Observation of Collective Excitations in the Fractional Quantum Hall Effect

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(Received 27 January 1993)

A long wavelength, low-energy excitation of the fractional quantum Hall state at $\nu=\frac{1}{3}$ has been observed by inelastic light scattering. The mode appears as a very sharp peak with marked temperature and magnetic field dependence. Its energy is consistent with theoretical predictions for the collective gap excitations of the incompressible quantum fluid. Spectra interpreted as $q=0$ collective spin-wave excitations also display the strong dependence on field and temperature associated with the fractional quantum Hall state.

PACS numbers: 73.40.Hm, 73.20.Dx, 73.20.Mf, 78.30.Fs

The 2D electron gas in the incompressible states of the fractional quantum Hall effect (FQHE) should exhibit new collective charge-density *intra*-Landau-level excitations which, in the absence of kinetic energy changes, are entirely due to electron-electron interactions in the condensate [1-3]. The excitations are associated with fractionally charged quasiparticles that obey fractional statistics [1-5]. The FQHE states should also have collective spin-wave excitations associated with changes of the spin degree of freedom in the lowest Landau level [6]. In the spin-polarized states with $\nu \lesssim 1$ the $q=0$ spin wave is required to be at the Zeeman energy by Larmor's theorem. The emergence of low-lying charge-density modes, or "gap excitations," is one of the most significant new behaviors in the fractional quantum Hall effect. These excitations display characteristic "magnetoroton" minima and the large wave-vector limit, $q \rightarrow \infty$, represents the infinitely separated quasiparticle-quasihole pairs that are associated with the energy gaps of the incompressible quantum fluid [1-7].

Gaps of the FQHE are obtained in activated magnetotransport experiments, where residual-disorder effects could be important even in the highest mobility systems [8]. Intrinsic [9,10] and extrinsic [11] photoluminescence spectra reveal anomalies in the FQHE regime. However, the quantitative interpretation of photoluminescence requires a detailed understanding of the complex dynamical response of the electron gas in optical recombination processes. The direct measurement of charge-density gap excitations in the FQHE states has not been reported. Optical experiments could access the long wavelength modes. However, at small wave vectors $q \ll 1/l_0$, where $l_0=(\hbar c/eB)^{1/2}$ is the magnetic length, intra-Landau-level excitations have vanishing oscillator strength and optical absorption methods are not expected to be effective [3].

The structure of the $q=0$ collective gap excitation of the FQHE is intriguing. Girvin, MacDonald, and Platzman [3] speculated that two gap excitations each near the magnetoroton minimum, at wave vectors $\sim 1/l_0$, could pair to produce a two-roton bound state with $q=0$. The $q=0$ mode has also been discussed within the Landau-Ginzburg framework [12,13]. It was proposed that it consists of two dipole excitations in a configuration that has a quadrupole moment but no net dipole moment [13]. These considerations suggest to us that inelastic light scattering, which as a two-photon process is sensitive to excitations that lack an electric dipole moment, might be the optical method to observe the gap excitations of the FQHE.

In this Letter we report observations of collective excitations in the FQHE by inelastic light scattering. In the state with $\nu=\frac{1}{3}$ a sharp low-energy peak is interpreted as a $q=0$ collective gap excitation of the incompressible state. Its spectra have the strong dependences on temperature and magnetic field that are characteristic of the FQHE [14]: The peak is observed only at temperatures $T \lesssim 1$ K and within the narrow field range $\Delta B=0.5$ T centered at $\nu=\frac{1}{3}$. The mode occurs at energy $\Delta_0 E_c$, where $E_c=e^2/\varepsilon_0 l_0$ and ε_0 is the dielectric constant of the semiconductor. The measured energy $\Delta_0=0.084$ is in the range of theoretical predictions for $q=0$ gap excitations. The observation of this mode is direct evidence that the incompressible quantum fluid of the FQHE supports well-defined charge-density intra-Landau-level excitations.

