Observation of Roton Density of States in Two-Dimensional Landau-Level Excitations

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Inelastic light scattering by inter-Landau-level excitations of the 2D electron gas in high-mobility GaAs structures in a perpendicular magnetic field was observed at the energies of the critical points in the mode dispersions. For Landau-level filling factors $\nu \gtrsim 1$, structure in the spectra indicates the excitonic binding and roton behavior predicted by the Hartree-Fock approximation. The large critical-point wave vectors, $q \gtrsim (\hbar c/eB)^{-1/2} \gtrsim 10^6$ cm^{-1}, are probably accessible in resonant light scattering through the residual disorder that broadens the Landau levels.

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A high-mobility two-dimensional (2D) electron gas in a large magnetic field perpendicular to the layer has unique properties that arise from quantization of the 2D continuum of kinetic energy states into sharp Landau levels.[1] Strong electron-electron correlations lead to remarkable phenomena, like the fractional quantization of the Hall effect (FQHE), that have been extensively studied in magnetotransport.[2,3] In principle, electron-electron interactions can be investigated by measurement of elementary excitations associated with transitions between Landau levels.[4-7] The inter-Landau-level modes, magnetoplasmons and spin-density excitations, have dispersions

$$\omega(q)=\omega_c+\Delta(q,B)\,, \tag{1}$$

where ω_c is the cyclotron frequency. A distinctive feature of the Hartree-Fock calculations of $\Delta(q,B)$ is the roton minimum at finite wave vector $q \gtrsim q_0 = 1/l_0$, where $l_0=(\hbar c/eB)^{1/2}$ is the magnetic length.[5-7] The roton is due to the reduction at large wave vectors of the excitonic binding between the electron in the excited Landau level and the hole in the lower state.[5-8] These interactions also play a leading role in the theory of collective excitations of the FQHE. The magnetoroton minimum, related to the gap of the FQHE and the Wigner crystal, is connected with the excitonic attraction between fractionally charged quasiparticles.[9] Unfortunately, the relevant range of wave vectors, $q \gtrsim 10^6$ cm^{-1}, is not easily accessible in infrared absorption or inelastic light-scattering experiments.[10,11] However, with the breakdown of translational symmetry due to impurities and disorder, the $q \sim 0$ Landau-level transitions are expected to couple to large wave-vector excitations.[5,12-14]

This Letter reports the observation of roton structure in the density of states of *inter-Landau-level excitations* by resonant inelastic light scattering. The measured spectra are interpreted on the basis of *critical points* in the calculated mode dispersions, where $\partial\omega/\partial q=0$. The observed modes have significant shifts from $\hbar\omega_c$ and the spectral line shapes reveal the multiple critical-point structure that is characteristic of roton minima. The experiments are conducted in high-mobility GaAs heterostructures,[15] and cover a broad range of electron areal density n and Landau-level filling factor $\nu=2\pi l_0^2 n$. Our observations indicate that light scattering is a powerful probe of 2D electron-electron interactions. The critical-point wave vectors are much larger than the light-scattering wave vectors ($k \approx 10^4$ cm^{-1}). The massive breakdown of wave-vector conservation in these experiments occurs in systems with ultrahigh electron mobility ($\mu \sim 10^6$ cm^2/V sec). While we do not have a full interpretation of this breakdown, we associate it with optical transitions of the disorder-broadened Landau levels.

Several modulation doping GaAs-($Al_{0.3}Ga_{0.7}$)As single heterojunctions (SH) and multiple quantum wells (MQW) were investigated. The SH show a persistent photoconductivity effect and have electron mobilities, in excess of 10^6 cm^2/V sec.[15] The densities are in the range $0.4\times10^{11} \lesssim n \lesssim 4\times10^{11}$ cm^{-2}. In the MQW there is no persistent effect of illumination. The GaAs layers have thickness $d_1 \leq 200$ Å and the superlattice period is $d \simeq 700$ Å. The mobilities and densities are in the ranges $1.5\times10^5 \lesssim \mu \lesssim 5\times10^5$ cm^2/V sec and $1.8\times10^{11} \lesssim n \lesssim 6\times10^{11}$ cm^{-2}. The samples were placed in a superconducting magnet cryostat with perpendicular fields as high as $B=11.5$ T. A backscattering geometry was used with in-plane component of the scattering wave vector $k \lesssim 10^4$ cm^{-1}. The light-scattering measurements were carried out with tunable infrared cw dye lasers at power levels of ~ 2 mW, power densities below 0.1 W/cm^2, and photon energies close to the optical transitions between higher-valence and lower-conduction Landau levels.

