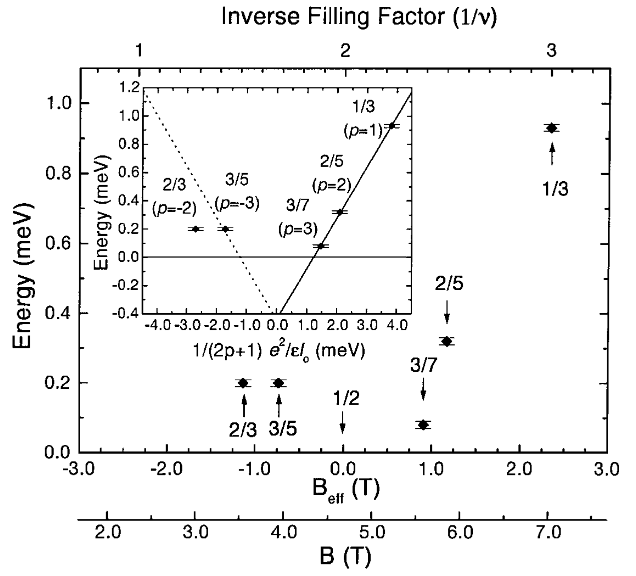

FIG. 3. The energies of long wavelength FQH state gap. Inset: The gap energy vs $(e^2/\epsilon l_0)/(2p + 1)$. The solid line indicates a linear fit of gap energies at $\nu = 1/3$, $2/5$, and $3/7$ to Eq. (1) and the dotted line a symmetric image of the linear fit around $\nu = 1/2$.

sample vanish more rapidly as ν approaches $1/2$. However, it should be noted that the electron density in our sample is about 2–4 times lower than in Ref. [9].

To interpret these results we recall that the dependence of activation gaps on ν has been considered within the CF framework [4,19]. The gap energy at $\nu = p/(2p + 1)$ is written as $\Delta(\nu) \sim \frac{1}{|2p+1|}E_c$. The scaling with $\frac{1}{|2p+1|}E_c$ is characteristic of CF quasiparticles moving in effective magnetic fields that incorporate Chern-Simons gauge fields [4]. This relation, however, predicts a collapse of the FQH gap exactly at $\nu = 1/2$. The collapse of the FQH gap before the system reaches $\nu = 1/2$ was attributed either to the broadening of the fermionic states due to residual disorder [9,10] or to the finite thickness of the 2D electron system [20]. The measured activation gaps are described by the empirical equation

$$\Delta(\nu) = \frac{C}{|2p + 1|}\frac{e^2}{\epsilon l_0} - \Gamma, \tag{1}$$

where Γ represents the effect of disorder or finite width of 2D electron systems.

The inset of Fig. 3 shows the results of a fit of the measured long wavelength gap modes with Eq. (1), which reveals that the long wavelength gap energies of FQH states at $\nu = 1/3$, $2/5$, $3/7$, and $3/5$ show an excellent scaling with $\frac{1}{|2p+1|}E_c$. It is intriguing that the measured gap energy at $\nu = 2/3$ not only shows a large deviation from the dotted line but has a value close to the one at $\nu = 3/5$.

The observation that the long wavelength gap excitation energies at $\nu = 1/3$, $2/5$, $3/7$, and $3/5$ are described by Eq. (1) is significant because scaling with $\frac{1}{|2p+1|}E_c$ was introduced to interpret activation gap energies (the collective gap modes in the $q \rightarrow \infty$ limit) [4,19,20]. At $\nu = 1/3$ the $q \approx 0$ gap excitation has been described as a two-roton [8,16]. However, the character of the long wavelength gap mode at other FQH states remains largely unknown. The results in Fig. 3 imply that the gap energies in the $q \approx 0$ and $q \rightarrow \infty$ limits may be linked, as proposed in Refs. [4,12].

