Temperature Dependence of the Spin Polarization of a Quantum Hall Ferromagnet

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The absolute spin polarization of a two-dimensional electron gas has been measured as a function of temperature at the $\nu = 1$ quantum Hall state by magnetoabsorption spectroscopy. We find that the electrons become fully polarized as $T \to 0$ and that the loss of spin polarization over the temperature regime of 500mK to 12K is consistent with a recently proposed continuum quantum ferromagnet model of the spin thermodynamics of the $\nu = 1$ QHE state.

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A rapidly growing body of evidence, both theoretical [1–3] and experimental [4–7], strongly suggests that the lowest-lying charged excitation of the spin-polarized $\nu = 1$ quantum Hall state is a spin-texture called a Skyrmion. This many-body state consists of radial spin density that is reversed at the center but gradually heals to the spin background over many magnetic lengths. The spin density distribution is determined by the interplay of the ferromagnetic exchange interaction and the Zeeman energy. The exchange interaction favors large Skyrmions while the Zeeman term favors smaller excitations. In GaAs samples presently under investigation the exchange energy can be up to two orders of magnitude larger than the Zeeman energy. Hartree-Fock calculations [2] predict that Skyrmions should consist of 3 $\sim$ 4 spin flips per unpaired flux quantum for small excursions about $\nu = 1$, a result consistent with early experimental work on the filling factor (ν) dependence of the spin polarization near $\nu = 1$ [4,6]. This dominance of the exchange interaction over the Zeeman energy has led theorists to refer to the $\nu = 1$ quantum Hall state as a quantum Hall ferromagnet. In GaAs heterostructures experimentalists are presented an unprecedented opportunity to probe the physics of two-dimensional electron ferromagnetism in a well-characterized system. Thus insights gained from the thermodynamics of the spin polarization will be of interest not only to those studying many-body effects in the integral quantum Hall regime, but also more generally, may elucidate the physics of 2D electron magnetism.

In this communication we report on the experimental determination of the spin polarization as a function of temperature for such a $\nu = 1$ quantum Hall ferromagnet. The system consists of a single-side n-modulation doped AlGaAs-GaAs single quantum well (SQW). The well thickness is 250 $\mathring{A}$ with an electron density of $N_s = 1.8 \cdot 10^{11} cm^{-2}$ and mobility $\mu = 2.6 \cdot 10^6 cm^2/Vs$. In order to perform absorption measurements the samples were mounted strain-free and thinned to $\sim 0.5 \mu m$. The spin polarization is monitored through band-to-band absorption spectroscopy which distinguishes the occupancy of the two electron spin states. Band-gap absorption spectra show striking temperature dependence due to changes in the occupations of the spin-split states of the ground Landau level at filling factors near $\nu = 1$. Knowledge of the temperature dependent occupations of the spin-up (0^+) and spin-down (0^-) electron levels leads to a thermodynamic measure of the spin polarization.

The data and discussion focus on transitions to states in the lowest Landau level in the regime from $\nu = 0.7$ to 1.3 about the spin gap. A detailed discussion of the filling factor (ν) dependence of the spin polarization has been presented previously [6]. An example of the absorption spectra as a function of magnetic field is shown in Figure 1. As the Fermi level moves through $\nu = 1$ the absorption to the lower energy spin-up state quenches, concomitant with a peaking of the absorption into the higher energy spin-down state. This is clearly seen in the inset to Figure 1 where the absorption coefficient $\alpha = -1/L_w \ln(I(B)/I(0))$ (L_w is the quantum well width and I the measured transmission intensity) is plotted as a function of B in the neighborhood of $\nu = 1$ for each polarization.

