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Absorption spectroscopy of charged spin texture excitations at $\nu = 1$

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Abstract

Both experimental and theoretical investigations of the $\nu = 1$ quantum Hall state have provided a broad range of evidence that the excitation gap and the resulting quasiparticle spectrum at $\nu = 1$ are dominated by the ferromagnetic many-body exchange interaction. We review recent experimental progress on Skyrmions and detail our own optical investigations of the $\nu = 1$ quantum Hall regime, with a focus on new data. In lower density samples, textures with as many as five spin flips are observed, and the temperature dependence matches both finite size calculations and quantum continuum ferromagnet models. Finally, simultaneous measurements of the absorption, photoluminescence and photoluminescence excitation spectra show that relaxation effects limit the use of emission spectroscopy in determining electron spin populations. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

It is now well established that the quantum Hall effect at filling factor $\nu = 1$ is best viewed as a strongly correlated state with an energy gap due to electron–electron interactions. Recent theoretical [1–3] and experimental studies [4–8] have shown the low-lying charged excitations of the $\nu = 1$ state to be finite-sized Skyrmions with non-trivial spin order. The presence of Skyrmions is manifest in the novel spin polarization versus magnetic field behavior around $\nu = 1$. In addition to Skyrmions, the quantum Hall ferromagnet at $\nu = 1$ possesses a rich spectrum of neutral spin excitations whose interactions control the low-temperature thermodynamics.

The theoretical studies of the effect of a small g-factor in GaAs in the regime of $\nu = 1$ began with the work of Sondhi et al. [1]. Their approach incorporated the use of the nonlinear σ model (NLσ) of isotropic ferromagnets into the study of the $\nu = 1$ quantum Hall effect. The elementary excitations of the NLσ model are called Skyrmions and possess highly nontrivial long-range spin order. They consist of a radial spin density that is reversed at the center but gradually heals to the ferromagnetic background over many magnetic lengths. An extended Hartree–Fock theory of quantum Hall Skyrmions was developed by Fertig and coworkers [2] and provides a quantitative basis for comparison with experiment. The energetics and spin of real

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quantum Hall Skyrmions, or charged spin texture excitations (CSTEs), are largely determined by the parameter $\tilde{g} = g\mu_B B/(e^2/\varepsilon_0 l_0)$, the ratio of the Zeeman energy to the Coulomb interaction scale. The Zeeman term favors small Skyrmions while the Coulomb term tries to maximize the size of the spin texture. Typically our samples have $\tilde{g} \sim 0.015$, though this has been varied recently by other experimenters who use the application of high pressure or alloying to reduce the g-factor. For $\tilde{g} \sim 0.015$ the CSTE is always lower in energy than the single spin-flip excitation and involves the reversal of ~ 3 spins. Since the number of spin flips per flux quanta is significantly greater than one, then Skyrmion excitations are responsible for the rapid suppression of the spin polarization for excursions away from $\nu = 1$.

2. Absorption spectroscopy and optical detection of skyrmions

The spin polarization of the $\nu = 1$ state is determined by using polarization-resolved magneto-absorption spectroscopy to monitor the final state electron population in the spin-up and spin-down state of the lowest Landau level. The two-dimensional electron systems (2DES) studied in these experiments are single-side n-modulation-doped AlGaAs-GaAs single quantum wells (SQWs). New results are reported here on measurements made on three distinct wafers. The GaAs wells are 250 Å wide, and for sample A, the electron density is $N_s = 1.8 \times 10^{11}\,\mathrm{cm}^{-2}$ with a mobility $\mu = 2.6 \times 10^6\,\mathrm{cm}^2/\mathrm{Vs}$. Sample B has a density of $N_s = 1.2 \times 10^{11}\,\mathrm{cm}^{-2}$ and a mobility $\mu = 2.0 \times 10^6\,\mathrm{cm}^2/\mathrm{Vs}$ and sample C, $N_s = 1.7 \times 10^{11}\,\mathrm{cm}^{-2}$ and $\mu = 3.6 \times 10^6\,\mathrm{cm}^2/\mathrm{Vs}$. Details of the experimental configuration have been provided elsewhere [6,9].

The data from sample A has been previously shown and exhibits a marked decrease in the absorption into the lowest spin state concomitant with an increase in absorption into the upper spin state when the Fermi energy passes through the spin-split levels of the lowest Landau level at a filling factor of $\nu = 1$. The correlation in the absorption is consistent with a transfer of carriers from the upper to the lower spin state, and is indicative of a large change in the spin polarization of the electron spin system. The same basic behavior is illustrated in new spectra taken from sample B in Fig. 1. The left-hand spectra are taken in σ^- and monitor the absorption into the lowest spin-up state, while the spectra at the right are in σ^+ and monitor the occupancy of the upper spin-down state. The spectra at the right are offset by 2.0 meV and show that the polarization selection rules are well obeyed. These data indicate the rapidly changing populations of the two spin states on both the high and low field sides of $\nu = 1$.

