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Rapid collapse of spin waves in non-uniform phases of the second Landau level

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The spin degree of freedom in quantum phases of the second Landau level is probed by resonant light scattering. The long wavelength spin wave, which monitors the degree of spin polarization, is at the Zeeman energy in the fully spin polarized state at ν=3. At lower filling factors the intensity of the Zeeman mode collapses indicating loss of polarization. A novel continuum of low-lying excitations emerges that dominates near ν=8/3 and ν=5/2. Resonant Rayleigh scattering reveals that quantum fluids for $\nu < 3$ break up into robust domain structures. While the state at ν=5/2 is considered to be fully polarized, these results reveal unprecedented roles for spin degrees of freedom.

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The study of the quantum Hall effect in the second (N=1) Landau level (LL) is at the forefront of physics research. In the second LL lies the state at filling factor $\nu = 5/2$ [1, 2], the best known even denominator quantum Hall state - defying the paradigm of odd-denominator fractional quantum Hall states[3, 4] and leaving a challenge to the understanding of quantum Hall physics. The 5/2 quantum Hall state is predicted to realize a non-abelian phase - the Moore-Read Pfaffian[5], an exotic form of matter, still unconfirmed experimentally. The Moore-Read state may facilitate the implementation of topological quantum computation[6]. Efforts are being made to confirm the non-abelian nature of the 5/2 state[7].

The Moore-Read state at $\nu = 5/2$ should be realized by a spin polarized ground state[5]. Many numerical simulations predict a polarized ground state. This prediction however lacks definitive experimental verification. For instance, transport measurements[8–10] suggest that the role of spin for the states at ν=5/2, 8/3 and 7/3 disagrees with accepted theoretical models. Great strides towards understanding the 5/2 quantum Hall state and the spin degrees of freedom have been made with recent experimental and theoretical work[11–18]; nevertheless a complete understanding still evades our grasp.

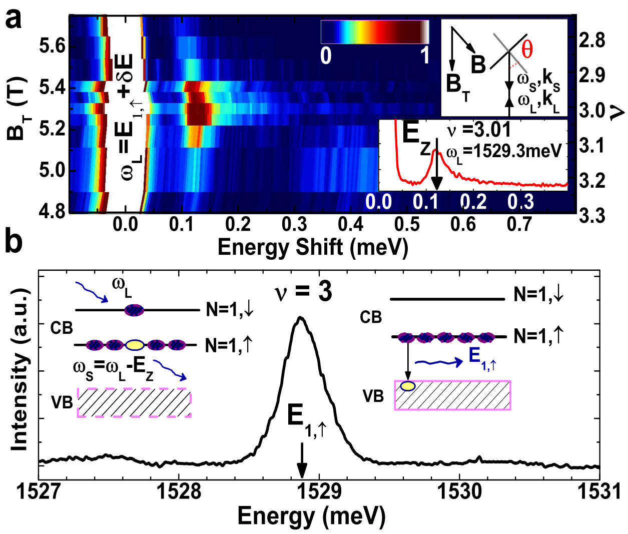

FIG. 1: Evidence of loss of spin polarization away from $\nu = 3$. **(a)** Color plot of resonant inelastic light scattering spectra with varying magnetic field shows the spin wave (SW) at the Zeeman energy, E_Z. The intensity of the SW attenuates away from $\nu = 3$ (B_T=5.32T). The top inset shows the light scattering geometry. The bottom inset exhibits a spectrum at $\nu = 3.01$. **(b)** N=1 optical emission involved in resonance enhancement of light scattering (B_T=5.3T,θ=20^o, T=40 mK). The left inset shows the two step inelastic light scattering process for the SW. The right inset is the energy level diagram for optical emission from the $N = 1, \uparrow$ LL.

Resolving the 'puzzle' of spin polarization of the 5/2 state has emerged as an important challenge that would create key insights on the physics of quantum fluids in the second LL. Read[19] had suggested using the Knight shift to study the spin polarization of the 5/2 state. Rhone et al.[13] have used inelastic light scattering to study the spin polarization of states in the second LL and at $\nu = 5/2$ in particular. The work suggests that quantum fluids observed at 5/2 do not have full spin polarization. Loss of spin polarization at 5/2 has been studied theoretically[14] and is reported in an optics experiment[16].