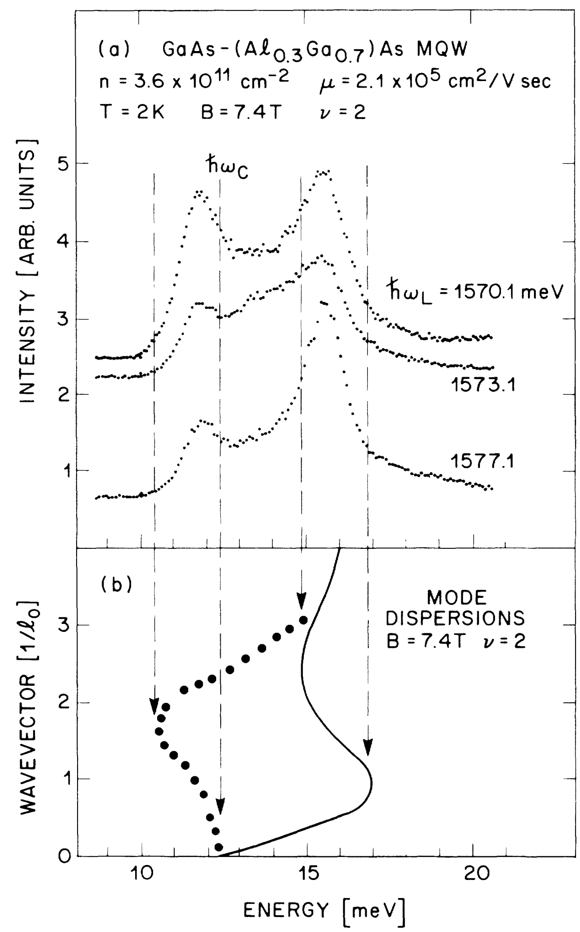

FIG. 1. (a) Inelastic light-scattering spectra from a MQW sample at three values of the incident photon energy $\hbar\omega_L$. (b) Calculated mode dispersions at Landau-level filling factor $\nu=2$ (after Ref. 6). The magnetoplasmons at $E_c/\hbar\omega_c=1$ are represented by the full line. The dotted line is for spin-density excitations.

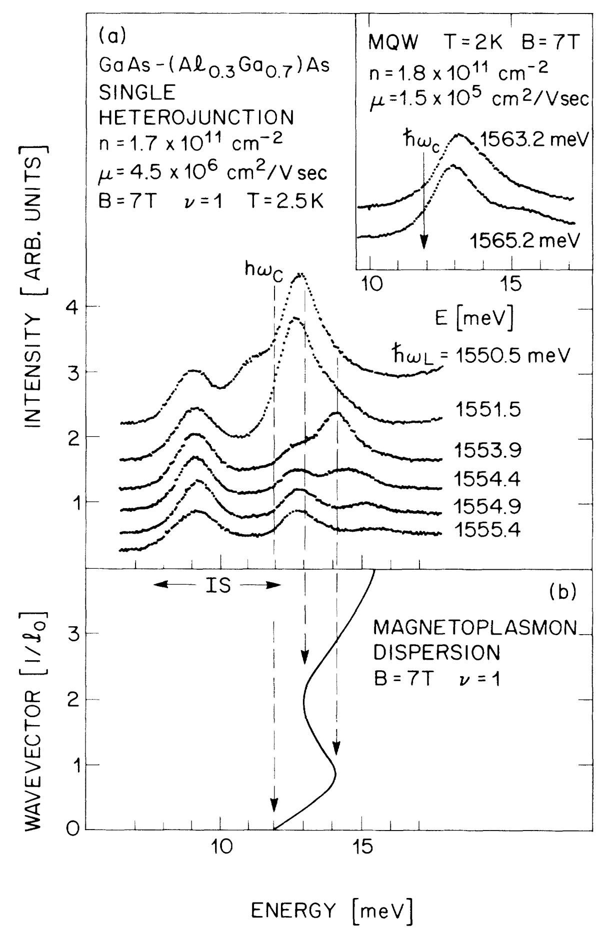

FIG. 2. (a) Resonant inelastic light-scattering spectra from a very high-mobility SH sample for different values of $\hbar\omega_L$. Inset: The spectrum of a MQW with comparable free-electron density and much lower mobility. (b) Calculated mode dispersions at Landau-level filling factor $\nu=1$ (after Ref. 6). IS represents the range of lowest intersubband excitations.

