Spin-texture and magneto-roton excitations at $\nu = 1/3$

Javier G. Groshaus $^{1,2}$, Irene Dujovne$^{1,2}$, Yann Gallais$^1$, Cyrus F. Hirjibehedin$^{1,2}$, Aron Pinczuk$^{1,2}$, Yan-Wen Tan$^5$, and Horst Stormer$^1$

$^1$ Physics & Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027
$^2$ Alcatel-Lucent Bell Labs, Murray Hill, NJ 07974

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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 magneto-roton minimum. With increasing in-plane magnetic field these modes 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 magneto-roton 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, $\Delta_s$, as done in Refs. [1, 2, 3, 4]. At filling factor $\nu = 1/3$, the transport activation mechanism is often attributed to neutral excitations in the charge degree of freedom, namely, magneto-roton modes in the limit of large wavevector $\Delta_{\infty}$ [3]. As depicted in Fig. 1a. The magneto-roton energies scale with the Coulomb energy $E_C = e^2/\epsilon l_B$, where $\epsilon$ 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 $\Delta_{\infty}$ [3, 5]. Moreover, for low values of the ratio of the Zeeman and Coulomb energies, $\eta = E_z/E_C$, at $\nu = 1/3$ the measured $\Delta_s$ fails to scale with $\sqrt{B_\perp}$. $\Delta_s$ presents a term increasing linearly with the Zeeman energy, $E_z = g \mu_B B$, where $B$ is the total magnetic field. More surprisingly, $\Delta_s$ grows with $E_z$ with a slope $s \equiv \partial \Delta_s/\partial E_z = 3/2$ or $s = 2$ [3]. Such energy evolution suggests that at low $\eta$, the relevant thermally excited modes are spin-texture modes (ST), 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 $\Delta S_z = h \omega$.

Transport measurements at $\nu = 1$ for varying values of the in-plane component of the field $B_\parallel$ unveiled a steep change of $\Delta_s$ with $E_z$ with a slope $s$ much larger than

![FIG. 1: (color online) (a) Dispersion of the lowest magneto-roton 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 $S_1$ ($T_0$). The diamond is the activated transport gap for $B = B_\perp = 7.8$ T at $\nu = 1/3$. Dashed lines are fits.](image-url)
\(\eta\) 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 \(\nu > 1\) (Antiskyrmion) \([12, 13]\). Spin textures have been invoked also to explain the ground state around \(\nu = 1/3\) and the activation energies at \(\nu = 1/3\) \([4, 12, 14, 15, 16, 17]\).

Resonant inelastic light scattering is a direct probe of collective excitations of FQH liquids. Light scattering experiments have identified the long wavelength magneto-roton mode \(\Delta_0\) \([6, 7]\), modes at the magneto-roton minimum (MR) and large wave-vector modes. \([18, 19, 20]\).

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 \([13]\). Moreover, no ST excitations have yet been found in inelastic light scattering either at \(\nu = 1\) nor 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 \(B_{\perp}\) (and thus \(\eta\)) at \(\nu = 1/3\), the energy of the ST increases and crosses that of the MR at a field of \(\sim 9.5\) T corresponding to \(\eta_c = 0.020 \pm 0.001\), as shown in Fig. 1c. The dependence of the ST energy \(\omega_{ST}\) on \(B\) indicates that the ST mode involves \(s = \partial \omega_{ST} / \partial E_z = 2\) 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 magneto-roton modes, which collapse in the same temperature range (\(\sim 0.2 - 1\) K). These results are consistent with the coexistence of phases supporting magneto-roton excitations and phases supporting ST modes.

Optical measurements were performed on a single side modulation doped \(\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}\) quantum well with electron density \(n = 5.3 \times 10^{10} \text{ cm}^{-2}\) and mobility \(\mu = 7.2 \times 10^6 \text{ cm}^2 / \text{Vs}\). 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. 1b). The value of \(\eta\) is changed by varying this angle and adjusting \(B\) to keep \(\nu = 1/3\). This procedure amounts to varying \(B_{\perp}\) at constant \(B_{\parallel}\). A laser beam of photon energy \(\omega_L\) is incident on the sample along \(B\), and the backscattered photon, of energy \(\omega_S\), 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. 1a). Transport measurements of \(\Delta_0\) were performed on a similar \(\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}\) quantum well with \(n = 6.3 \times 10^{10} \text{ cm}^{-2}\) and \(\mu = 14 \times 10^6 \text{ cm}^2 / \text{Vs}\) in a perpendicular magnetic field.

Figs. 2a and 2b show resonant light scattering spectra at \(\nu = 1/3\) and total field \(B = 8\) T which is in the low \(\eta\) 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 \(\omega_L\). This selectivity is due to intermediate virtual states in the scattering process that are resonant with the scattered photon energy \(\omega_S\). A similar outgoing resonance has been observed for the long wavelength spin-wave \([22]\).

