Resonant Inelastic Light Scattering Investigation of Low-Lying Gapped Excitations in the Quantum Fluid at ν=5/2

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Experimental evidence of low-lying gapped excitations in the quantum fluid at ν=5/2

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Abstract

The low-lying neutral excitation spectrum of the incompressible quantum Hall fluid at $\nu = 5/2$ is investigated by inelastic light scattering. Gapped modes are observable only in a very narrow filling factor range centered at 5/2 at energies that overlap estimates from transport activation gaps. The modes are interpreted as critical points in the wave-vector dispersion of excitations that preserve spin orientation. For very small changes $|\delta\nu| \lesssim 0.01$ the gapped modes disappear and a continuum of low-lying excitations takes over indicating the transition from an incompressible fluid at 5/2 to a compressible state. Observations of spin wave modes indicate spin polarization of the 5/2 and 2+1/3 quantum Hall fluids.

The impact of electron interactions in the first excited Landau level (N=1) differs significantly from those in the lowest (N=0) Landau level. While a compressible fermi sea is formed at filling factors ν=1/2 and ν=3/2, at ν=5/2 and 7/2 incompressible fluids manifest by quantum Hall plateaus. The enigmatic states of the even denominator fractional quantum Hall effect (FQHE) states are the focus of intense research efforts. The Moore-Read (MR) Pfaffian many-body wave function is a prime candidate for the 5/2 state [1]. In the MR description a weak attractive interaction among spin polarized fermion quasiparticles (QP) in the second LL results in a condensed state of p-wave paired QPs. An exciting property of the MR state is that QP excitations obey non-Abelian braiding statistics [1], making the state a candidate to realize fault tolerant quantum computation [2, 3]. Numerical evaluations consistently indicate that either the MR Pfaffian wave function [4–7] or its particle-hole conjugate the Anti-Pfaffian (AP) wave function [8–10] represent the 5/2 ground state. Experimental observations support predictions of the MR or AP frameworks [11–18]. The state of spin polarization of the 5/2 quantum fluid attracted much recent attention [17–19], largely because full spin-polarization is a distinctive property of a non-Abelian state.

The low-lying excitation spectrum of the non-Abelian state is understood to support three types of neutral excitations: spin-wave modes (SW) of a fully spin-polarized FQHE ferromagnet [20], charge density excitations that conserve spin (dispersive 'gap-excitation') and neutral fermions (NF's a.k.a. 'topological excitons') [21–24]. Numerical calculations show that the wave vector dispersions of NF and gap excitations display distinct 'roton-minima' at finite wave vector but converge to the same value in the large wave vector limit [22, 23].

Neutral excitations that conserve spin (a.k.a. charge density excitations) exhibit characteristic wave-vector dispersions that are unique to each FQHE state. Inelastic light scattering experiments offer insights on the collective excitation spectrum of incompressible quantum fluids. Light scattering spectra yield determinations of the $q \to 0$ mode [25] and of critical points in the wave vector dispersion that occur at roton minima and in the large wave vector limit ($q \to \infty$) [26, 27]. The charge density mode at $q \to \infty$ is regarded as the gap of the FQHE state [28]. There is consistent quantitative agreement between mode energies determined by inelastic light scattering experiments and calculated energies of neutral collective excitations of FQHE states in the N=0 LL [27, 29]. Gap energies determined from activated transport are significantly smaller than calculated gap energies for realistic sample parameters [30–33]. The discrepancy is interpreted as arising from impact of residual-disorder on charge transport.

In this letter we report observations of low-lying excitations at ν=5/2. The neutral modes are revealed in resonant inelastic light scattering (RILS) spectra. These are gapped excitations in which the lowest modes have non-vanishing energy. The lowest energy band is the strongest in the RILS spectra. This band is interpreted as a roton critical point in the q-dispersion of neutral charge density excitations. Remarkably, the gapped modes are observed only in a very narrow filling factor range centered around 5/2. Very minor changes in filling factor of $|\delta\nu| \lesssim 0.01$ result in a transition from an incompressible quantum fluid with gapped excitations at 5/2 to compressible states with gapless excitations at filling factors only slightly away. These results provide experimental evidence that the intriguing incompressible quantum fluid that emerges at $\nu = 5/2$ supports gapped low-lying excitations.

A mode that apears at the bare Zeeman energy E_Z is assigned to a $q \to 0$ SW excitation. Its presence in the spectra reveals a high degree of spin-polarization at 5/2. However, the mode at E_Z disappears for very small changes $\nu = 5/2 \pm \delta$ ($0.04 \geq \delta \geq 0.01$) indicating either a rapid loss of spin polarization away from the incompressible state at 5/2 or the impact of competing phases in the bulk diminishing the SW mode and dominating the low-energy excitation spectrum by gapless excitations. Distinct SW modes at E_Z are also observable in the range $2 + 1/3 \geq \nu > 2$, suggesting a high degree of spin polarization at those filling factors. These findings are in agreement with recent experiments showing a spin polarized ground state for 5/2 [17, 18] and 2+1/3 [34].