Other long wavelength collective excitations are also measured. In the energy range of intra-Landau-level excitations a sharp peak at the energy of the Zeeman splitting of the free electrons is explained as the $q=0$ spin-wave excitation. We also observe *inter*-Landau-level excitations in which electrons from the condensate are promoted to the next higher Landau level. Two modes occur in these spectra. One at the cyclotron energy ω_c corresponds to the $q=0$ magnetoplasmon [15]. The other which is blueshifted from ω_c by an energy nearly equal to Δ_0 could be explained as a higher-order inter-Landau-level excitation also involving a $q=0$ gap excitation [16]. In an alternate interpretation, this peak is explained as a $q=0$ spin-flip inter-Landau-level excitation, where the blueshift is due to enhanced exchange in the spin-polarized state [17,18]. The light scattering intensities of the spin-wave and blueshifted inter-Landau modes have the marked temperature and magnetic field dependence displayed by the $q=0$ gap excitation.

This work is carried out in asymmetric GaAs-$Al_xGa_{1-x}As$ single quantum wells with $x \simeq 0.1$. The growth sequence starts with a 0.5 μm GaAs "buffer" layer and 200 periods of a superlattice having 30 Å of GaAs and 100 Å of $Al_xGa_{1-x}As$. This is followed by the 250 Å GaAs quantum well, the 1700 Å $Al_xGa_{1-x}As$ top barrier layer, and a 100 Å GaAs layer. The Si doping in the top barrier layer is set back at 700 Å from the GaAs quantum well. The samples were designed to incorporate "overdoping" of donors. In this manner, free charge remaining in the doped layer acts to screen and smooth the disorder potential due to ionized impurities. These samples show low temperature electron mobilities in excess of 3×10^6 cm^2/V sec. They also have very narrow (FWHM <0.2 meV) intrinsic optical emission peaks in the FQHE regime, considerably sharper than those previously reported in quantum wells [9].

Because of parallel conduction under illumination, a consequence of sample design, magnetoresistance oscillations could not be measured for $\nu<1$ [19]. For this reason, the states of the FQHE were characterized by well-known optical anomalies of the intrinsic photoluminescence intensities [9]. An example of the anomaly at $\nu=\frac{1}{3}$ is shown in Fig. 1. The peaks labeled L_0 and L_0' are intrinsic photoluminescence doublets. They are sharper than those in Ref. [9], but otherwise show similar temperature and field dependences. The field of the FQHE state with $\nu=\frac{1}{3}$ is taken as that of the maximum intensity of L_0 and minimum of L_0'. At incident powers smaller than 10^{-2} W/cm^2 this determination is in agreement with the magnetotransport measurement of $\nu=1$.

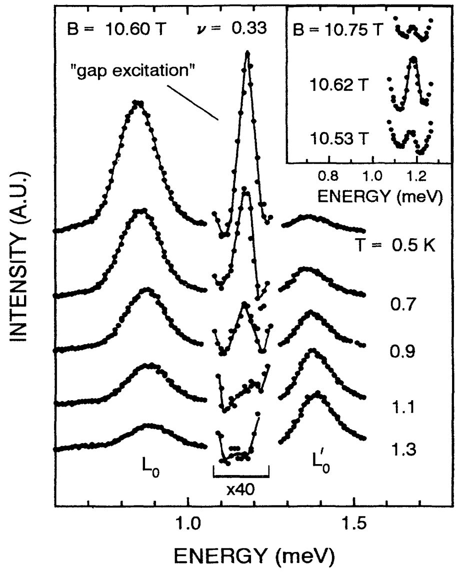

FIG. 1. Temperature dependence of inelastic light scattering spectra of a low-lying excitation of the FQHE at $\nu=\frac{1}{3}$. The single quantum well has density $n=8.5\times10^{10}$ cm^{-2}. The inset shows the B dependence of the 0.5 K spectra. The light scattering peak, labeled "gap excitation," is interpreted as a $q=0$ collective gap excitation. The bands labeled L_0 and L_0' comprise the characteristic doublets of intrinsic photoluminescence. The temperature dependence of the L_0 and L_0' intensities is due to the optical anomaly at $\nu=\frac{1}{3}$.