Figure 1(a) displays results from a MQW sample at $\nu=2$. The spectra have an onset at 1 meV below $\hbar\omega_c$ (for electron effective mass $m^*=0.0695$)[16] and a cutoff at an energy that lies well below the onset of intersubband excitations at 28 meV. The spectra overlap with the energy of calculated dispersions of inter-Landau-level excitations shown in Fig. 1(b). This indicates that they are magnetoplasmons and spin-density excitations at large wave vectors $q \gtrsim q_0 = 1/l_0 = 1.1\times10^6$ cm^{-1}. The intensities of the two types of excitations are comparable, as in $B=0$.[17] Similar spectra were measured in all MQW samples. The onset and cutoff energies vary with filling factor and electron density. Excitations associated to higher Landau-level transitions $m\hbar\omega_c$ are also observed. At $\nu \gtrsim 10$ we found the modes of $m \le 5$. Figure 2(a) shows the spectra measured in the SH sample of ultrahigh electron mobility at filling factor $\nu=1$. The scattering in the range $12 \le \hbar\omega \le 16$ meV, also agrees with the calculated large wave-vector magnetoplasmons shown in Fig. 2(b). The structures measured at lower energies, in the range labeled IS, involve intersubband excitations as verified in ir absorption.[18] The agreement with ir absorption also verifies that incident power densities do not cause significant changes in electron density. The inset shows that the magnetoplasmon spectrum measured in a MQW sample of comparable density and much lower mobility is very similar. In fact, we do not expect much difference because for $q \gtrsim q_0$ coupling between oscillations in different quantum wells is negligible ($q_0 d \gg 1$).[19]

These results indicate an extensive breakdown of wave-vector conservation in which the observed spectral line shapes are related to structure in the density of states. The roton in the magnetoplasmon dispersion appears as the structure between $\hbar\omega_c$ and the high-energy maximum. Cyclotron resonance at $q=0$ is weak in light scattering.[17] The structure near $\hbar\omega_c$ is assigned to critical points at $q \sim 0$ and $1.6q_0$ in the dispersion of spin-density excitations. The rich critical point structure associated with the roton is also evident in the asymmetric magnetoplasmon band observed in spectra of Fig. 2(a). The maximum at 12.7 meV indicates the position of the roton minimum in the mode dispersion. In the range labeled IS there is overlap and coupling[12] between intersubband and Landau-level excitations. This could explain the complex structure seen in the spectra. The higher-energy features of the density of states are revealed in the asymmetry of the magnetoplasmon band and in its changes with increasing $\hbar\omega_L$.

We investigated the profile of resonant enhancement of the intensities in the SH sample. The results in Fig. 3 show a linear B dependence for $\nu \leq 2$, when only the lowest Landau level is occupied. The slope is $(l+\frac{1}{2})\hbar\omega_c' = 4.5$ meV/T. $l=2$ is the Landau-level index of the optical transitions and $\omega_c' = \omega_c m^*/\mu^*$, where $\mu^* = 0.064 m_0$ is the reduced effective mass. This field dependence suggests a third-order resonant light-scattering process as described in the inset of Fig. 3.[17] The virtual and real optical transitions take place between valence states $|v\rangle$ and conduction Landau levels $|c_0, l\rangle$ and $|c_0, l-1\rangle$, where c_0 labels the lowest confined conduction subband. The emission of Landau-level excitations $\omega(q)$ is due to coupling of the electron optically excited in a $|c_0, 2\rangle$ state with the Fermi sea in $|c_0, 0\rangle$ states. The requirement of wave-vector conservation is relaxed for transitions among Landau levels broadened by disorder. For the scattering intensity we approximate

$$I(\omega) \sim \left| \frac{M(\omega)}{(E_2 - \hbar\omega_L)(E_1 + \hbar\omega - \hbar\omega_L)} \right|^2 \rho(\omega). \quad (2)$$

In Eq. (2) $\rho(\omega)$ is the density of states of inter-Landau-level excitations. $M(\omega)$ is the product of the two optical matrix elements with the matrix element of the electron-electron interaction that causes the transition $|c_0, 2\rangle \rightarrow |c_0, 1\rangle$ with emission of a mode at $\omega(q)$. Equation (2) represents the scattering cross section under the simplifying assumption that the resonant energies have constant values $E_l = (l+\frac{1}{2})\hbar\omega_c'$.