In this letter, the physics of the spin degrees of freedom of the N=1 LL is addressed by resonance inelastic light scattering (RILS) and resonance Rayleigh scattering (RRS). The spin degrees of freedom are monitored by changes in the RILS intensity of the long wavelength spin wave (SW) at the Zeeman energy, E_Z [20]. Unexpectedly, the SW intensity, an indicator of spin polarization, collapses rapidly for $\nu < 3$. The RRS effect that, like the collapse of the mode at E_Z, appears below $\nu = 3$, reveals that the quantum fluids in the partially populated N=1 LL are highly inhomogeneous, breaking up into 'puddles' that have characteristic sub-micron dimensions.

The collapse of the SW mode at E_Z for $\nu < 3$ is accompanied by the emergence of continua of excitations (below and above E_Z) that can be regarded as low-lying excitations of new quantum phases in the N=1 LL. The similar resonance enhancements of the low lying continua and of RRS is evidence that the lost spin polarization, seen as the replacement of the peak at E_Z by a low-lying continuum of excitations, arises from the domains ('puddles') of quantum fluids that emerge for $\nu < 3$.

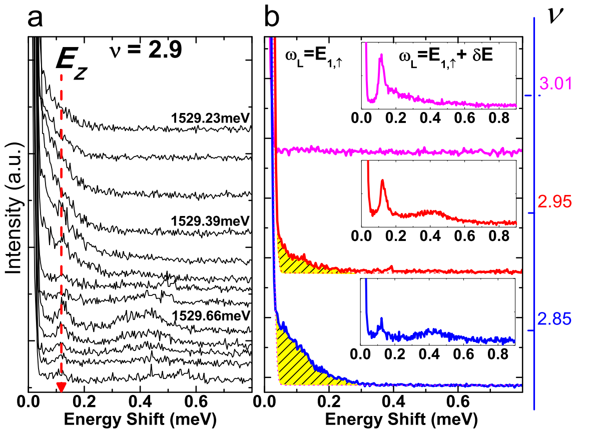

FIG. 2: Coexistence of novel quantum phases with the ferromagnetic SW. **(a)** Tuning the incident photon energy for excitations at filling factor slightly away from ν=3 (ν=2.9, B_T=5.5 T, T=40mK) induces the collapse of the SW and the emergence of a continuum of low lying energy excitations. The SW resonance is at higher photon energy than that of the continuum. **(b)** We monitor the behavior of the low lying excitations while tuning the filling factor [23]. We track two distinct modes below $\nu = 3$ - the SW and continuum of low-lying excitations. The insets show the SW collapse while the main panel shows the emergence of the continuum of low lying excitations. The continuum is resonant at slightly lower incident photon energy,$\omega_L(B)$ than the SW.

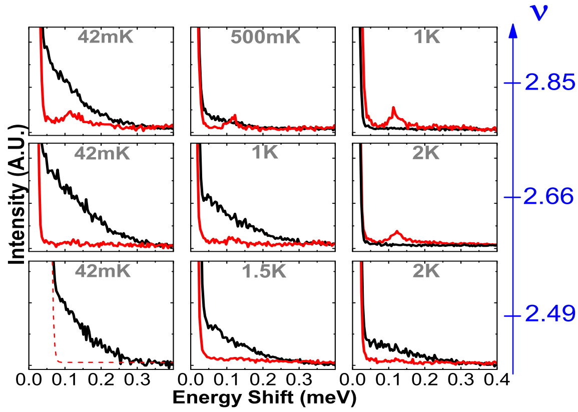

FIG. 3: Temperature dependence measurements at various filling factors of low lying modes. The continuum (black lines) melts at elevated temperature. The SW (red lines) reemerges at elevated temperature for $\nu \simeq$8/3 (B_T=6.0 T) and 5/2 (B_T=6.42 T, in the red spectrum at 2K there is a glitch at E_Z not visible on the scale shown). The dashed line in the lower left panel is a guide to the eye.