The spin polarization is determined from the absorption spectra by relating the integrated absorption intensity to the available density of states in each spin band, and on a simple sum rule which enforces particle conservation, $N_\uparrow + N_\downarrow = N$ where $N_{\uparrow(\downarrow)}$ is the number of spin-up (-down) electrons in the lowest Landau level. The sum rule constrains the total available density of states at any given magnetic field. S_z is calculated 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

$$\frac{I_{ij}}{f_{ij}} = CN_{A_i}, \tag{1}$$

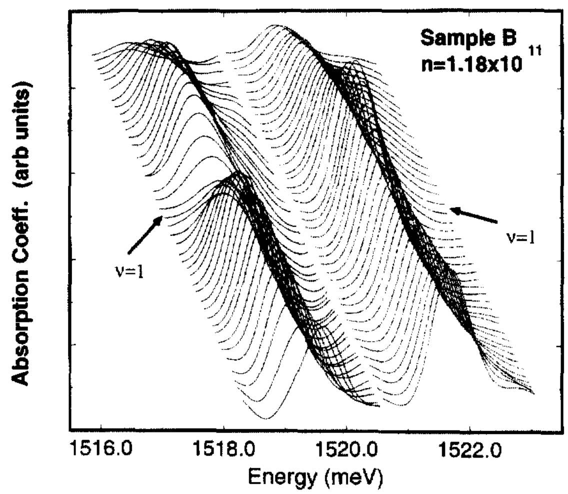

Fig. 1. Absorption spectra in LCP and RCP as a function of magnetic field at $T = 0.5$ K for sample B. The RCP spectra are offset by $+2$ meV in energy for clarity.

where I_{ij} is the integrated absorption, f_{ij} is the optical matrix element and C is the constant of proportionality which accounts for all unmeasured experimental couplings – optical collection efficiency, detector efficiency, etc. – which otherwise would be needed to relate the measured integrated intensity to the available density of states. Since only the magnetic field direction is switched between different polarization scans, the coupling C is identical in the two measurements. Then the left and right circularly polarized spectra provide two independent equations and the additional constraint enforced by (2) allows for determination of $N_{A_{\uparrow(\downarrow)}}$ and the elimination of C. This ability to determine C is the experimental consequence of the high degree of polarization in the absorption spectra to the two distinct final states. If significant mixing had occurred, as it does in heterojunctions or in emission in general, then the two spectral sets would not have been truly independent and one could not have used the above procedure to fully eliminate experimental couplings. In this sense, the ability to determine an absolute spin polarization depends somewhat sensitively on the independence of the polarization spectral measurements. Finally, the spin polarization per particle is

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

As discussed above, this experiment allows for the determination of the absolute spin polarization, free of any fitting parameters.

Fig. 2 plots the spin polarization versus filling factor for sample A 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]. The reason for this is that the exchange-enhanced model cannot account in any way for depolarization for filling factors less than $\nu = 1$. Varying either the temperature or the level width can depress the sharpness of the change at $\nu = 1$ but a negative slope is not possible to achieve, as lower filling factors separated the levels and quickly saturates the polarization at unity. On the

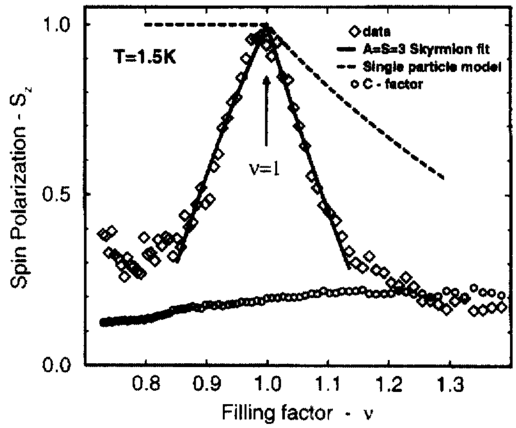

Fig. 2. Spin polarization of sample A plotted versus filling factor and compared with both a single particle and Skyrmion-based model. The single-particle polarization is based on a simple counting argument, one spin flip per unpaired flux quantum for $\nu > 1$ and $S_z = 1$ for $\nu < 1$. The Skyrmion 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.

