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Spin Texture and Magnetoroton Excitations at $\nu = 1/3$

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Neutral spin texture (ST) excitations at $\nu = 1/3$ are directly observed for the first time by resonant inelastic light scattering. They are determined to involve two simultaneous spin flips. At low magnetic fields, the ST energy is below that of the magnetoroton minimum. With increasing in-plane magnetic field these mode energies cross at a critical ratio of the Zeeman and Coulomb energies of $\eta_c = 0.020 \pm 0.001$. Surprisingly, the intensity of the ST mode grows with temperature in the range in which the magnetoroton modes collapse. The temperature dependence is interpreted in terms of a competition between coexisting phases supporting different excitations. We consider the role of the ST excitations in activated transport at $\nu = 1/3$.

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Collective excitations of two dimensional electron systems (2DES) are a revealing probe into the physics of fractional quantum Hall (FQH) fluids. A common approach to probe collective modes in the FQH regime consists of measuring the thermal activation energy of the longitudinal resistivity, Δ_a, as done in Refs. [1–4]. At filling factor $\nu = 1/3$, the transport activation mechanism is often attributed to neutral excitations in the charge degree of freedom, namely, magnetoroton modes in the limit of large wave vector Δ_∞ [5–9]. The magnetoroton wave-vector dispersion at $\nu = 1/3$ is depicted in Fig. 1(a). The magnetoroton energies scale with the Coulomb energy $E_C = e^2/\epsilon l_B$, where ϵ is the dielectric constant, $l_B = (hc/2\pi e B_\perp)^{1/2}$ is the magnetic length, and $B_\perp$ is the magnetic field normal to the 2DES. Thus $E_C \propto \sqrt{B_\perp}$.

Even in the cleanest samples, the ones with minimal residual disorder, the measured activation gap is significantly smaller than the calculated energies for Δ_∞ [8,9]. Moreover, for low values of the ratio of the Zeeman and Coulomb energies, $\eta = E_z/E_c$, at $\nu = 1/3$ the measured Δ_a fails to scale with $\sqrt{B_\perp}$. Δ_a presents a term increasing linearly with the Zeeman energy, $E_z = g\mu B$, where B is the total magnetic field. More surprisingly, Δ_a grows with E_z with a slope $s \equiv \partial\Delta_a/\partial E_z = 3$ [2] or $s = 2$ [3,4]. Such energy evolution suggests that at low η, the relevant thermally excited modes are spin texture (ST) modes, namely, modes involving s simultaneous spin flips. Upon excitation of an ST mode, the component along the magnetic field of the total spin of the 2DES S_z is decreased by $\Delta S_z = \hbar s$.

Transport measurements at $\nu = 1$ for varying values of the in-plane component of the field $B_\parallel$ unveiled a steep change of Δ_a with E_z, with a slope s much larger than at $\nu = 1/3$. The activation mechanism was attributed to ST modes consisting of a Skyrmion–anti-Skyrmion neutral pair created at $\nu = 1$. These modes involve the flipping of s spins [10,11]. Skyrmion and anti-Skyrmions were predicted to be the ground state of the system at low η and away from $\nu = 1$ by one magnetic flux quantum. Such states are described as a radial distribution of spin density and charge, with a total charge of $-|e|$ for $\nu > 1$ (Skyrmion), and $+|e|$ for $\nu > 1$ (anti-Skyrmion) [12,13]. Spin textures have been invoked also to explain the ground state around $\nu = 1/3$ and the activation energies at $\nu = 1/3$ [4,12,14–17].

