Evidence of Skyrmion Excitations about $\nu = 1$ in n-Modulation-Doped Single Quantum Wells by Interband Optical Transmission

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A dramatic reduction in the spin polarization of a two-dimensional electron gas in a magnetic field is observed when the Fermi energy moves off the midpoint of the spin gap of the lowest Landau level, $\nu = 1$. The spin polarization is measured by magnetoabsorption spectroscopy which distinguishes the occupancy of the two electron spin states. The rapid decay of spin alignment over small changes to both higher and lower magnetic field provides experimental evidence for the presence of Skyrmion excitations where exchange energy dominates Zeeman energy in the quantum Hall regime at $\nu = 1$.

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The exchange energy dominates the basic physics in GaAs two-dimensional electron systems (2DES's) when the Fermi energy is located between spin-split Landau levels at odd-integral filling factors ν. This is because the small g factor in GaAs makes the Zeeman energy much less than the Coulomb energy which is responsible for the exchange. The small g results in a spin degree of freedom, even at high magnetic fields, leading to spin-unpolarized ground states and to novel excited states at fractional filling factors [1]. Recent theoretical work has pointed out that the response of a 2DES with a small g factor in the spin-polarized state ($\nu = 1$) to a change of one quantum of magnetic flux is not a single-particle spin-flip excitation, but rather a macroscopic spin object called a Skyrmion or charged spin-texture excitation (CSTE) [2,3]. Evidence of these excitations has been recently observed in NMR and in tilted-field transport measurements [4,5]. They consist of a radial spin density distribution that is reversed at the center but gradually heals to the spin background over a distance of many magnetic lengths. With each particle in a nearly spin-aligned neighborhood, the exchange contribution lowers the energy of the CSTE relative to a single flipped spin. The size of the CSTE is then governed by the relative strength of the Zeeman and Coulomb energies, parametrized by $\tilde{g} \equiv E_Z/E_C = \frac{g\mu_B B}{e^2/\epsilon l_0}$ [3], where $l_0 = \sqrt{\hbar/eB}$ is the magnetic length and ϵ the dielectric constant. In the limit of vanishing g factor, the radius extends to nearly the edge of the sample, while for $\tilde{g} \geq 0.02$ the size shrinks to zero, eliminating the distinction between single-particle and Skyrmion excitations. In GaAs samples with 2DES densities of 1.5×10^{11} cm^{-2}, $\tilde{g} \sim 0.015$ at $\nu = 1$. CSTE's are then expected to be the lowest energy excitations with the change in total spin per flux quantum significantly greater than 1, destroying the spin polarization of the electron system for small excursions from $\nu = 1$.

In this Letter we present an experimental observation of Skyrmions through the rapid loss of spin polarization about $\nu = 1$ measured with polarized absorption spectroscopy. The spectra show quenching of absorption to the lower energy, spin-up electron band directly correlated to an increase in the higher energy, spin-down absorption at $\nu = 1$ [see Fig. 1(a)]. As we will show, this indicates that the spin-up state fills with electrons while the

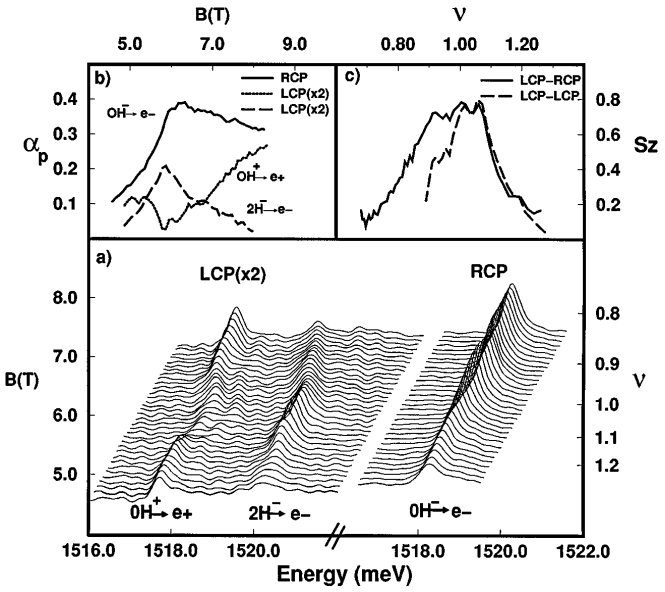

FIG. 1. (a) Absorption spectra in LCP and RCP in the neighborhood of $\nu = 1$. The quenching of absorption to the lower spin state is directly correlated to an increase in the absorption to the upper spin state. The peak absorption (α_p) of the displayed spectra is plotted vs magnetic field in (b). The calculated spin polarization is plotted in (c) as a function of filling factor ν using the lowest energy LCP transition for the spin-up occupancy and data from both the RCP (solid line) and LCP (dashed line) transitions for the spin-down state occupancy.