other hand, the data conform well to the Skyrmion-based model. In this scheme the number of reversed spins is quantized [3] so that the component of total spin along the direction of the Zeeman field is given by

$$S_z = N/2 - (A+1)|N - N_\phi| \quad (3)$$

for $N > N_\phi$, where N is the number of electrons in the system, N_ϕ is the number of states available and $|N - N_\phi|$ is the number of Skyrmions present. For $N < N_\phi$, S_z is given by

$$S_z = N/2 - (A)|N - N_\phi|. \quad (4)$$

A is an integer quantum number which depends on the relative strength of the Zeeman and Coulomb interaction terms and is the relevant measure of the Skyrmion size [3]. For samples with $\nu = 1$ at 7 T, Hartree–Fock calculations [2] predict A should be close to 3, indicating each excitation induces 3 spin flips. Sample A, with $\nu = 1$ at 7.2 T, is in agreement with this prediction. A simple check on the procedure can be done by inverting the process: Demand in the equations that the spin-polarization S_z be that of the single-particle model, use the spectral data together particle conservation at every magnetic field value, and finally observe the value of the matrix elements resulting. Having done this on the data shown in Fig. 2, we see that the *ratio* of the matrix elements would have to change by a factor of 5 or more, quite inconsistent with the lack of any significant energy shift in the absorption peaks through $\nu = 1$.

The measured spin polarizations for sample B and C are shown in Fig. 3. Again in each of these samples we see a rapid quenching of the degree of polarization for excursions away from $\nu = 1$. In both these samples, however, the polarization does not approach unity exactly at $\nu = 1$. Despite the seemingly similar behavior, we believe that different mechanisms are involved for each sample. First a discussion of sample B, for which $\nu = 1$ occurs at 4.75 T. The solid line drawn corresponds to $A = 5$, implying five spin flips per unpaired flux quanta. This result is expected since at smaller magnetic field, $\tilde{g}$ is smaller, resulting in a larger effective spin texture. What distinguishes sample B is its very pronounced temperature dependence. At a high temperature of 4.2 K, no evidence of $\nu = 1$ exists in the optical spectra. Changes begin to occur as the temperature is lowered through $\sim$2.5 K, and the polarization at $\nu = 1$ is still increasing for decreasing temperature at $T = 0.5$ K, the lowest temperature obtainable in this experimental configuration. Experiments at lower temperatures are presently underway to attempt to observe the full polarization of the electron system for sample B.

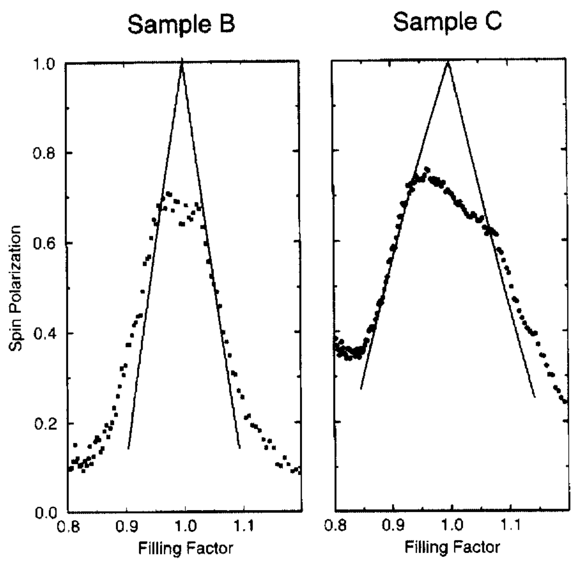

Fig. 3. Spin polarization of sample B and sample C plotted versus filling factor. The lines drawn show the expected polarization for a Skyrmion model with 5 (3) spin flips per excitation, respectively. Sample B absorption data was taken at $T = 0.5$ K and the spectra are displayed in Fig. 1. Sample C data was taken at $T = 0.5$ K.

A somewhat different behavior is seen in sample C for which $\nu = 1$ occurs at 7 T. For deviations away from $\nu = 1$ sample C is also well fit by a theory with 3 spin flips per excitation, a result consistent with the behavior observed in sample A. Yet like sample B, sample C's spin polarization does not reach unity at $\nu = 1$. Unlike sample B, below $T = 1$ K the $\nu = 1$ polarization of sample C is largely independent of temperature. The peaking of the RCP absorption coefficient has essentially saturated. Additionally, in transport this sample exhibits a relatively wide quantum Hall plateau, approximately $\Delta B \sim 1$ T at $\nu = 1$, suggesting that localization associated with reduced screening of impurity potentials in the incompressible $\nu = 1$ quantum Hall state may be having a significant impact on the physics of this sample. Further indication of the effects of localization is given by the slightly broader and asymmetric absorption peaks observed in this sample. Allowed absorption transitions outside the defined region of energy integration would naturally lead to the observed saturation in polarization. In fact, in sample C absorption to higher, unoccupied states show some evidence of changes in the neighborhood of $\nu = 1$, indicative of the fact that absorption matrix element effects are not fully incorporated by the artificial cutoff in the integration over energy. It is likely that the effects of localization must be dominating the state spectrum right in the region of $\nu = 1$ for sample C. Note that away from the very center of the plateau, the polarization does follow well the standard Skyrmion picture.