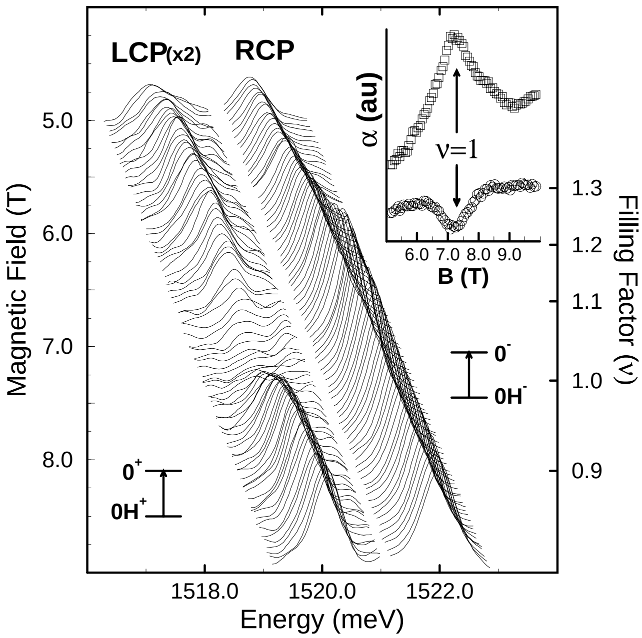

FIG. 1. Absorption spectra in LCP and RCP as a function of magnetic field at T=1.5K. The RCP spectra are offset by +1meV for clarity. The main optical transitions to the two lowest electron spin states are shown alongside the spectra. The inset displays the peak absorption coefficient α in the vicinity of $\nu = 1$.

Our determination of the spin polarization from the absorption spectra is based on a simple sum rule which enforces particle conservation,

$$\frac{N_\uparrow + N_\downarrow}{N} = 1 \quad (1)$$

where $N_{\uparrow(\downarrow)}$ is the number of spin up (down) electrons in the lowest Landau level. This can be recast as

$$\frac{N_{A_\downarrow} + N_{A_\uparrow}}{N} = \frac{2-\nu}{\nu} \quad (2)$$

where $N_{A_{\uparrow(\downarrow)}}$ is the available density of states in the spin up (down) band of the lowest Landau level. The sum rule constrains the total available density of states at any given magnetic field. We proceed with the calculation of S_z by first dividing the integrated peak absorption in each polarization by the calculated optical matrix elements. The resulting quantity is proportional to the available density of states

$$\frac{I_{ij}}{f_{ij}} = C N_{A_j} \quad (3)$$

where I_{ij} is the integrated absorption, f_{ij} is the optical matrix element and C is the constant of proportionality to be determined. Since the left and right circularly polarized (LCP and RCP) spectra provide two such independent equations – one for each spin band – the additional constraint enforced by (2) allows for the determination of $N_{A_{\uparrow(\downarrow)}}$ and C. Finally the spin polarization per particle is

$$S_z = \frac{N_\uparrow - N_\downarrow}{N} = \frac{N_{A_\downarrow} - N_{A_\uparrow}}{N}. \quad (4)$$

We note here that the sum rule which determines the proportionality between the measured absorption and the density of final states can be made rigorous when a full integration over energy is used. The energy integrated absorption is independent of excitonic or many-body interactions and can be understood simply as counting the total number of available k-states in the system [8]. The uncertainty is in determining the cut-off energy for the integration. In our case the optical transitions are well separated in energy, and it suffices to use the transitions which have as final states the spin-up and spin-down states of the lowest Landau level.

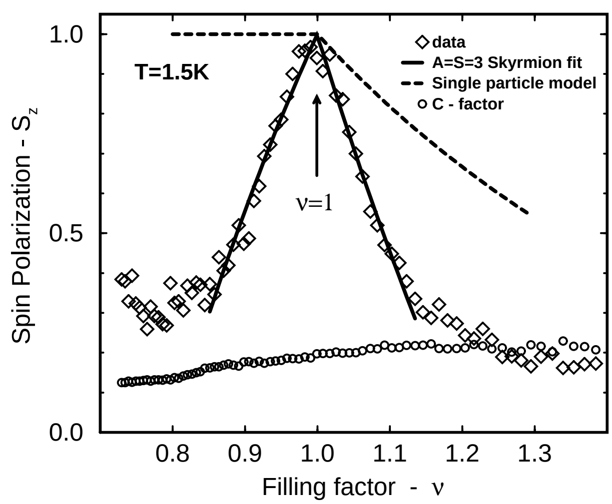

FIG. 2. Spin polarization plotted versus filling factor and compared with both a single particle and Skyrmion-based model. The single particle polarization is based on a simple counting argument, one spin flip per unpaired flux quantum for $\nu > 1$ and $S_z = 1$ for $\nu < 1$. The Skyrmion model has been detailed elsewhere [6] and fits well for 3 spin flips per unpaired flux quanta. The magnetic field dependence of the constant of proportionality C is also shown.