A ^{3}He cryostat with silica windows for optical access was used in conjunction with a superconducting magnet. Spectra were excited by the linearly polarized emission of a tunable dye laser. The photon energies are resonant with the sharp ($\sim$0.2 meV) optical transitions of the GaAs quantum well. Spectra of the 2D electron gas were excited with incident power densities of about 10^{-4} W/cm^2 and recorded with multichannel detection. The spectral resolution of 0.02 meV$\equiv$0.16 cm^{-1} is due to pixel size in the charge-coupled-device camera (20 μm $\equiv$0.008 meV), to the FWHM of the laser line (0.01 meV), and to monochromator slit width (40 μm). We consider here the sharpest inelastic light scattering peaks with FWHM$\lesssim$0.04 meV. The extremely narrow widths, consistent with the high electron mobility, identify the peaks as excitations of the free electrons. Interpretations based on transitions of electrons weakly bound to impurities are ruled out because, due to inhomogeneous broadening, they have much wider spectral features [20]. The conventional backscattering geometry allows for a small in-plane component $k\lesssim10^4$ cm^{-1} of the light scattering wave vector. Under wave-vector conservation long wavelength excitations with $q=k\ll 1/l_0\approx0$ are active.

The sharp peaks at 1.18 meV in Fig. 1 and 0.26 meV in Fig. 2 are due to inelastic light scattering by low-lying

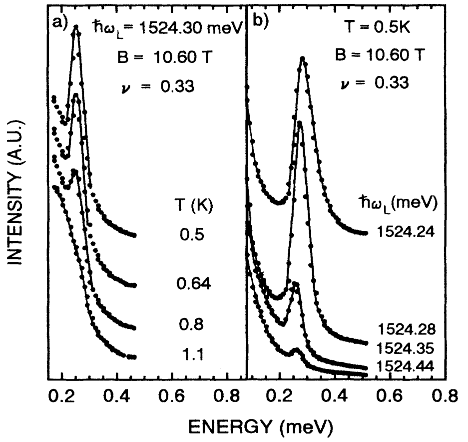

FIG. 2. Inelastic light scattering spectra of a low-lying excitation at $\nu=\frac{1}{3}$. The sample is the same as in Fig. 1. The sharp peak is identified as the $q=0$ spin-wave excitation. The background is due to L_0 luminescence. (a) Temperature dependence. (b) Dependence on incident photon energy $\hbar\omega_L$, which displays the large resonant enhancement close to the energy of L_0.

($\omega \ll \omega_c$) excitations. The sharpness of the peaks indicates that the wave vector is conserved ($k = q \sim 0$). If this were not the case, much larger widths, due to mode densities of states and residual disorder [18], would be observed. The intensities have the striking temperature dependence shown in the figures. We also find a marked dependence on magnetic field in which the two modes are observed only in the small interval $\Delta B \simeq 0.5$ T near $\nu = \frac{1}{3}$. Such field dependence is shown in the inset to Fig. 1 for the mode at 1.18 meV.

The temperature and magnetic field dependences of the low-lying excitations are characteristic of the fractional quantum Hall effect [8,14]. They indicate that the sharp peaks in Figs. 1 and 2 are due to long wavelength intra-Landau-level excitations in the FQHE state at $\nu = \frac{1}{3}$. The peak at 1.18 meV is interpreted as the $q = 0$ gap excitation of the incompressible state. We show below that calculations of gap excitations are in agreement with the measured energy. The peak at 0.26 meV is assigned to the $q = 0$ collective spin wave in the lowest Landau level because its energy can be understood as a Zeeman splitting $E_Z = g\mu_B B$ with $g = 0.43$. This value of g factor is close to those reported for the 2D electron gas in GaAs heterostructures [21].

Figure 3 shows light scattering spectra in the energy range of inter-Landau-level and intersubband excitations. The sharp peak (FWHM$\simeq$0.02 meV) labeled MP in spectrum a is a $q = 0$ magnetoplasmon at energy ω_c with $m^* = 0.0704 m_0$. In spectrum b the peak at $\omega_c + \delta$ is also an inter-Landau-level excitation because its energy tracks ω_c with changes of magnetic field. The sharp peak labeled CDE is the $q = 0$ charge-density intersubband excitation. The broader bands could be due to large wave-vector excitations, with $q \gg k$, that are made active by residual disorder [18]. The intensities of the blueshifted inter-Landau mode, at $\omega_c + \delta$, and the broader features display strong temperature and magnetic field dependences similar to that of intra-Landau-level excitations. In contrast, the intensities of MP and CDE excitations are observed over a wide magnetic field range and have weak temperature dependence for $T \lesssim 2$ K.