One should note finally, that the dominant behavior observed in all samples is completely consistent with the Skyrmion model: the system depolarizes on both sides of $\nu = 1$ and the excitations involve a large number of spin flips.

2.1. Neutral excitations of the quantum hall ferromagnet

Skyrmions are the lowest *charged* excitations of the system driven by adding or removing charge, or equivalently, adding or removing magnetic flux. The charged nature of Skyrmions is seen by the sensitivity of transport measurements to their presence [5,8]. But Skyrmions are not the only excitations of the quantum Hall ferromagnet. As with any highly correlated spin system, a branch of low-lying neutral spin-wave excitations is expected which may affect the spin polarization even at $\nu = 1$ for finite temperatures. In order to explore the nature of the neutral excitations of the quantum Hall ferromagnet we have completed a detailed study of the thermal behavior of the spin polarization exactly at $\nu = 1$.

Fig. 4 displays the temperature dependence of the absorption taken in LCP and RCP at $\nu = 1$ for sample A. 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 and more available in the higher-energy spin component. This data is convincing evidence that the temperature-dependent absorption monitors the Fermi distribution of a two-level system. Note that the energy position of the peak is quite independent of energy over the range of temperatures. This is indicative of the weak role played by excitonic effects in sample A.

S_z versus T is plotted from 500 mK to 12 K in Fig. 5. It is important to note that C is independent of temperature (see Fig. 5) in sample A, 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 quite good.

The rapid quenching of the $\nu = 1$ polarization with increasing temperature is further evidence for the highly correlated nature of the quantum Hall ferromagnet. Any theoretical approach to its thermodynamics must 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

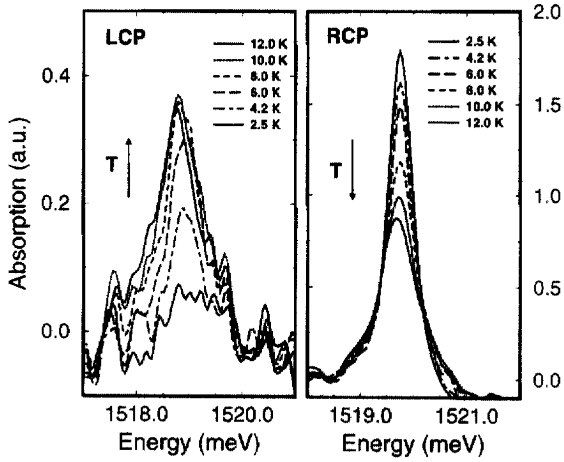

Fig. 4. Absorption spectra taken in LCP and RCP at $\nu = 1$ as a function of temperature for sample A. The arrows point in the direction of spectral change for increasing temperature.

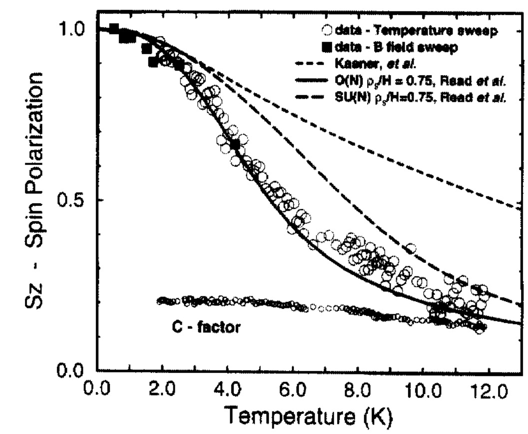

Fig. 5. Temperature dependence of the spin polarization at $\nu = 1$ as determined by polarized absorption spectroscopy. The theoretical curves from the CQFM of Read et al. and the many-body perturbation curve of Kasner et al. are also displayed.

dependence of the spin polarization than our data indicate. Kasner and MacDonald [11] 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. Their theoretical S_z versus T curve appropriate to our experimental conditions, including finite well thickness effects, is shown in Fig. 5. 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. This perturbative approach is limited by its inability to consistently account for spin-wave–spin-wave interactions.