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spin-down state empties, providing a large spin polarization S_z [see Fig. 1(c)] which exhibits a pronounced, symmetric decay when ν deviates from 1. This technique provides a measurement of the absolute electron spin and has identified saturation in the spin polarization not previously resolved. The temperature dependence of absorption in a multiple quantum well was earlier used to determine the exchange enhanced spin gap [6] at high magnetic fields, where, however, the distinction between single spin flips and Skyrmions is lost.

The samples were two single-side n-modulation-doped AlGaAs-GaAs 250 Å single quantum wells (SQW's). Sample A had mobility $\mu = 3.2 \times 10^6$ cm^2/V s and 2DES carrier concentration of $N_s = 1.5 \times 10^{11}$ cm^{-2}, and sample B had $\mu = 2.6 \times 10^6$ cm^2/V s and $N_s = 1.8 \times 10^{11}$ cm^{-2}. In transport these wafers exhibited strong fractional Hall minima at $\nu = 1/3$ and $2/3$. The SQW's were chosen to minimize inhomogeneous broadening, and for absorption measurements were mounted strain-free and thinned to ~ 0.5 μm [7]. Incident power of ~ 1 mW/cm^2 yielded typical signal-to-noise ratios of >20 with linewidths of 0.2 to 0.5 meV (FWHM). The absorption coefficients α^+ and α^- were calculated neglecting reflection which has been measured in similar samples to contribute only a small variation ($<5\%$). The raw transmission spectra $I(w, B)$ were then normalized to obtain the magnetoabsorption coefficient $\alpha(w, B) = -1/L_w \ln(I/I_0)$, where L_w = quantum well width.

In this work we concentrate only on the lowest Landau level in the regime from $\nu = 0.6-1.4$ about the spin gap. Representative spectra taken in left and right circular polarizations (LCP and RCP) are displayed in the lower left and right of Fig. 1(a), respectively, with peak absorption as a function of field plotted in Fig. 1(b). As described below, the final electron spin state for the lowest energy LCP (RCP) absorption is the lower (higher) energy spin-up (spin-down) state. The interband optical absorption is proportional to the available density of states in these final electron spin levels. The total spin polarization is then given by the difference between the number of spin-up and spin-down states under the constraint that the sum yields the particle number. This determines the total spin within 10% accuracy. Figure 1(c) shows the spin polarization S_z as a function of filling factor determined in this way for the data presented.

We should mention that a wealth of data on a seemingly similar effect, the quenching of the photoluminescence from the lowest energy transition accompanied by an increase in the emission from the higher energy transition, has been observed by one of the authors and others [8]. The total integrated emission was relatively constant, yielding an explanation based on a decrease in the recombination rate in the lowest energy state due to localization. In the absence of significant nonradiative channels, the minority photoexcited hole must eventually emit a photon on recombination, and hence the emission from the two electron levels must be correlated. However, not only is absorption largely unaffected by localization, but also the photons absorbed which cause transitions into the lower and higher energy spin states are completely uncorrelated. This leads to the conclusion that the correlation observed in the absorption data is due to the changes in the occupancy and thus the total spin of the electron system.

To determine the occupancy of the electron spin states and hence the spin polarization, we have first calculated the interband transitions and optical matrix elements. Subband energies and wave functions for electrons and holes were determined self-consistently within the local density approximation. The hole Landau levels were then calculated by employing the Luttinger Hamiltonian [9] to take into account the valence band mixing [10]. Figure 2 compares calculated and measured peak intensities [2(a) and 2(b)] and peak energy positions [2(c)]. The level diagram in the lower right identifies the relevant transitions: The lowest energy transition in RCP is from a pure heavy-hole state with $m_j = -3/2$ to the upper electron spin state $m_j = -1/2$ which we label $0H^- \rightarrow e^-$. The lowest energy state in LCP is from a mixed heavy-hole state with dominant character in the $m_j = +3/2, +1/2$ components to the lower energy spin state $m_j = +1/2$, labeled $0H^+ \rightarrow e^+$.