Most likely, the emergence of 'puddles' are linked to competition between quantum phases reported in other experiments [8–10, 21, 22]. The present results differ from prior work in revealing a loss of full spin polarization and that this remarkable character persists to temperatures as high as 1K and above. Domains lacking full spin polarization are here a key feature of the quantum phases of the N=1 LL. We note that while emerging from spin unpolarized domains, further studies of condensation into the quantum Hall state at $\nu = 5/2$ may still result in an incompressible fluid that has spin polarization.

The high-quality 2D electron system studied here is formed in an asymmetrically doped, 240 Å wide GaAs single quantum well. The electron density is n=3.7x10^{11} cm^{-2} and the mobility is μ=17.5x10^6 cm^2/Vs at T=300 mK. Samples are mounted on the cold finger of a dilution refrigerator with a base temperature of 40 mK inserted into a 17 T superconducting magnet. The magnetic field perpendicular to the sample is $B = B_T cos\theta$ as shown in the inset of Fig.1(a). Light scattering measurements are performed through windows for optical access. The energy of the linearly polarized photons, ω_L (incident) and ω_S (scattered), are tuned close to fundamental optical transitions of the N=1 spin up LL, $E_{1,\uparrow}$ (see Fig. 1(b)). Due to resonance enhancements, light scattering spectra have a marked dependence on ω_L - displayed in Fig. 2(a). The power density is kept less than 10^{-4}Wcm^{-2} to avoid heating of the electron gas. Scattered light is dispersed and recorded by a triple grating spectrometer with resolution of 30 μeV. RILS data focus on spectral weight with non-zero energy shifts from the incident laser wavelength, while RRS data comprise only the spectral weight of elastically scattered light.

The striking collapse of the SW intensity at E_Z for $\nu \lesssim 3$ is shown in Fig. 1(a). The color plot shows RILS spectra, taken at different B fields at the resonance value of ω_L (the value for ω_L that induces resonance enhancement varies with the cyclotron energy and $E_{1,\uparrow}$). All the features appear predominantly in the depolarized configuration (VH) which, according to light scattering selection rules, indicates their spin origin[25]. While Larmor's theorem requires that the SW's energy remains at the bare Zeeman energy, its overall spectral weight is expected to depend sensitively on the degree of spin polarization [20, 24]. The collapse of the SW is thus interpreted as the reduction of spin polarization in the N=1 LL from its maximum value at $\nu = 3$. While, a reduced SW intensity is expected for $\nu > 3$ (both $N = 1,\uparrow$ and $N = 1,\downarrow$ are populated reducing the overall spin polarization), the attenuation of the SW for $\nu < 3$ is surprising ($N = 1,\uparrow$ depopulates as B increases) and suggests a rapid loss of spin polarization below $\nu = 3$.

Tuning ω_L results in striking spectral changes that are due to differences in resonance enhancements. This is illustrated in Fig. 2(a) which shows the metamorphosis of the sharp SW at E_Z to a broad continuum of lower energy excitations at ν=2.9 when tuning ω_L. The continuum extends from well below E_Z to 0.3 meV. In Fig. 2(b) the evolution of the continuum (main panel) and SW (inset) intensities is shown as a function of filling factor. Since the intensity of the SW and continuum resonate at different values of ω_L, RILS spectra are shown for values of ω_L corresponding to their maximum resonant enhancement: $E_{1,\uparrow}$ for the continuum and $E_{1,\uparrow}$+δE for the SW. While the SW is clearly reduced for $\nu \lesssim 3$, the continuum intensity, absent at $\nu = 3$, gains in strength away from $\nu = 3$ indicating its link with the loss of spin polarization. Moreover, in contrast to the N=0 LL, where Skyrmions proliferate at $\nu \sim 1$ [20], we surmise that the continuum of low-lying excitations at $\nu \lesssim 3$ have a different origin. We speculate that the continuum is a novel type of spin excitation associated with loss of polarization. This interpretation is bolstered by the absence of continua for $\nu \lesssim 3$ in polarized configuration (HH) while still being present in depolarized configuration (VH).

