Spin and Charge Density Excitations and the Collapse of the Fractional Quantum Hall State at $\nu = 1/3$

H. D. M. Davies, J. C. Harris, J. F. Ryan, and A. J. Turberfield
Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom
(Received 19 July 1996)

Inelastic light scattering from 2D electrons below 100 mK reveals collective charge and spin density excitations of the incompressible electron liquid at Landau level filling factor $\nu = 1/3$ and provides experimental evidence for a magnetoroton minimum in the charge density dispersion curve. The temperature scale for the collapse of electron correlation in the spin-polarized electron liquid is determined by thermal excitation of long-wavelength spin waves. [S0031-9007(97)03255-9]

PACS numbers: 73.40.Hm, 73.20.Mf, 75.40.Cx, 78.30.Fs

The fractional quantum Hall effect (FQHE) is a collective phenomenon characteristic of a two-dimensional electron system (2DES) in a perpendicular magnetic field: at certain fractional values of the Landau level filling factor ν the Hall resistance is quantized and electrical transport is dissipationless [1]. This is a manifestation of a qualitatively new class of ground state—an incompressible electron liquid [2]—in which strong electron correlation suppresses short-range electron-electron repulsion.

Elementary excitations of the spin-polarized [3] electron liquid at $\nu = 1/3$ are of central importance to theories of the FQHE. Neutral charge density (CD) excitations have nonzero energy at zero wave vector, and a deep "magnetoroton" minimum in the dispersion curve, characteristic of short-range order, is predicted to occur at a wave vector $\mathbf{q}_{\mathrm{MR}}$ close to the inverse magnetic length $l_0^{-1} = \sqrt{eB/\hbar}$ [4]. Large wave vector $\mathbf{q}_\infty$ neutral CD excitations consist of pairs of fractionally charged quasiparticles [2,5]. In a model system with zero g factor a branch of spin density (SD) excitations lies below the CD branch [6]; the two branches approach each other near $\mathbf{q}_{\mathrm{MR}}$ [7]. In GaAs the energy of SD excitations is increased by the Zeeman energy: at sufficiently high magnetic fields the SD and CD branches may cross.

The energy of a $\mathbf{q}_\infty$ excitation can be obtained by measurement of thermally activated resistivity, but it is much more difficult to measure the energies of excitations with finite wave vectors. Pinczuk and co-workers have measured $\mathbf{q} \approx 0$ CD and SD excitations using inelastic light scattering [8]; phonon absorption measurements, without wave-vector resolution, have also been used to investigate intra-Landau level excitations [9]. In this Letter we report measurements of SD and CD excitations at $\nu = 1/3$ using resonant inelastic light scattering. Disorder-induced breakdown of wave-vector conservation at resonance [10] allows measurement of $\mathbf{q} \neq 0$ wave-vector-forbidden scattering. We observe four distinct low-energy electronic excitations: their extreme sensitivity to temperature, together with the ν dependence of their intensities and energies, identifies them as SD and CD excitations at $\mathbf{q} \approx 0$ and at finite wave vector. From their resonant enhancement profiles we find evidence for the existence of a continuum of CD excitations between the energies of the $\mathbf{q} \approx 0$ and $\mathbf{q} \approx \mathbf{q}_{\mathrm{MR}}$ (magnetoroton) modes. From the temperature dependence of the exchange enhancement of the $\mathbf{q} \neq 0$ SD mode we infer that the thermal collapse of electron correlation at $\nu = 1/3$ is mainly due to excitation of long-wavelength spin waves.

Two samples of a high-mobility 2DES ($\mu \approx 10^7\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$, $n = 9.7 \times 10^{10}\ \mathrm{cm^{-2}}$ and $9.1 \times 10^{10}\ \mathrm{cm^{-2}}$) confined at a single $\mathrm{GaAs/Ga_{0.67}Al_{0.33}As}$ heterojunction were studied in the temperature range 50 mK–3 K. Laser excitation (<1 μW) from an etalon-tuned Ti:sapphire laser with linewidth 2 μeV passed through windows into the dilution refrigerator. Scattered light was collected by optical fibers and analyzed with a quadruple spectrograph allowing measurement of Raman scattering down to a Stokes shift of 120 μeV with a spectral resolution of 20 μeV. Simultaneous resistivity measurements were used to check both temperature and filling factor: we estimate that the electron temperature was <50 mK above the sample temperature.