The outgoing resonance is illustrated in Fig. 2c, where we present a compilation of spectra such as those in Fig. 1(a,b) as a function of \(\omega\) and \(\omega_S\). The intensity of the signal is color coded (dark red means high intensity). Each mode, ST or MR, is identified by its corresponding \(\omega\). In addition, it can be seen that the ST and MR modes become resonant at different values of \(\omega_S\). Figure 2d 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 singlet and triplet excitonic states, respectively \([22, 23]\). Figures 2c and 2d 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 \(B_{\perp}\) is increased. Fig. 3 shows measurements at a higher \(B_{\perp}\) corresponding to \(\eta > \eta_c\). These measurements reveal that while the 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 magneto-roton modes have strikingly different temperature behaviors. As the temperature is raised, the strength of the ST mode increases while that of the MR and \(\Delta_0\) decreases. The quenching of \(\Delta_0\) with increasing temperature has been observed before \([6]\). A higher energy mode at 0.75 meV at \(B = 7.15\) T, possibly corresponding to \(\Delta_{\infty}\), shows a similar quenching behavior as the MR and \(\Delta_0\) (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 magneto-rotons 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 \(\alpha\) 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 $\nu = 1/3$ \cite{22}. Fig. 4 shows that the intensity of the MR and $\Delta_0$ 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 magneto-rotons quench. Therefore, we fit the ST with a dashed line proportional to $1 - n_0(T)$ using the same $\alpha$ and $T_c$ that we used for the magneto-rotons. It is noteworthy that the temperature range in which the magneto-roton modes survive largely overlaps the limited range at which longitudinal resistivity presents activated behavior \cite{1, 3, 4}. These results are consistent with a weakly disordered inhomogenous quantum fluid \cite{26} in which phases supporting magneto-roton excitations occupy a fraction $n_0(T)$ of the sample and coexist with and phases supporting ST modes in the remaining area.

We also find that the MR and $\Delta_0$ modes are rapidly quenched as the filling factor is tuned away from $1/3$. Such behavior has been reported before for the $\Delta_0$ \cite{6}. These findings suggest that as the system is rendered compressible, the quantum fluid that supports magneto-roton 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 $\nu = 1/5$ \cite{18, 19}. We find this mode to be resonant with $S_1$. At $\nu = 1/3$, it corresponds to the ST mode.

Turning again to Fig. 1c, we find that the MR mode energy remains approximately constant at 0.046$E_C$. This value is close to the calculated value of 0.052$E_C$, including finite width effects \cite{4, 8}, and consistent with the experimental value of 0.045$E_C$ obtained from $\Delta_a$ measurements for $\eta > \eta_c$ \cite{2, 3, 4}. Disorder may cause a slight decrease in the MR energy as $B$ increases \cite{27}.

Our activated transport measurements at $\nu = 1/3$ in a similar sample yield $\Delta_a = 5.3$ K, as shown in Fig. 1c (diamond). It is seen that the value $\Delta_a$ is consistent with the energy of the ST mode (both $\Delta_a$ 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 $\Delta_a$ in the same range of $\eta$, for $\eta < \eta_c$ \cite{2, 3, 4}.

The energy of the ST mode in Fig. 1c is well fitted by the linear expression $\omega_{ST} = sE_z + E_0$ with $s = 2$ and

![FIG. 2: (color) (a,b) Excitation spectra for different laser energies $\omega_L$ at 70 mK, $\nu = 1/3$ and total field $B = 8 T$. (c) Spectra such as those in (a,b) as a function of $\omega$ and $\omega_S$. Dark red means high intensity. (d) Resonant enhancement profiles of the ST and MR modes (dots) superimposed to the photoluminescence spectrum (black line).](image1)

![FIG. 3: (color online) Spectra at 40 mK and $\nu = 1/3$ as in Fig. 2c, but at the higher total field of $B = 10.1 T$ ($B_\perp$ is unchanged). The white line is the photoluminescence spectrum (PL).](image2)

![FIG. 4: (color online) Temperature dependence of the intensity of the MR, $\Delta_0$ 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.](image3)
$E_0 = 0.06 \text{ meV} = 0.005E_C$. We stress that for an accurate extraction of $s$, the value of $E_s$ as measured in situ by inelastic light scattering was used, 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 $\Delta_s$ at $\nu = 1/3$ for Ref. 3 (with $s = 2$), and Refs. 2, 11 (with $s = 3$). In Ref. 1, $\Delta_s$ 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 Antiskyrmions at $\nu = 1/3$. In Ref. 2, the activation of the resistivity process at low $\eta$ was described as the creation of a spin-reversed quasiparticle and a small Antiskyrmion in which one additional spin is flipped, yielding a total $s = 2$. The flipping of an extra spin to form an Antiskyrmion has a cost of $E_z$ in energy, while simultaneously obtaining a Coulomb gain in energy. $E_0$ can be obtained 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 $\Delta_{11} \sim 0.05E_C$. Calculations have been done both the strict 2D limit and including finite width effect 4, 12, 17, 23, 24. For $s = 2$, $E_0$ is predicted to be in the range $0.024 - 0.061E_C$, 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-Antiskyrmion 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 23. If indeed the energy of the ST is lowered due to disorder, such 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 magneto-roton peaks present strikingly opposite temperature behavior. The ST mode energy is consistent with the activation energies for activated transport.

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* Electronic address: [jgg@phys.columbia.edu](mailto:jgg@phys.columbia.edu) Institute for Optical Sciences, Dept. of Chemistry & Dept. of Physics, University of Toronto, Toronto, ON, Canada.
1 Tu Delft, Kavli Inst. of Nanoscience, The Netherlands.
2 Laboratoire Matériaux et Phénomènes Quantiques, CNRS UMR 7162, Université Paris 7, France.
3 London Centre for Nanotechnology, Deps. of Physics & Astronomy and Chemistry, UCL, London, U.K.
4 Dept. of Physics, UC Berkeley, CA 94720.

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