The ultra-clean two dimensional electron system is confined in a 300Å symmetric single GaAs/AlGaAs quantum well. The sample is mounted on the cold finger of a ^{3}He/^{4}He-dilution refrigerator with windows for direct optical access and inserted in the bore of a 16T superconducting magnet. All measurements were performed at $T \lesssim 45$mK. The back scattering geometry is described in Fig. 1 (a). The tilt angle θ is kept small ($\theta \approx 20^{\circ}$) to minimize the impact of the small in-plane component of magnetic field on the 5/2 state [35]. The finite momentum transfer in back scattering is $k = |\vec{k_L} - \vec{k_S}| = (2\omega_L/c)\sin\theta$, where $k_{L(S)}$ is the in-plane component of the incident (scattered) photon, ω_L the incoming photon energy and c the speed of light in vacuum. Spectra are excited by the linearly polarized light from a Ti:Sapphire laser. ω_L is finely tuned to be close to the optical emission from the N=1 LL

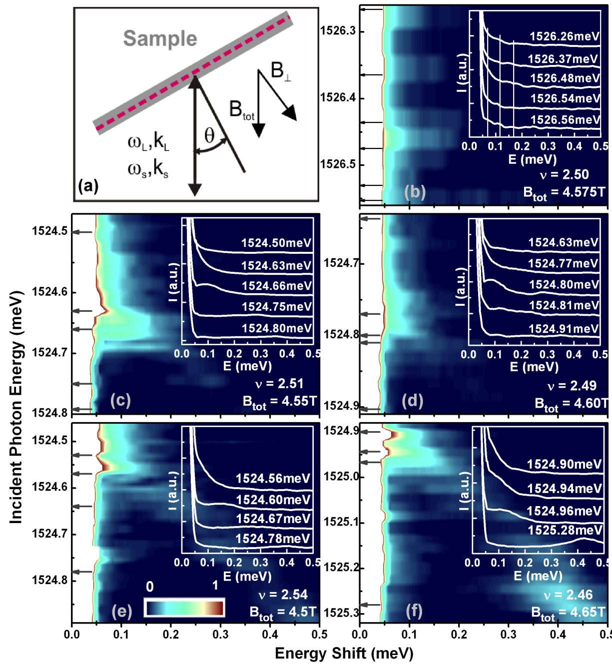

FIG. 1. (Color online) (a) Schematic of the light scattering geometry. (b)-(f) Color plot of RILS intensities for photon energies close to the optical emission of the N=1 LL at $\nu = 5/2 \pm \delta$ ($\delta \leq 0.04$) as a function of ω_L (see [37]). The spectra in the insets are at ω_L's marked by horizontal arrows in the color plot. The broad peak at higher enrgies and large photon energies at $\nu = 2.46$ (f) is from luminescence.

to resonantly enhance the light scattering intensity [19, 36]. The scattered light is dispersed by a triple grating spectrometer and recorded by a CCD camera with a combined spectral resolution of $< 20\mu$eV. The incident power density was kept well below 10^{-4}W/cm^2. The determination of the magnetic field for $\nu = 3$ from the maximum of the SW intensity in RILS measurements precisely identifies the filling factor as a function of magnetic field [37] and yields a density $n = 2.6 \times 10^{11}$cm^{-2}. Carrier mobility at $T = 300$mK in a different sample from the same wafer is $\mu = 23.9 \times 10^6$cm^2/Vs (at $n = 2.9 \times 10^{11}$cm^{-2}).

Figures 1 (b) to (f) display RILS spectra in close vicinity to ν=5/2. In Fig. 1(b) spectra at $\nu = 5/2$ reveal gapped (i.e. at non-vanishing energy) low energy modes marked by the vertical lines. However, the low energy part of the spectrum in 1 (b) is obscured by the tail from an extremely strong resonant Rayleigh scattering (RRS) [19]. Figures 1(c) and (d) show that by tuning the filling factor slightly away from 5/2 ($|\delta\nu| \approx 0.01$ and $\Delta B_{tot} = 25$mT), the intensity of the low energy tail is enhanced. Figures 1(e) and (f) show that for $|\delta\nu| \approx 0.04$

from 5/2 the spectra consist of a strong continuum of gapless excitations similar to that reported by Rhone *et al.* [19] that is attributed to a robust domain structure that emerges slightly away from 5/2.