Figure 3 shows the temperature dependence of the RILS spectra at three filling factors reaching to 5/2. At ν=2.85, the continuum seen at 40 mK melts entirely at 1 K, while the SW intensity at E_Z remains or even gains in strength. At $\nu \simeq 8/3$, the continuum dominates at low temperature, begins to melt at 1 K and is destroyed by 2 K. The SW at E_Z reemerges at 1 K and is fully recovered by 2 K. While the spectral weight of the continua at $\nu \sim 8/3$ are greater in VH than in HH, they are the same in both VH and HH at $\nu \sim 5/2$ indicating a more complex excitation spectrum at ν=5/2, possibly involving both charge and spin degrees of freedom (data not shown to avoid clutter).

The temperature dependence for excitations at $\nu \simeq 5/2$ is remarkable. As the temperature is raised to 1.5K, the continuum begins to melt, and is still present, albeit reduced, at 2K. In addition, a small bump is seen at E_Z - hinting at a reemerging SW. We note that the continuum does not seem to be a unique feature of the magic filling factors or gapped quantum Hall states. However it is a feature of the quantum fluids of the 2nd LL and appears to grow more robust as ν is tuned below three.

The spectra in Figs. 2 and 3 suggest competing quantum phases. One phase is associated with a SW at E_Z and the other with the continua of excitations. To further explore these behaviors we measured RRS spectra. Figure 4 reports the results at several filling factors: RRS spectra at $\nu \sim$ 5/2 and 8/3 show marked resonance enhancements at energies that coincide with the maximum resonance enhancement of the continuum, and contrasts with the unremarkable RRS profile of the ferromagnetic state at $\nu \sim 3$.

RRS is linked to spatial inhomogeneities (domains) which are on the order of the photon wavelength [26]. RRS results demonstrate formation of domains in the quantum fluid at $\nu \lesssim 3$, that are consistent with transport measurements showing the competition between nearly degenerate quantum phases in the 2nd LL which include spatially inhomogeneous ones associated with a Re-entrant Integer Quantum Hall Effect (RIQHE) [8, 21].

The temperature dependence of RRS shown in Fig. 5 shows a weakening of the RRS upon increasing temperature and supports the picture that at low temperatures an inhomogeneous electron condensate forms at 5/2 and 8/3. We interpret the attenuation of RRS at higher temperatures as the melting of puddles of quantum phases. The inset to Fig. 5 shows that a Langmuir adsorption isotherm (Eqn. 1), that interprets the formation of inhomogeneous integer quantum Hall fluids [26], also describes results at 5/2 and 8/3. In this framework, we describe nucleation of "quantum puddles" to binding sites - forming domains in the quantum fluid. The areal intensity of the RRS, I_{RRS} is given by,

$$I_{RRS}(T) = \frac{I^0_{RRS}}{1 + CTexp(-E_b/kT)} \quad (1)$$

E_b is the binding energy of particles to binding sites and $C = 2\pi M k_b / N_p h^2$, where N_p is the density of binding sites and M as the mass of the bound particle. A fit

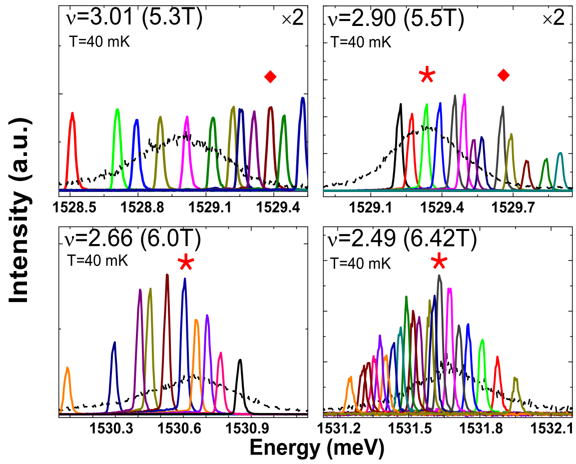

FIG. 4: RRS resonance profiles for ν=3.01, 2.9, 2.66 and 2.49. No resonance enhancement is seen for the ferromagnetic state at $\nu = 3$. At $\nu = 2.9$ some structure in the resonance profile develops. At $\nu = 2.66$ and $\nu = 2.49$, a resonance is seen at $E_{1,\uparrow}$. Black dashed lines represent optical emission while colored peaks represent elastically scattered light intensity. Diamonds (Stars) represent the spectra in which the SW (continuum) has a maximum resonance.

to data shown in the Fig. 5 inset yields an estimate of $N_P \sim 5 \times 10^9 cm^{-2}$, with M as the composite fermion (CF) mass of about 10 times the effective electron mass[27]. E_b is 0.06 meV. The presence of domains in the quantum fluid in the N=1 LL has implications for the spin properties of the system. The formation of domains has the potential to destroy the long range magnetic order and its associated long wavelength excitations. Consequently, the SW at E_Z might not effectively monitor local polarization. Thus, within the domains, determining the exact nature of the spin polarization remains challenging.