Figure 1 shows low-energy Raman scattering at 50 mK. Each spectrum corresponds to a different laser energy within the band of photoluminescence due to interband recombination of electrons in the 2DES [11]. Highlighted peaks have a fixed Stokes shift below the laser photon energy and correspond to resonant inelastic light scattering. The laser energies at which scattering is resonantly enhanced are fixed relative to the photoluminescence spectrum of the 2DES [11] (the absolute resonance energies are different in the two samples) confirming all four peaks as scattering from 2D electronic excitations.

Very sharply resonant scattering from excitations C ($\varepsilon_{\mathrm{C}} = 1.07$ meV) and M ($\varepsilon_{\mathrm{M}} = 0.68$ meV) is observed when the laser is tuned so that the outgoing photon matches a resonance energy common to the two modes. C is observed at different magnetic fields in the two samples but in the same narrow range of filling factors $\nu = 1/3 \pm 1\%$; the width of the resonance is at most

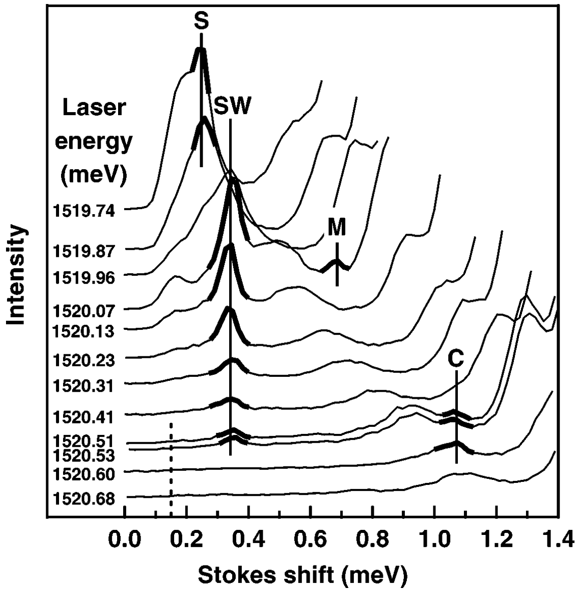

FIG. 1. Resonant light scattering at 50 mK from spin and charge density excitations of the 2DES at $\nu = 1/3$. The roll-off at 150 μeV is due to the spectrograph's bandpass slits.

$\approx$0.1 meV and narrows away from $\nu = 1/3$. Scattering from C is extremely sensitive to temperature and vanishes at $\sim$1 K. These characteristics provide strong evidence that C is a collective excitation of the 2DES. We have observed M over a wider range of filling factors $0.31 \leq \nu \leq 0.38$. The scattering resonance of peak M is so narrow (<0.05 meV) that it cannot be determined whether it has a constant Stokes shift: its assignment as inelastic light scattering is based on its sharp resonance, its common resonance energy with C and its correlation with spin wave scattering (see below) [12]. C and M are identified as CD excitations. Small wave vector $\mathbf{q} \approx 0$ CD excitations are expected to be extremely sensitive to changes in filling factor as there is no excitation gap where the 2DES is compressible away from $\nu = 1/3$: C, which is seen only in a narrow range of filling factors around the incompressible state at $\nu = 1/3$, is identified as wave-vector-allowed scattering [13] from $\mathbf{q} \approx 0$ CD modes in agreement with Pinczuk and co-workers [8,14]. We expect magnetoroton modes, characteristic of short-range order in the electron liquid, to be relatively robust to changes in filling factor: M is identified as disorder-activated scattering [10,15] from a magnetoroton peak in the density of states. These assignments are consistent with theoretical estimates of $0.15\beta E_c \simeq 1.1$ meV for $\mathbf{q} \approx 0$ CD modes and $0.063\beta E_c \simeq 0.5$ meV for the magnetoroton mode [4,16] where $E_c = e^2/4\pi\epsilon l_0$ and $\beta \simeq 0.5$ is a correction for the finite thickness of the 2DES [17]. They are also compatible with the $\mathbf{q}_\infty$ quasiparticle gap of 0.50 meV deduced from transport measurements [18].