Figure 2 plots the spin polarization versus filling factor determined from the data in Figure 1 and compares it with both single particle and Skyrmion-based models. Previous calculations have shown that a single particle model based on the exchange enhanced g-factor that modulates the overlap of the two electron spin levels fails to capture the behavior of S_z, especially for $\nu < 1$ [6]. On the other hand, the data conform well to the Skyrmion-based model with 3 spin flips per unpaired flux quantum, close to the theoretically predicted value [2]. Since our newly processed samples show no saturation of the absorption (see Figure 1), the measured spin polarization does indeed approach unity exactly at $\nu = 1$ as $T \to 0$, unlike our initial results which displayed a saturation at $S_z \sim 0.8$ [6]. Additionally, the complete lack of structure in the proportionality factor C as a function of filling factor (see Fig 2) in this recent data indicates that our sum rule is strictly observed. The inconsistencies with our earlier data can be understood in terms of the small (10%), but significant, deviations from linearity observed then in the factor C in the neighborhood of $\nu = 1$. We interpret those variations in C as a failure to account for all electrons in the energy-integrated absorption. It is possible that non-uniform strain due to the process of mounting, thinning, and cooling the sample created potential fluctuations in the quantum well. These inhomogeneities could lead to energy shifts in the absorption which would place some transitions outside the sum-rule region. Incomplete counting of states naturally leads to the previously observed saturation in S_z. Better process control has reduced this effect in the present data set.

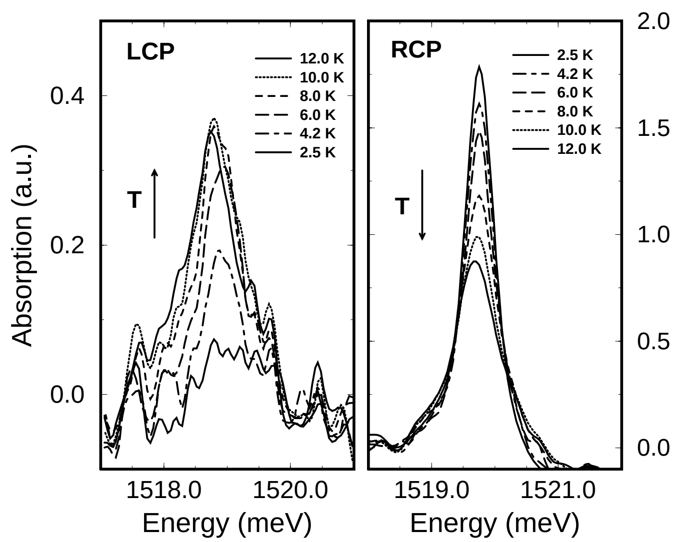

FIG. 3. Absorption spectra taken in LCP and RCP at $\nu = 1$ as a function of temperature. The arrows point in the direction of spectral change for increasing temperature.

We turn now to the temperature dependence of the spin polarization exactly at $\nu = 1$. Figure 3 displays the temperature dependence of the absorption taken in LCP and RCP at $\nu = 1$. The decrease in absorption for decreasing temperature into the lower energy spin state in LCP is correlated to the increase in absorption into the higher energy spin state in RCP. As the temperature decreases, there are fewer available states for optical transitions in the lower-energy spin component (0^+) and more available in the higher-energy spin component (0^-). This data is convincing evidence that the temperature-dependent absorption monitors the Fermi distribution of a two-level system. S_z vs T is plotted from 500mK to 12K in Figure 4. It is important to note that C is independent of temperature (see Fig 4), giving further indication that only the occupancy of the two levels is changing over this temperature range. Additionally we display several values of $S_z(T)$ obtained independently by sweeping magnetic field at constant temperature. The consistency between the spin polarization determined from magnetic field sweeps and the spin polarization determined from temperature sweeps is very good.

The simplest theoretical model that includes interactions is the Hartree-Fock approximation [9]. It modifies the single-particle model with the inclusion of exchange-enhanced level splitting. The HFA magnetization curve has the familiar form

$$S_z(T)/S_{z_0} = \tanh[\beta \epsilon_{\downarrow}^{HF}(\beta)/2] \qquad (5)$$

where $\epsilon_{\downarrow}^{HF}$ is the HFA orbital energy measured from the chemical potential. The HFA overestimates S_z at all intermediate temperatures and does not deviate from unity on the temperature scale of Figure 4. The HFA is limited by its inability to consistently account for the collective-magnetization excitations of the ferromagnetic ground state which are expected to dominate the finite-temperature spin polarization. Initial theoretical work [10] which included independent spin-waves displays a much weaker temperature dependence of the spin polarization than our data indicate. Kasner and MacDonald have incorporated spin-wave excitations into a many-body perturbation theory through the inclusion of a self-energy insertion consisting of a ladder sum of repeated interactions between HF electrons of one spin and holes of the opposite spin [11]. Their theoretical S_z vs T curve appropriate to our experimental conditions, including finite well thickness effects, is shown in Figure 4. The low-temperature reduction of $S_z(T)$ is dominated by the long-wavelength spin-wave contribution and compares favorably with the data. At higher temperatures however, agreement is less convincing.