The results in Fig. 3 also highlight the collapse of the FQH gaps at filling factors in the range $4/9 \lesssim \nu \lesssim 4/7$, similar to the one first observed in magnetotransport. We believe it occurs here at smaller values of $|p|$ because of the lower electron density in our sample. This implies that in a narrow range of filling factors centered at $\nu = 1/2$ the long wavelength gap mode is unstable and a FQH liquid should not exist. ILS spectra obtained in this range of ν reveal a new collective excitation mode with a remarkable temperature dependence, as shown in Fig. 4 for $\nu = 0.54$.

The spectra in Fig. 4 display a sharp ILS peak (FWHM $\approx$ 0.06 meV) that has a temperature dependence for $T \leq 100$ mK and disappears at temperatures $T \geq 150$ mK. Such temperature dependence is extraordinary, particularly when detected in ILS measurements.

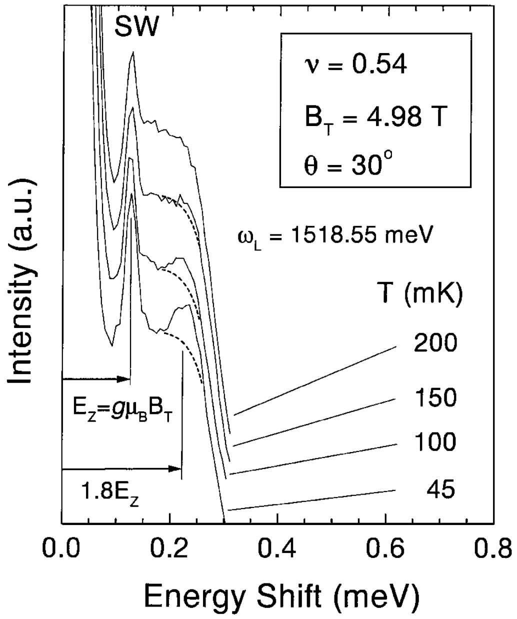

FIG. 4. Temperature dependence of light scattering at $\nu = 0.54$. Dashed lines denote luminescence backgrounds.

This excitation is observed at all investigated magnetic fields within the range in which the FQH liquid is expected to be unstable. In fact, the range of ν to observe the new excitation mode ($0.43 \le \nu \le 0.57$) coincides with the range where the gap collapses in the linear fit in the inset of Fig. 3 ($0.44 \le \nu \le 0.56$). In this range of filling factors, the mode energy displays a dependence on total magnetic field B_T that may be represented as $1.8E_Z$. We note that an energy which is proportional to total magnetic field is characteristic of an excitation mode associated with the spin degree of freedom.

Given that the excitation mode appears close to $\nu = 1/2$, when the FQH states give way to a liquid of CF quasiparticles, we may conjecture that the mode is characteristic of a novel ground state. This state emerges at very low temperatures $T \le 100$ mK, and could be caused by interactions in the CF liquid. We may conceive a scenario in which a mode at energy $1.8E_Z$ is constructed as a collective excitation which involves two spin waves. While a single $q \approx 0$ spin wave excitation is required to have energy E_Z by Larmor's theorem [6], the energy shift of the second-order spin excitation from $2E_Z$ could be a manifestation of interactions among CF quasiparticles. We note that there is extensive theoretical literature that considers novel correlation effects at $\nu = 1/2$ as well as experimental reports of anomalies at $\nu = 1/2$ [21,22]. Our results suggest that the inelastic light scattering method could offer an experimental venue to explore liquid states of CF quasiparticles that emerge near $\nu = 1/2$.

In summary, we measured collective gap excitations of FQH states at filling factors $1/3 \le \nu \le 2/3$ by inelastic light scattering. The narrow linewidths suggest wave vector conservation at values $ql_0 \approx 0.1$. The results indicate an instability of the FQH states in the vicinity of $\nu = 1/2$, similar to those observed in transport measurements. In a range of ν near 1/2, we found a new excitation mode that exists only at temperatures below 150 mK. Further low temperature studies could reveal fundamental interactions within the liquid of CF quasiparticles at filling factors close to $\nu = 1/2$.

We are grateful to B. I. Halperin, J. K. Jain, S. H. Simon, and H. L. Stormer for many discussions. We are also grateful to K. W. Baldwin for magnetotransport measurements.

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