Figure 1 also shows Raman scattering from low-energy excitations S ($\varepsilon_S = 0.27$ meV) and SW ($\varepsilon_{SW} = 0.35$ meV). SW is resonantly enhanced within a range of laser energies between those at which M and C are observed, and within a second range within luminescence from the ground subband (not shown). S is resonant over a broader range of laser energies $\sim$2 meV spanning the spectrum of photoluminescence from the 2DES; in general S is enhanced where SW is weak or absent from the Raman spectrum. The intensity of scattering from S and SW falls above 1 K (by a factor of $\sim$5 at 2.5 K). Figure 2 shows the magnetic field dependence of the energies of both modes. The energy of S is proportional to magnetic field over (at least) the range 8–16 T (i.e., $1/2 < \nu < 1/4$) and is close to the Zeeman splitting expected for electrons confined in the 2DES [19]. SW increases in energy with field with approximately the same slope as S, but with a slight but distinct dip at $\nu = 1/3$. On the basis of their field dependence and resonance profiles both modes are identified as SD excitations: S corresponds to wave-vector-allowed scattering from $\mathbf{q} \approx 0$ modes [8]; SW is attributed to disorder-activated scattering from $\mathbf{q} \neq 0$ modes whose energy is increased by exchange.

The narrow linewidth of SW suggests that it is due to a narrow peak in the spin wave density of states. Exact [7,20] and Hartree-Fock [21] calculations show a large density of states where the dispersion curve comes close to the continuum of SD (and CD) multiple excitations near $q \sim l_0^{-1}$; flattening of the dispersion curve may be regarded as due to interaction with continuum SD modes [22]. This part of the dispersion curve has an energy close to the $\mathbf{q}_\infty$ asymptote [7]; the difference between ε_{SW} and ε_S, which corresponds to the exchange enhancement of ε_{SW} above the bare Zeeman energy, is much smaller than the calculated $\mathbf{q}_\infty$ spin wave energy, however. A peak in the spin wave density of states at such a low energy may be due to interaction between SD and CD excitations allowed by the inversion asymmetry of the GaAs/GaAlAs heterojunction [23] leading

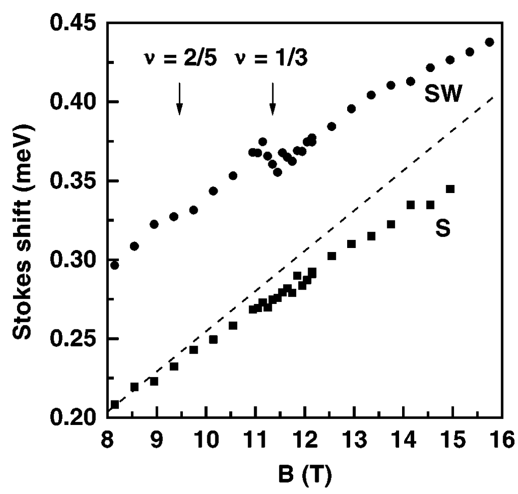

FIG. 2. Energies of spin excitations S and SW vs magnetic field. The dashed line corresponds to $g^*_{\mathrm{GaAs}} = -0.44$ [C. Weisbuch and C. Hermann, Phys. Rev. B **15**, 816 (1977)].

to an avoided crossing near $\mathbf{q}_{MR}$: SW and M might correspond to scattering from the lower and upper branches, respectively. The dip in ε_{SW} is consistent with a lowering of the magnetoroton energy due to particularly strong short-range order at $\nu = 1/3$, but the fact that the exchange enhancement $(\varepsilon_{SW} - \varepsilon_S)$ changes so little is surprising as the magnetoroton energy is predicted to be strongly dependent on filling factor [4]. However, the resonance profile, magnetic field dependence, and correlation with scattering from CD excitations, as well as the temperature dependence described below, provide definitive evidence that SW corresponds to a spin excitation of the 2DES.