It is interesting to compare the RILS results at 8/3 and 5/2 with those for the states of their analogs in the N=0 LL - ν=2/3 and ν=1/2. At similar B fields, states at ν=2/3 and ν=1/2 are characterized by a SW[20, 28]. This indicates spin polarization at 2/3 and 1/2.

The temperature dependence of the continuum close to 5/2 is reminiscent of work reported by Willett et al. [29], showing that a CF Fermi sea at ν=5/2 exists within the temperature range 300mK<T<1100mK. The signature of the CF Fermi sea becomes weaker with elevated temperatures. It is possible that the continuum of low-lying excitations at 5/2 might be a signature of CFs. The above results seem to indicate that the loss of spin polarization found in the N=1 LL occurs in domains of characteristic sub-micron length. It is thus conceivable that there may be no contradiction among works reporting spin polarized states at 8/3 [10] and at 5/2 [5, 11, 12, 15, 31–33]. In this scenario, spin polarized domains could coexist with quantum Hall fluids that have lost spin polarization. The presence of residual disorder suggests that at 5/2, a new type of Skyrmion structure may proliferate in the ground state that may be the origin of the spin un-polarized domains at this filling factor[14]. At 5/2 the dimension of the spin polarized domains might be sufficiently small to disrupt completely the long wavelength SW. Therefore at this fill-

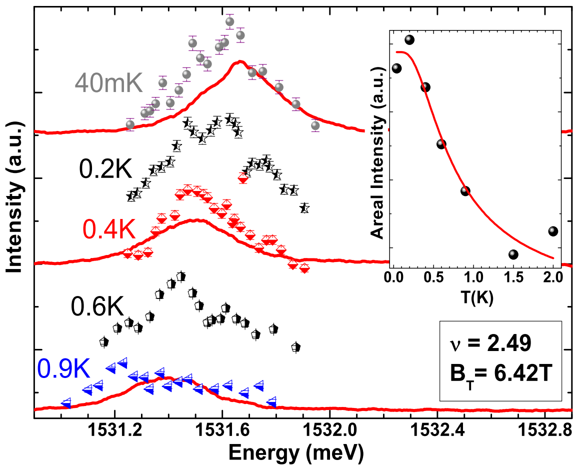

FIG. 5: Temperature dependence of the Rayleigh scattering resonance (RRS) profile for $\nu \sim 5/2$. Optical emission spectra (continuous lines) along with the laser peak heights (scatter plots) of RRS intensity are displayed. A peak in the resonance enhancement of the elastically scattered light coincides with the maximum intensity of the continuum. This enhancement is attenuated at elevated temperatures. The inset shows the relationship between the area under the RRS profile and temperature. The solid line represents a fit to the data using the Langmuir isotherm[26].

ing factor we cannot dismiss the possibility of polarized domains at low temperature.

Our work suggests that un-polarized, together with polarized domains may be a general feature of the quantum fluids in the 2nd LL (including at $\nu = 5/2$) - continua being linked to partially polarized or un-polarized domains. A possible mechanism for the formation of continua of spin excitations as reported here could be similar to that of spin-flip excitations in the N=0 LL[28], whose spectral weight below E_Z emerges if the CF Fermi energy is greater than the CF spin reversal gap energy.

In summary, a collapse of the SW at for $\nu \lesssim 3$ indicates loss of spin polarization in the N=1 LL from its maximum at $\nu = 3$. The SW's absence for $\nu \simeq$8/3 and 5/2, and the emergence of quantum phases composed of submicron domains seen in RRS pose striking new challenges for the interpretation of roles of spin degrees of freedom in the 2nd LL.

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