The remarkable changes in spectral line shapes seen in Fig. 2(a) are explained by the dependence of resonant denominators in Eq. (2) on both $\hbar\omega_L$ and $\hbar\omega$. The weaker structure in the density of states is revealed at the "double-resonance" condition $E_2 - E_1 \simeq \hbar\omega$ of the largest resonance enhancement. The scattering intensities have a striking temperature dependence that is not seen in the MQW. The measured intensities drop by a factor of ~ 10 when the temperature is raised from 2 to 10 K. Such a change is much faster than that reported for shallow donors.[20]

The dispersions $\Delta(q,B)$ have been evaluated to lowest order in $E_c/\hbar\omega_c$, where $E_c = e^2/l_0\epsilon_0$ is the Coulomb energy and ϵ_0 is the dielectric constant ($\epsilon_0 = 13.1$ in GaAs).[5-7,21] The dispersions shown in Figs. 1(b) and 2(b) are based on the calculations reported in Ref. 6, that considers coupling to higher Landau-level transitions when $\hbar\omega_c \simeq E_c$. For magnetoplasmons at $\nu = 2$ the couplings reduce by $\sim 30\%$ the maximum in $\Delta(q,B)$ calculated in Ref. 5. Kallin[21] has recently shown that finite-thickness effects, that weaken the strength of the electron-electron interactions,[1] cause similar reductions in $\Delta(q,B)$.

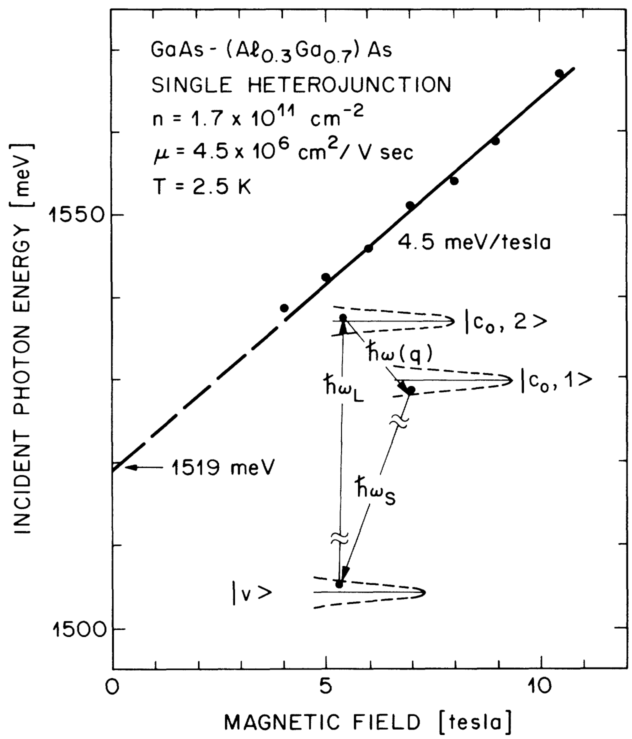

FIG. 3. Incident photon energy of the maximum in resonant enhancement of the light-scattering intensities of critical-point magnetoplasmons in a high-mobility SH sample as a function of magnetic field. The line extrapolates to the energy gap of GaAs at $B=0$. Inset: A light-scattering process that explains the slope of 4.5 meV/T.

In Fig. 1, there is agreement between the observed cutoff in the magnetoplasmon band and the calculated energy of the critical point at $q \simeq q_0$. Finite-thickness effects could lower the calculated critical-point energies by 0.5–1 meV,[21] and give a better numerical agreement with measured energies. The maximum in scattering intensity measured at $\hbar\omega \lesssim 15.6$ meV appears to result from the superposition of the roton minimum at $q \simeq 2.5q_0$ and the large density of states for larger values of q. The spectra in Fig. 1(a) have an onset at ~ 11 meV and a well-defined maximum at 11.7 meV, both below ω_c. This is evidence of the excitonic binding and roton minimum of spin-density level excitations.[5,6] However, there is a significant discrepancy with the calculated roton energy shown in Fig. 1(b). The difference is likely to arise from sizable finite-thickness effects.[21] In Fig. 2(b) there is agreement between the calculated energy of the roton-minimum at $q \simeq 2q_0$ and the position of the maximum of the magnetoplasmon band. There is also good agreement of the energy of the critical point at $q = 0.9q_0$ with the position of the weaker maximum at 14 meV in the asymmetric magnetoplasmon band. The much weaker scattering intensities measured at $\hbar\omega > 14$ meV are due to magnetoplasmons with $q > 2q_0$. Finite-thickness effects could lower calculated critical-point energies by ~0.4 meV.[21]

The present light-scattering observations reveal features of the density of states of two-dimensional Landau-level excitations in high magnetic fields. We found direct evidence of the excitonic binding and roton minima predicted by Hartree-Fock theories. The required extensive breakdown of wave-vector conservation could occur in intermediate transitions between disorder-broadened Landau levels. The experiments in the ultrahigh electron mobility samples show that these studies could also unravel intriguing physics of electron-electron interactions in the lowest-disorder systems. Of special interest is the extreme magnetic quantum limit, where condensation into the incompressible fluid of the FQHE is predicted to alter the mode dispersions.[7]

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