Figure 3 shows the temperature dependence of ε_{SW} at $\nu = 1/3$. As temperature increases ε_{SW} falls continuously to the energy of the long-wavelength spin wave ε_S. We interpret this as evidence for a decrease in exchange energy due to a rapid loss of spin polarization and the collapse of the $\nu = 1/3$ correlated state at ~1 K. The Hartree-Fock exchange contribution to spin wave energies at all wave vectors is proportional to spin polarization [24]: the energy shift $(\varepsilon_{SW} - \varepsilon_S)$ is therefore a measure of the spin polarization of the 2DES. This interpretation does not rely on any assumption about the spin wave dispersion or the wave vector of SW. We have modeled our results by comparing the exchange enhancement of ε_{SW} to the polarization calculated assuming a spin wave dispersion:

$$\varepsilon(q) = |g^*|\mu_B B + (\nu_\uparrow - \nu_\downarrow) \times \Delta\{1 - \exp[-(\alpha/\Delta)(ql_0)^2]\},$$

where $\nu_\uparrow$, $\nu_\downarrow$ are the partial filling factors of the two $N = 0$ Landau levels and α and Δ are chosen to match (at zero temperature) the short- and long-wavelength behaviors of the spin wave dispersion calculated by Rezayi [7] corrected for the thickness of the 2DES [4,17]. The density of reversed spins is calculated self-consistently by integrating the Bose-Einstein distribution function over phase space for SD modes [25]. This approach is reasonable at low temperatures when the polarization is large (it gives a good approximation to the polarization calculated by Kasner and MacDonald [26] at $\nu = 1$ using many-body perturbation theory while the polarization is above 70%). The results of this calculation are displayed in Fig. 3, curve A; it is remarkably successful in reproducing the sharp depolarization at 1 K. For comparison we also show curves corresponding to the following: B, a non-self-consistent calculation in which the dispersion curve always corresponds to that of the fully polarized system; C, the polarization of a system of composite fermions [27] at $\nu^* = 1$ with an excitation gap to a spin-reversed composite fermion Landau level equal to the large-wave-vector spin excitation energy $\varepsilon(\infty) = |g^*|\mu_B B + (\nu_\uparrow - \nu_\downarrow)\Delta$. It is clear that both the self-consistent reduction in the energy of spin excitations at high temperature and the presence of low-energy, long-wavelength spin modes significantly hasten the onset of depolarization.

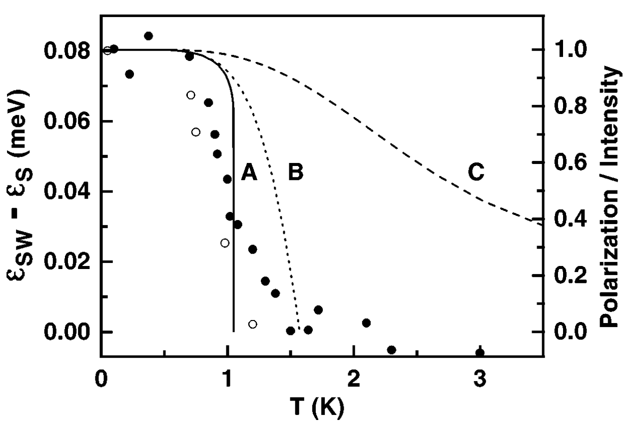

FIG. 3. • Exchange enhancement of $\mathbf{q} \neq 0$ spin excitation SW over a range of temperatures; ∘ intensity of light scattering from $\mathbf{q} \approx 0$ charge density excitation C. Lines show spin polarization of the 2DES calculated using approximations described in the text.