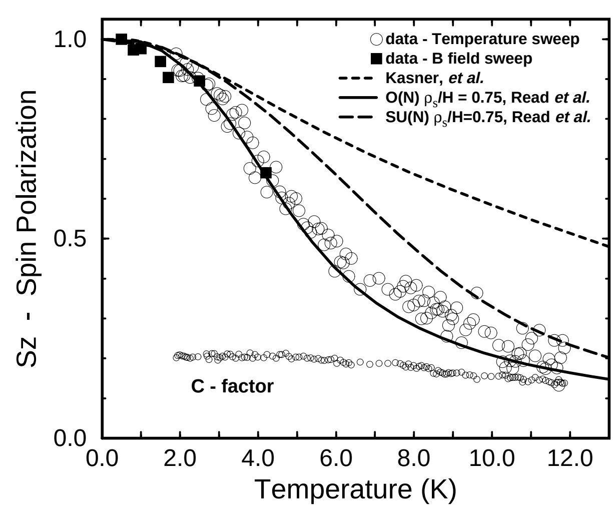

FIG. 4. Temperature dependence of the spin polarization at $\nu = 1$ as determined by polarized absorption spectroscopy. The theoretical curves from the CQFM of Read *et al.* and the many-body perturbation curve of Kasner *et al.* are also displayed.

Read and Sachdev have put forth a continuum quantum field theory of systems with a ferromagnetic ground state that is applicable to the $\nu = 1$ quantum Hall state [12]. The description is analogous to an insulating quantum Heisenberg ferromagnet, and the low-temperature behavior of the two systems is expected to be similar. The continuum quantum ferromagnet (CQFM) contains a conserved topological current representing the number density and current of Skyrmions. Most importantly to our discussion of the $\nu = 1$ spin thermodynamics, the finite temperature CQFM systematically accounts for spin-wave–spin-wave interactions which dominate the spin thermodynamics in the regime $k_B T > H$, where $H = g\mu_B B$ is the Zeeman energy. The only parameter in the system is set by the ratio of the energy scales ρ_s, the ferromagnetic spin stiffness, and H. In the limit of zero well thickness, $\rho_s = e^2/(16\sqrt{2\pi}\epsilon l_B)$. The ratio calculated for our GaAs SQW, including the effects of finite well thickness, is $\rho_s/H \sim 0.77$ [13]. Scaling functions for the spin polarization can be generated in the large N limit when the symmetry group $O(3)$ is generalized to $O(N)$ or $SU(N)$. It is important to note the large N expansion is not a perturbative expansion in the strength of the interactions but rather a saddle point expansion which preserves the symmetry of the underlying Hamiltonian. Thus evaluating the spin polarization for both $O(N)$ and $SU(N)$ in the $N \to \infty$ limit does not correspond to choosing different symmetry groups for the physical system since $O(3) \cong SU(2)$. It will, however, alter the resulting form of the scaling functions at the mean field level. In Figure 4 the $O(N)$ and $SU(N)$ limits of the CQFM with $\rho_s/H = 0.75$ are displayed. We find excellent agreement over the entire range of measured temperatures. While the degree of agreement between the $O(N)$ theory and the data may be somewhat fortuitous [14], it is nevertheless clear that the physics of collective-magnetization excitations captured by the CQFM is crucial to reproducing the observed temperature dependence of S_z.

In conclusion we have made detailed measurements of the temperature dependence of the spin polarization of the $\nu = 1$ quantum Hall state via magnetoabsorption spectroscopy. The data indicate that the ground state of the $\nu = 1$ quantum Hall state is fully spin-polarized at low temperatures. Our measured spin polarization evolves in accord with a continuum quantum ferromagnet model, where the temperature dependence of the magnetization is dominated by multiple spin-wave interactions at $k_B T \sim H$.

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