Figure 2(a) displays RILS spectra measured for a higher lying resonance [36]. These spectra are better defined because the RRS is significantly weaker. They reveal three modes at the positions highlighted by vertical lines in the color plot and also in the individual spectra shown in the inset. These are low-lying gapped excitations of the 5/2 state. The suppression of the continuum of gapless modes at 5/2 suggests that the phase of the quantum fluid at 5/2 overwhelms the compressible phases that are predominant at filling factors slightly away from 5/2. The narrow magnetic field range for the observation of low-lying gapped excitations of the 5/2 state is similar to the magnetic field range of the 5/2 signatures observed in magneto-transport.

The strongest band in Fig.2 (a) is the lowest mode labeled Δ_R that is centered at 0.07meV. There are two weaker features in the spectra. One, at energy 0.12meV is at the bare Zeeman energy E_Z of GaAs. The other one at $\Delta_\infty = 0.17$meV is the highest energy mode in these spectra. The band of the mode at Δ_R is significantly below the spin-reversal energy E_Z indicating that the mode is not a spin excitation. Δ_R is close to gap energies reported in activated magneto transport at $\nu = 5/2$ [31–33, 38–40]. This similarity strongly suggests that the modes at Δ_R are low-lying spin-conserving neutral excitations of the incompressible quantum fluid at $\nu = 5/2$. The excitations in Fig. 2 (a) are interpreted with the conceptual framework that was successful for RILS by quantum Hall fluids of the N=0 LL. For FQHE states with $\nu < 1$ RILS spectra display wave vector conserving modes at $k = q \to 0$ [25]. There are stronger modes at large q ($q > k$) that are activated by breakdown of wave vector conservation due to weak residual disorder. These RILS spectra display maxima at critical points in the mode dispersion [26, 27, 29].

To extend this framework to the quantum Hall state at $\nu = 5/2$ we show in Fig.2 (b) a tentative schematic wave vector dispersion of low-lying gapped excitations. This dispersion displays a characteristic magnetoroton minimum at wave vector $q_R \approx 1/l_B$, where $l_B = [\hbar/eB_{perp}]^{1/2}$ is the magnetic length [21–23]. Within this framework the lowest mode Δ_R is interpreted as the critical point that occurs at the roton. The intensities at Δ_R are found to collapse quickly for $T > 250$mK. Such temperature dependence is consistent with the interpretation of Δ_R as a roton of the 5/2 state. The highest energy mode Δ_∞ is identified

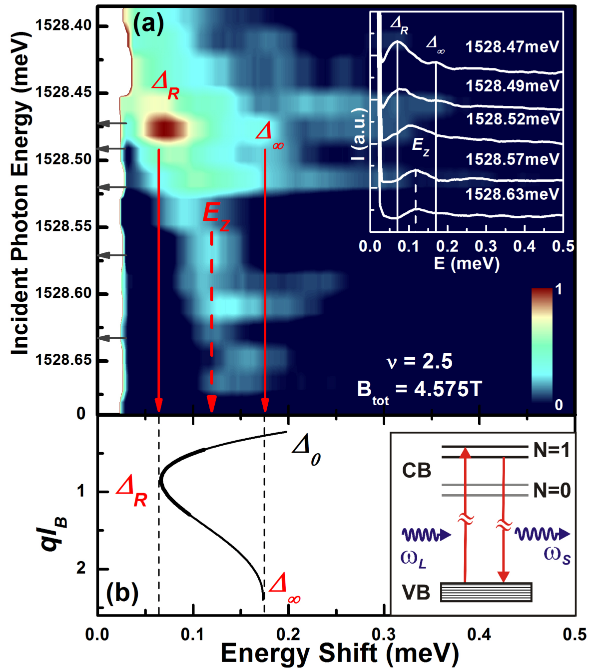

FIG. 2. (Color online) (a) Color plot of RILS intensities in smoothed spectra measured at $\nu = 5/2$ as function of ω_L. Three modes are resonantly enhanced at the energies Δ_R, E_Z and Δ_∞. The spectra in the inset are at at ω_L's marked by horizontal arrows in the color plot. (b) Empirical wave vector dispersion based on the RILS mode energies showing at least one deep roton minimum in the neutral collective excitation spectrum. The inset is a schematic of optical transitions in RILS.

as the large q limit of the mode dispersion. This limit represents a neutral particle-hole pair at large separation that is understood as the intrinsic transport gap of the $\nu = 5/2$ state. The energy $\Delta_\infty = 0.17$meV (see Fig. 1) is in very good agreement with a calculation of the intrinsic gap that includes finite width and LL mixing [30]. The value of Δ_∞ also agrees well with experimental determinations of the intrinsic transport gap (from activated transport) that take into account the impact of residual-disorder by a subtractive broadening term Γ [32].