Figure 3 shows that the collapse in the intensity of the $\mathbf{q} \approx 0$ charge density mode C occurs at the same temperature as the loss of spin polarization. This suggests that, at least at small wave vectors, the branch of CD excitations that at large wave vectors dominate low-temperature transport ceases to be well defined when thermal fluctuations depolarize the electron spins. The quasiparticle gap is usually deduced from transport measurements below the temperature at which spin polarization is abruptly lost (~1 K); at higher temperatures the resistivity deviates from a simple activated behavior.

Chakraborty and Pietiläinen [28] find that the spin polarization of five electrons on a sphere at $\nu = 1/3$ decays by 50% at 3 K. To model our experimental results it will be important to take into account the finite thickness of the electron system. The absence of long-wavelength modes in a small system will also affect the comparison.

The resonance behavior of collective excitations also reveals important details of the dispersion of CD modes. Resonant scattering from CD excitations C and M (Fig. 1) has different Stokes shifts but is observed at the same absolute photon energy. We conclude that scattering for both processes is enhanced by a common *outgoing* resonance: this is indicated schematically in Fig. 4(a). Figure 1 shows that when the laser is tuned such that C or M is observed then scattering from SW also occurs; this suggests that in these spectra scattering from SD and CD excitations is enhanced by a common *incoming* resonance. Scattering from C and M is thus *doubly* resonant [Fig. 4(b)]. Similar double resonance effects were reported by Pinczuk and co-workers in disorder-activated Raman scattering at $\nu = 1$ [10]. The existence of real transitions resonant with the incoming photons is confirmed by using the intensity of luminescence from the 2DES as a measure of interband absorption (photoluminescence

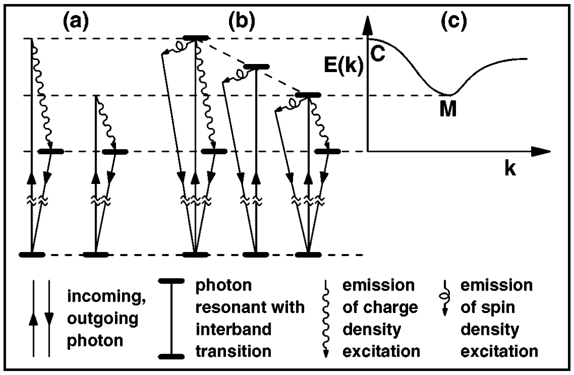

FIG. 4. Light scattering resonances for (a) charge density and (b) spin density excitations in relation to (c) the dispersion of charge density excitations.

excitation spectroscopy). The common outgoing resonance is likely to correspond to a transition from the first excited subband of the confining potential. We propose that incoming resonances involve the same transition dressed by CD excitations of the 2DES; the energy difference between incoming and outgoing resonance energies is thus that of a CD excitation [Fig. 4(c)], ensuring double resonance. The continuous resonant enhancement of SW between these limits leads us to conclude that there is a continuum of CD excitations with energies between limits corresponding to the $\mathbf{q} \approx 0$ and $\mathbf{q}_{\mathrm{MR}}$ modes. The peak and sharp cutoff in the intensity of SW at the magnetoroton resonance is consistent with the large density of states at a minimum of the CD dispersion curve.

In conclusion, we have observed inelastic light scattering from spin and charge density excitations at $\mathbf{q} \approx 0$, from a $\mathbf{q} \neq 0$ spin density excitation and from charge density modes near the magnetoroton wave vector. These measurements provide experimental evidence for a minimum in the charge density dispersion curve near the energy of the predicted magnetoroton minimum [4]. By studying the temperature dependence of both spin and charge density excitations we find that the temperature scale for the collapse of electron correlation in the spin-polarized electron liquid at $\nu = 1/3$ is determined not by the quasiparticle gap but by thermal excitation of long-wavelength spin waves. Work on grating-coupled light scattering [29] using line spacings on the scale of the magnetic length is now in progress in order to study directly the dispersion of modes at $\mathbf{q} \lesssim \mathbf{q}_{\mathrm{MR}}$.