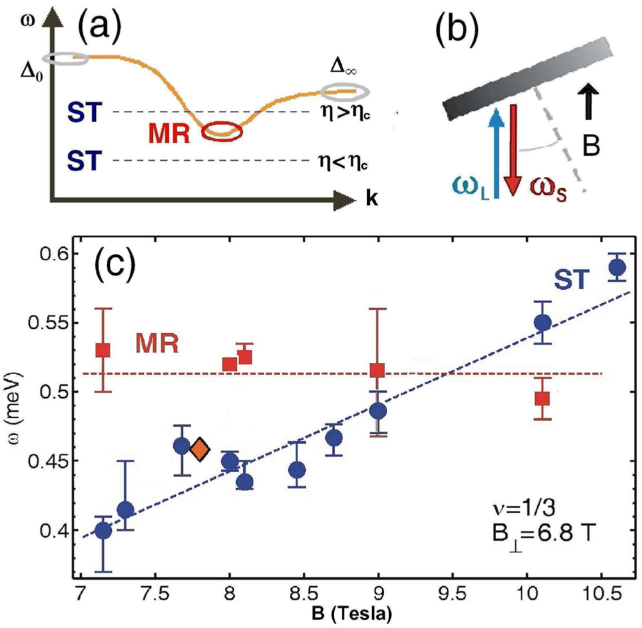

FIG. 1 (color online). (a) Dispersion of the lowest magnetoroton branch for excitation in the charge degree of freedom at $\nu = 1/3$. The ST is lower in energy than the MR for $\eta < \eta_c$ and larger at $\eta > \eta_c$. (b) Experimental setup. (c) Energies of the ST and MR as the total field B increases at constant $B_\perp$. Circles (squares) denote peaks resonant with S_1 (T_B). The diamond is the activated transport gap for $B = B_\perp = 7.8$ T at $\nu = 1/3$. Dashed lines are fits.

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Resonant inelastic light scattering is a direct probe of collective excitations of FQH liquids. Light scattering experiments have identified the long wavelength magnetoroton mode Δ_0 [6,7], modes at the magnetoroton (MR) minimum, and large wave-vector modes [18–20]. The experimental picture arising from these light scattering measurements is still far from complete. Several peaks were observed near the MR energy and their identification is not unequivocal [19]. Moreover, no ST excitations have yet been found in inelastic light scattering either at $\nu = 1$ or at $\nu = 1/3$. Measurements of the spin polarization were not able to provide conclusive evidence for STs in the ground state away from $\nu = 1/3$ [21].

We report here the first direct observation of a neutral spin texture by resonant inelastic light scattering at $\nu = 1/3$. Identification of the ST mode comes from the observation that as we raise $B_{\|}$ (and thus η) at $\nu = 1/3$, the energy of the ST increases and crosses that of the MR at a field of ~9.5 T corresponding to $\eta_c = 0.020 \pm 0.001$, as shown in Fig. 1(c). The dependence of the ST energy ω_{ST} on B indicates that the ST mode involves $s \equiv \partial\omega_{\mathrm{ST}}/\partial E_z = 2$ spin flips.

A surprising property of the discovered ST mode is that its intensity is greatly enhanced with increasing temperature. This behavior contrasts that of the magnetoroton modes, which collapse in the same temperature range (~0.2–1 K). These results are consistent with the coexistence of phases supporting magnetoroton excitations and phases supporting ST modes.

Optical measurements were performed on a single side modulation doped $\mathrm{Al}_{0.06}\mathrm{Ga}_{0.94}\mathrm{As/GaAs}$ 33 nm quantum well with electron density $n = 5.3 \times 10^{10}\ \mathrm{cm}^{-2}$ and mobility $\mu = 7.2 \times 10^6\ \mathrm{cm}^2/\mathrm{V\,s}$. The sample was mounted on the cold finger of a dilution fridge with optical windows and cold finger temperatures reaching 40 mK. The sample was mounted at an angle with respect to the magnetic field B [see Fig. 1(b)]. The value of η is changed by varying this angle and adjusting B to keep $\nu = 1/3$. This procedure amounts to varying $B_{\|}$ at constant $B_{\perp}$. A laser beam of photon energy ω_L is incident on the sample along B, and the backscattered photon, of energy ω_S, is dispersed in a double spectrometer and recorded with a CCD camera. By energy conservation, the energy of the excited mode in the 2DES is given by the energy shift $\omega = \omega_L - \omega_S$. The in-plane wave vector is not strictly conserved due to the presence of weak disorder. Hence, this technique allows for the excitation of relatively large density of states modes of wave vector larger than that provided by photon recoil, such as the MR [see Fig. 1(a)]. Transport measurements of Δ_a were performed on a similar $\mathrm{Al}_{0.1}\mathrm{Ga}_{0.9}\mathrm{As/GaAs}$ 33 nm quantum well with $n = 6.3 \times 10^{10}\ \mathrm{cm}^{-2}$ and $\mu = 14 \times 10^6\ \mathrm{cm}^2/\mathrm{V\,s}$ in a perpendicular magnetic field.