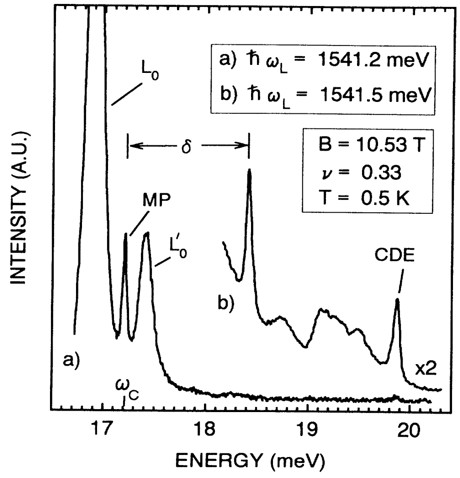

FIG. 3. Inelastic light scattering spectra of inter-Landau-level intersubband excitations. The sample is the same as in Fig. 1. Spectrum a: The sharp peak MP is a $q = 0$ magnetoplasmon at ω_c. Spectrum b: The sharp peak at $\omega_c + \delta$ is an inter-Landau-level excitation and the peak labeled CDE is the sharp $q = 0$ charge-density intersubband excitation. $\hbar\omega_L$ are the incident photon energies.

The observation of a gap excitation of the FQHE at $\nu = \frac{1}{3}$ is the most striking of the results presented here. In Fig. 1 we find that at $B = 10.60$ T and $E_c = 14.1$ meV the $q = 0$ gap excitation has $\Delta_0 = 0.084$. Current calculations in the strict 2D limit give $\Delta_0 \simeq 0.18$ [2,3]. For a rigorous comparison with experiment, the theory needs to incorporate the effect of finite width of the 2D layer [3,22]. Its impact on the $q = 0$ gap excitation has been evaluated within the single-mode approximation (SMA) by means of a variational form for the charge distribution normal to the plane [3]. The effect is represented by an effective Coulomb interaction that incorporates a dimensionless thickness parameter $b l_0$. Interpolation in the calculations of Girvin, MacDonald, and Platzman [3] with $b l_0 = 3$, appropriate for 250 Å quantum wells, yields the value $\Delta_0 = 0.11$, which is close to the measured energy. Inclusion of effects of residual disorder would improve the agreement.

The splitting between the two inter-Landau-level excitations in Fig. 3, $\delta \simeq 1.2$ meV, is very close to the energy of the $q = 0$ gap excitation. This suggests that the blueshifted inter-Landau-level peak could be due to a higher-order mode involving the $q = 0$ magnetoplasmon and gap excitations. In a second interpretation, the blueshifted mode could be assigned to a $q = 0$ spin-flip inter-Landau-level excitation. In this case the blueshift is $\delta = E_Z \Delta_{SF}$, where Δ_{SF} arises from the enhancement of exchange self-energies in the spin-polarized electron gas [17]. From the results in Figs. 2 and 3 we find $\Delta_{SF} = 0.067$ (in units of E_c). For $b l_0 = 3$ the SMA calculation predicts $\Delta_{SF} = 0.06$ [17,23] in excellent agreement with the measured value.

The marked temperature dependence of the $q = 0$ gap excitation is consistent with magnetotransport measurements that show well-defined activated behavior only for $T \lesssim 1$ K [8]. In contrast, the strong temperature and magnetic field dependences of light scattering by $q = 0$ spin-wave excitations are unexpected. The temperature dependence of these excitations should be governed by the Zeeman energy $E_Z = 0.26$ meV $\equiv 3$ K. We find instead that the intensities have a strong temperature dependence for $T < 1$ K similar to that of FQHE.

To conclude, we reported the light scattering measurements of long wavelength collective excitations in the FQHE state at $\nu = \frac{1}{3}$. A well-defined low-lying collective excitation associated with the incompressible quantum fluid has been observed for the first time. Its energy is explained by theoretical predictions for $q=0$ gap excitations. The observation is evidence that the 2D electron system supports collective excitations characteristic of the states of the FQHE. The definitive identification of blueshifts observed in inter-Landau-level excitations as well as the unexpected temperature dependence of spin waves require further consideration. Measurements of spin excitations could yield quantitative determinations of exchange interactions and reveal spin states of the incompressible fluid. We believe that light scattering experiments carried out at other filling factors and lower temperatures will make further significant contributions. The method could also give insights on electromagnetic responses in the FQHE regime [24,25].

We thank L. Brey, J. P. Eisenstein, Song He, D. Heiman, C. Kallin, B. D. McCombe, A. H. MacDonald, P. M. Platzman, and H. L. Stormer for discussions on several aspects of this work.

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