We thank C. T. Foxon and J. J. Harris for the provision of samples and acknowledge helpful discussions with H. Aoki, J. T. Chalker, A. H. MacDonald, and V. N. Nicopoulos.

[1] D. C. Tsui, H. L. Störmer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982); H. L. Störmer *et al.*, *ibid.* **50**, 1953 (1983).
[2] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).
[3] F. C. Zhang and T. Chakraborty, Phys. Rev. B **30**, 7320 (1984).
[4] S. M. Girvin, A. H. MacDonald, and P. M. Platzman, Phys. Rev. Lett. **54**, 581 (1985).
[5] C. Kallin and B. I. Halperin, Phys. Rev. B **30**, 5655 (1984).
[6] M. Rasolt, F. Perrot, and A. H. MacDonald, Phys. Rev. Lett. **55**, 433 (1985).
[7] E. H. Rezayi, Phys. Rev. B **36**, 5454 (1987).
[8] A. Pinczuk *et al.*, Phys. Rev. Lett. **70**, 3983 (1993).
[9] C. J. Mellor *et al.*, Phys. Rev. Lett. **74**, 2339 (1995).
[10] A. Pinczuk *et al.*, Phys. Rev. Lett. **61**, 2701 (1988).
[11] A. J. Turberfield *et al.*, Phys. Rev. Lett. **65**, 637 (1990).
[12] The extremely sharp resonance of Raman peak M makes it impossible to assess its temperature dependence.
[13] The maximum in-plane wave-vector transfer allowed by the experimental geometry is 6×10^4 cm $^{-1}$.
[14] P. M. Platzman and Song He, Phys. Rev. B **49**, 13 674 (1994); Song He and P. M. Platzman, Surf. Sci. **361**/**362**, 87 (1996).
[15] The electrostatic potential is most disordered when screening is minimal at $\nu = 1/3$: screening produces density disorder in the 2DES at other filling factors.
[16] R. K. Kamilla, X. G. Wu, and J. K. Jain, Phys. Rev. Lett. **76**, 1332 (1996).
[17] A. H. MacDonald and G. C. Aers, Phys. Rev. B **29**, 5976 (1984); F. C. Zhang and S. Das Sarma, *ibid.* **33**, 2903 (1986).
[18] D. R. Leadley *et al.*, Phys. Rev. B **53**, 2057 (1996).
[19] M. Dobers, K. von Klitzing, and G. Weimann, Phys. Rev. B **38**, 5453 (1988); M. J. Snelling *et al.*, *ibid.* **44**, 11 345 (1991).
[20] T. Nakajima and H. Aoki, Phys. Rev. Lett. **73**, 3568 (1994).
[21] J. P. Longo and C. Kallin, Phys. Rev. B **47**, 4429 (1993).
[22] H. Aoki (private communication).
[23] P. Pfeffer and W. Zawadzki, Phys. Rev. B **52**, 14 332 (1995).
[24] T. Ando and Y. Uemura, J. Phys. Soc. Jpn. **37**, 1044 (1974).
[25] At low temperatures this integral correctly counts small-wave-vector ($q \lesssim l_0^{-1}$) boson spin excitations but not large-wave-vector, single-particle excitations. The upper limit of integration of the curve shown is $q_c = 10 l_0^{-1}$. The depolarization temperature is a slow function of this cutoff wave vector (it increases to 2 K at $q_c = l_0^{-1}$).
[26] M. Kasner and A. H. MacDonald, Phys. Rev. Lett. **76**, 3204 (1996).
[27] J. K. Jain, Phys. Rev. Lett. **63**, 199 (1989).
[28] T. Chakraborty and P. Pietiläinen, Phys. Rev. Lett. **76**, 4018 (1996).
[29] L. L. Sohn *et al.*, Solid State Commun. **93**, 897 (1995).