Figures 2(a) and 2(b) show resonant light scattering spectra at $\nu = 1/3$ and total field $B = 8$ T, which is in the low η region ($\eta < \eta_c$). It can be seen that although the MR and ST modes are very close in energy, the modes can be selectively excited by varying ω_L. This selectivity is due to intermediate virtual states in the scattering process that are resonant with the scattered photon energy ω_S. A similar outgoing resonance has been observed for the long wavelength spin wave [22].

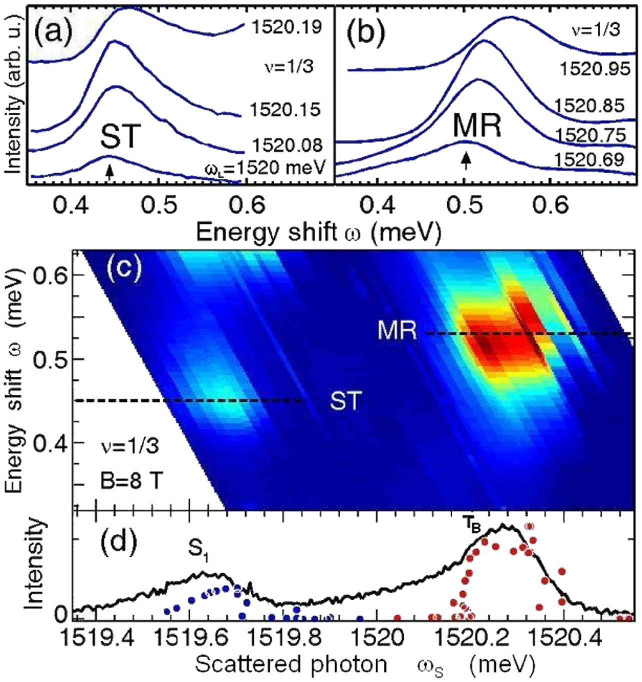

FIG. 2 (color online). (a),(b) Excitation spectra for different laser energies ω_L at 70 mK, $\nu = 1/3$, and total field $B = 8$ T. The peak corresponding to Δ_0 is observed at $\omega = 0.93$ meV, outside the scope of the plot (see a recent paper on the same sample [6]). (c) Spectra such as those in (a),(b) as a function of ω and ω_S. Dark red means high intensity. (d) Resonant enhancement profiles of the ST and MR modes (dots) superimposed to the photoluminescence spectrum (black line). Dashed lines are guides to the eye.

The outgoing resonance is illustrated in Fig. 2(c), where we present a compilation of spectra such as those in Figs. 1(a) and 1(b) as a function of ω and ω_S. The intensity of the signal is color coded. Each mode, ST or MR, is identified by its corresponding ω. In addition, it can be seen that the ST and MR modes become resonant at different values of ω_S. Figure 2(d) shows the profiles of resonant enhancement of the intensities of the ST (blue dots) and MR modes (red dots) and the photoluminescence spectrum (PL, black line). The PL is mainly composed of two peaks, S_1 and T_B, which have been extensively studied. They are associated with negatively charged excitonic states, namely, the singlet and triplet states, respectively [22,23]. Figures 2(c) and 2(d) reveal that the profile of resonant enhancement of the ST mode overlaps with S_1 while that of the MR peaks at the T_B energy.