The energy of the band at E_Z in Fig. 2 (a) is written as $E_Z = \mu_B g B_{tot}$, where μ_B is the Bohr magneton and g is a bare g-factor. $E_Z = 0.12$meV yields $|g|$=0.44, close to the bare g-factor of GaAs. This spin excitation can be regarded as the $q \to 0$ limit of a dispersive SW mode as required by Larmor's theorem. To explore this interpretation, which implies that the quantum fluid at 5/2 has spin polarization, we show in Fig. 3(a) spectra

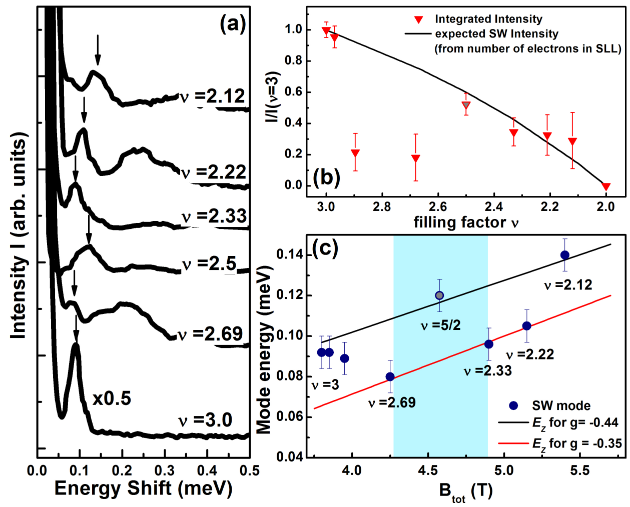

FIG. 3. (Color online) (a) Spin wave modes at E_Z in the range $3 \geq \nu > 2$.The broad peak at higher energy at $\nu = 2.69$ and 2.22 are due to luminescence. (b) Integrated SW mode intensity after background substraction relative to the intensity of the SW at $\nu = 3$. The solid line depicts the population of electrons residing in the lower spin-branch of the SLL. The solid triangles are the measured integrated mode intensities. (c) SW mode energy as a function of total magnetic field. Solid lines are E_Z for effective g-factors 0.44 (black) and 0.35 (red).

where a band at E_Z is present for $\nu \leq 5/2$. The SW spectra at $\nu = 3$ and 2.69 are also shown. For filling factors $\nu < 3$ the lowest spin-up branch of the N=1 LL is depopulated and the expected intensity of the SW quickly drops. Figure 3(b) shows measurements of the integrated intensity at E_Z relative to the integrated intensity of the E_Z band at $\nu = 3$. There is good agreement of the measured points at 5/2 and $2 + 1/3 \geq \nu > 2$ with a calculation of the drop in population of the lowest spin-up branch of the SLL shown in Fig.3 (b) as a solid line. The finding that the intensity of the SW at E_Z is linked to the expected population of the spin-up branch of the of the N=1 LL suggests that FQHE states at $\nu = 5/2$ and $2+1/3$ could have full polarization of spin as found in NMR experiments [17, 18].

The SW mode energies are plotted as a function of B_{tot} in Fig. 3(c). At filling factors 3, 5/2 and 2.12 the mode energies are on a line for a g-value of $|g| = 0.44$ (black line). For $\nu \approx 2 + 2/3, 2 + 1/3, 2 + 1/5$ the SW energies are falling on a line with $|g| = 0.35$ (red line). This redshift is not fully understood. In one scenario, it could result from breakdown of wave-vector conservation in RILS in conjunction with a negative SW dispersion [29] or the formation of spin-textures [41].

The absence of SW modes in the near vicinity of 5/2 and the emergence of a strong scattering continuum of gapless low-lying excitations for $\nu = 3 \pm \delta$ resemble the behavior of the SW mode at and around the quantum Hall ferromagnet $\nu = 1$ [41]. The findings at $\nu = 1 \pm \delta$ were interpreted as evidence of Skyrme textures in the ground state [41]. While the formation of Skyrmions at 5/2 has been numerically investigated [42], changes such as the absence or reduction of the SW intensities could also be caused by the fluid at 5/2 breaking-up into domains thus suppressing the intensity of collective excitations. In Fig. 3(a) the SW modes measured at $\nu = 5/2$ and at $\nu = 2.12$ are significantly broader than those at the other filling factors. The enhanced broadening could be a signature of a more complex interplay of interactions and onset of localization from non-uniform domains.

In summary, we report the discovery of gapped low-lying excitations in a narrow range of filling factor around $\nu = 5/2$. The resonant inelastic light scattering experiments reveal that for filling factor changes $|\delta\nu| \lesssim 0.01$ the gapped excitations are replaced by gapless modes. The experiments also show spectra in which the observation of a SW mode at the bare Zeeman energy is consistent with full spin-polarization at 5/2 and also in the filling factor range $2 + 1/3 \geq \nu > 2$. These findings demonstrate new experimental venues to study intriguing FQHE fluids that could have applications in topological quantum information processing.

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