Read and Sachdev have developed 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, $\rho_s = e^2/(16\sqrt{2\pi}\varepsilon l_B)$. 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). 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 and couplings 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 Fig. 5 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. It is important to note that there are no free parameters in this comparison of data and theory. All couplings are known and are specific to our system. It is clear that the physics of collective-magnetization excitations captured by the CQFM is crucial to reproducing the observed temperature dependence of S_z.

Recently Chakraborty et al. have performed exact diagonalization studies of the temperature dependence of the spin-polarization [14]. In general, such finite-size calculations are especially relevant in the regime of larger $\tilde{g}$ where the field theoretic approaches are less accurate. When combined with a softening of the Coulomb interaction due to the extent of the wave function in $\hat{z}$, the calculations show excellent agreement with our experimental data. Again, in these finite-size calculations, no fitting parameters are used, it is a direct comparison between the theory and the experimental data.

3. Emission spectroscopy and the role of the exciton in absorption

In magneto-absorption spectroscopy the integrated absorption intensity can be related, in a very straightforward way, directly to the available density of states in the lowest Landau level. Emission, on the other hand, depends sensitively on the minority carrier concentration, and the intensity is in general not directly related to the initial state electron population. Absorption is also largely unaffected by complicated relaxation and impurity effects that may obscure population changes, and often dominate in emission. This is manifest in the strict adherence to the angular momentum selection rules in the absorption process and the good agreement between observed and calculated oscillator strength as discussed earlier. Additionally absorption gives two uncorrelated measurements: the absorption in the LCP channel is *independent* of absorption in the RCP channel so that the relative changes in intensity do in fact reflect changes in the

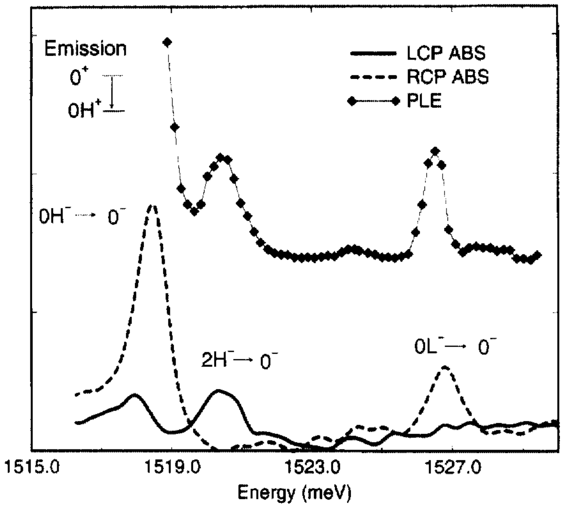

Fig. 6. Photoluminescence excitation spectra collected in LCP, ground-state emission, at $\nu = 1$ as a function of laser excitation energy. Displayed toward the bottom are the LCP and RCP direct absorption versus energy at $\nu = 1$. Main absorption transitions are labeled.

population of the two spin bands. In emission, however, coupling occurs since in the absence of significant non-radiative channels, the minority photo-excited hole must eventually emit a photon on recombination. Thus if lower energy channels are suppressed, higher energy channels are necessarily enhanced. Many experimental studies have shown enhancement in higher energy state emission when the ground state is quenched.

Experimental evidence of the mixing of polarization states upon relaxation of the hole is observed in our data. In Fig. 6 we plot the photoluminescence excitation spectra, collected at an emission energy of 1519.0 meV in LCP, the ground state emission channel, at $\nu = 1$ and $T = 0.53$ K for sample A. Displayed in the lower part of the figure in this figure are both the LCP and RCP absorption coefficients taken at the same time. The correspondence between *all* features in the PLE and the *combined* LCP and RCP absorption is clear. It shows that emission in LCP increases whenever the laser excitation is scanned across an absorption peak, regardless of the angular momentum of the hole state created by the absorbed photon. Thus valence holes created at absorption change angular momentum character before recombining which is expected to be facilitated by the non-zero spin–orbit coupling in the valence band. Because of this intrinsic mixing of the hole states upon relaxation, we are unable to make any definitive statements regarding the electron spin polarization from emission spectra.

4. Summary

In summary, magneto-absorption spectroscopy is used to probe the occupancy of the two spins bands of the lowest Landau level. Consistency on data presented from three distinct wafers shows that the Skyrmion model works well for describing the spin polarization about $\nu = 1$. The temperature dependence of the spin polarization at $\nu = 1$ is consistent with the both the thermodynamic model showing the importance of spin-wave–spin-wave interactions as well as recent finite size calculations.

Acknowledgements

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