Selective excitation of the ST and MR modes enables us to follow the evolution of their energy as $B_{\|}$ is increased. Figure 3 shows measurements at a higher $B_{\|}$ corresponding to $\eta > \eta_c$. These measurements reveal that while the

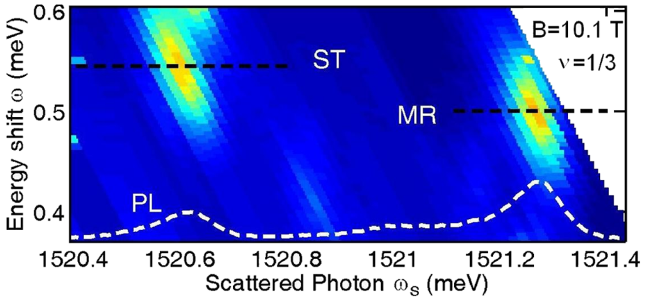

FIG. 3 (color online). Spectra at 40 mK and $\nu = 1/3$ as in Fig. 2(c), but at the higher total field of $B = 10.1$ T ($B_\perp$ is unchanged). The white line is the photoluminescence spectrum (PL).

energy of the MR mode has hardly changed, the ST has increased in energy above that of the MR.

Figure 4 shows that the ST and magnetoroton modes have strikingly different temperature behaviors. As the temperature is raised, the strength of the ST mode increases while that of the MR and Δ_0 decreases. The quenching of Δ_0 with increasing temperature has been observed before [6]. A higher energy mode at 0.75 meV at $B = 7.15$ T, possibly corresponding to Δ_∞, shows a similar quenching behavior as the MR and Δ_0 (not shown). No change in energy or in width is observed for the peaks associated with any of the aforementioned modes.

The quenching of the magnetorotons at $\nu = 1/3$ is reminiscent of the observed quenching of the rotons in superfluid helium excitation spectra [24]. In those experiments, the strength of the peak was fitted by a line proportional to $n_0(T) = n_0(0)[1 - (T/T_c)^\alpha]\Theta(T_c - T)$, where $n_0(T)$ was interpreted to be the fraction of particles that have condensed at a given temperature, T_c and α are fitting parameters, and $\Theta(x)$ is the Heaviside step function. Helium analogies are supported by a formulation of the theory that maps the 2DES to a system of interacting bosons in the ground state at $\nu = 1/3$ [25]. Figure 4 shows that the intensity of the MR and Δ_0 can be well fitted as proportional to $n_0(T)$, with a quenching occurring near $T_c = 0.85$ K. Remarkably, the ST intensity starts saturating at the same characteristic temperature at which the magnetorotons quench. Therefore, we fit the ST with a dashed line proportional to $1 - n_0(T)$ using the same α and T_c that we used for the magnetorotons. It is noteworthy that the temperature range in which the magnetoroton modes survive largely overlaps the limited range at which longitudinal resistivity presents activated behavior [1,3,4]. These results are consistent with a weakly disordered inhomogenous quantum fluid [26] in which phases supporting magnetoroton excitations occupy a fraction $n_0(T)$ of the sample and coexist with phases supporting ST modes in the remaining area.

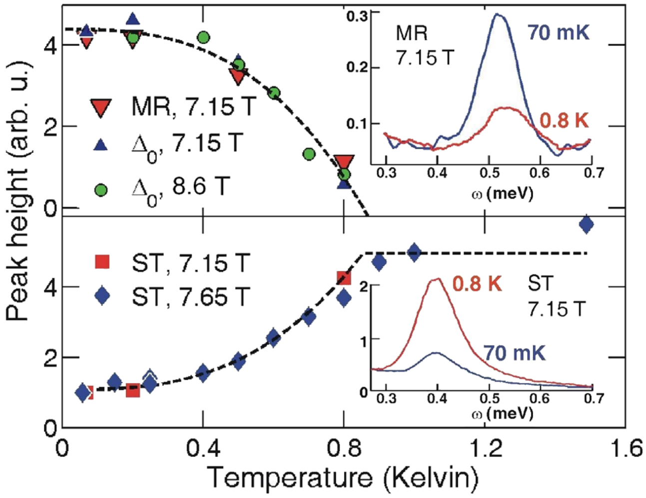

FIG. 4 (color online). Temperature dependence of the intensity of the MR, Δ_0, and ST peaks at $\nu = 1/3$ at different values of B. Each mode was normalized independently for clarity. The dashed lines are fits with $T_c = 0.85$ K, $\alpha = 2.84$, $n_0(0) = 0.78$. (Insets) Spectra at two temperatures.

We also find that the MR and Δ_0 modes are rapidly quenched as the filling factor is tuned away from 1/3. Such behavior has been reported before for the Δ_0 [6]. These findings suggest that as the system is rendered compressible, the quantum fluid that supports magnetoroton excitations disappears. We note that a mode with energy close to the MR has been reported to exist for a broad range of filling factors down to $\nu = 1/5$ [18,19]. We find this mode to be resonant with S_1. At $\nu = 1/3$, we reinterpret it as corresponding to the ST mode.

Turning again to Fig. 1(c), we find that the MR mode energy remains approximately constant at $0.046E_C$. This value is close to the calculated value of $0.052E_C$, including finite width effects [4,8], and is consistent with the experimental value of $0.045E_C$ obtained from Δ_a measurements for $\eta > \eta_c$ [4]. Disorder may cause a slight decrease in the MR energy as B increases [27].

Our activated transport measurements at $\nu = 1/3$ in a similar sample yield $\Delta_a = 5.3$ K, as shown in Fig. 1(c) (diamond). It is seen that the value Δ_a is consistent with the energy of the ST mode (both Δ_a and E_z are expressed in units of the corresponding E_C). The ST energy is also consistent (within <15%) with the latest published results for Δ_a in the same range of η, for $\eta < \eta_c$ [2–4].

The energy of the ST mode in Fig. 1(c) is well fitted by the linear expression $\omega_{\text{ST}} = sE_z + E_0$ with $s = 2$ and $E_0 = 0.06\text{ meV} = 0.005E_c$. We stress that for an accurate extraction of s, the value of E_z as measured *in situ* by inelastic light scattering was used [6,7,22], resulting in a g-factor value of $g = 0.41$, lower than the bulk value of $g = 0.44$. Experimentally, E_0 is given by the extrapolated $E_z = 0$ intercept. This value of E_0 is consistent with the values obtained by linearly extrapolating to $E_z = 0$ the published values of Δ_a at $\nu = 1/3$ for Ref. [3] (with $s = 2$), and Refs. [2,11] (with $s = 3$). In Ref. [4], Δ_a extrapolates at $E_z = 0$ to a negative value.

The experimental values of E_0 are significantly lower than theoretical estimates of E_0 for Skyrmions and anti-

Skyrmions at $\nu = 1/3$. In Ref. [4], the activation of the resistivity process at low η was described as the creation of a spin-reversed quasiparticle and a small anti-Skyrmion in which one additional spin is flipped [4], yielding a total $s = 2$. The flipping of an extra spin to form an anti-Skyrmion has a cost of E_z in energy, while simultaneously obtaining a Coulomb gain in energy. E_0 can be expressed as the difference between the Coulomb gain that results from flipping an extra spin and the energy cost (due to loss of exchange energy) to spatially separate a quasihole from a spin-reversed quasiparticle $\Delta^{\uparrow\downarrow}$ ($\Delta^{\uparrow\downarrow} \sim 0.05 E_C$ [20]). Calculations have been done both in the strict 2D limit and by including the finite width effect [4,9,12,14,17,28,29]. For $s = 2$, E_0 is predicted to be in the range (0.024–0.061)E_c, much higher than observed.

A similar discrepancy with theory is found in the case of $\nu = 1$, where the Coulomb energy is expected to be large for a Skyrmion–anti-Skyrmion pair, but nevertheless E_0 varies widely among samples, and even vanishes [10,11]. The low value of E_0 is often accounted for by a negative term attributed to the existence of disorder that lowers the gap [4]. The role of disorder in transport and in optical measurements is not well understood and is still a subject of active research [30]. If indeed the energy of the ST is lowered due to disorder, such an effect would be stronger at incompressible fractions where the disorder is not screened. This is consistent with our observation that the energy of the ST mode presents minima at $\nu = 1/3$ and 2/7 (not shown).

In conclusion, we have identified an ST mode in which two spins are flipped upon inelastic light scattering at $\nu = 1/3$. We found a crossover between the ST mode and the MR mode as B is increased. The ST and the magnetoroton peaks present strikingly opposite temperature behavior. The ST mode energy is consistent with the activation energies for activated transport.

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