Note that the $m_j = +1/2$ part of the hole envelope function for $0H^+ \rightarrow e^+$ is associated with a higher oscillator index and cannot cause an optical transition to the lowest electron Landau level [7]. This is corroborated

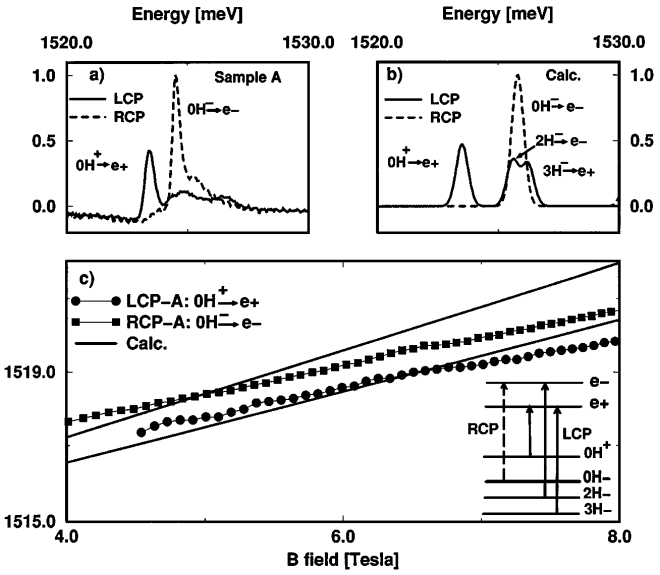

FIG. 2. The energy of the two lowest transitions (in LCP and RCP) to the ground Landau level are plotted as a function of magnetic field and compared to the calculations. The transitions are identified in the lower left, and spectra and calculations at 12 T are plotted vs energy in the upper insets. Note that while some discrepancy exists in the absolute energy position, the calculated matrix elements capture very closely the strength of the optical transitions.

by both the absence of absorption peaks at the same energy in the different polarizations and the narrowness (less than the bare Zeeman energy) of the $0H^+ \rightarrow e^+$ transition at high fields. These observations confirm the validity of the matrix element calculations in the axial approximation.

We proceed to determine the spin level occupancy from the raw data as follows: The spin polarization per particle is given by

$$S_z = \frac{N_\uparrow - N_\downarrow}{N} = \frac{N_{A_\downarrow} - N_{A_\uparrow}}{N}, \tag{1}$$

where $N_{\uparrow(\downarrow)} = N_B - N_{A_{\uparrow(\downarrow)}}$. N_B is the Landau level degeneracy eB/h, and N_{A_j} is the available density of states in the $j = \uparrow$ ($\downarrow$) spin up (down) band of the lowest Landau level. The integrated absorption peaks are linearly related to the number of available final states N_{A_j} of the transition as

$$I_{ij} = C f_{ij} N_{A_j}, \tag{2}$$

where $I_{ij} = \int \alpha_{ij} d\omega$, the oscillator strengths $f_{ij}(\omega)$ are taken to be constant over the narrow absorption peaks, and i and j label the initial and final states, respectively. The constant of proportionality C may be found using the sum rule

$$\frac{N_{A_\downarrow} + N_{A_\uparrow}}{N} = \frac{(N_B - N_\uparrow) + (N_B - N_\downarrow)}{N} = \frac{2 - \nu}{\nu}, \tag{3}$$

which conserves particle number $\frac{N_\uparrow + N_\downarrow}{N} = 1$. Then

$$C(B) = \frac{\nu}{2 - \nu}\left(\frac{I_{i,\uparrow}}{f_{i,\uparrow}} + \frac{I_{k,\downarrow}}{f_{k,\downarrow}}\right), \tag{4}$$

and the available densities of states are obtained from (2). The calculated scaling factor $C(B)$ changes by less than 15% over the range $\nu = 0.6-1.4$, while typical S_z's change by nearly an order of magnitude, demonstrating that the raw data come very close to obeying the sum rule over this field range and indicating that few higher-order processes are affecting the absorption.

Several additional self-consistency checks exist for this treatment, providing confidence in our hole level and matrix elements calculations. The calculation of S_z from the $0H^- \rightarrow e^-$ and $0H^+ \rightarrow e^+$ transitions, and the one from the $2H^- \rightarrow e^-$ and $0H^+ \rightarrow e^+$ transitions are nearly identical in the range where the transitions have good signal to noise [see Fig. 1(c)]. Since the $0H^- \rightarrow e^-$ and the $2H^- \rightarrow e^-$ independently monitor the occupancy of the upper electron spin state, the similarity of the spin polarizations calculated means that the matrix elements are internally consistent with our simple sum rule and that the data truly reflect a change in occupancy of the electron spin states. We believe the discrepancy at $\nu < 1$ is largely due to the strongly mixed nature of the initial $2H^-$ hole level. Finally, the matrix elements themselves are varying relatively slowly over the filling factor range of interest $\nu = 0.6-1.4$, typically less than 20%, and hence cannot simply account for the structure observed. Nor are they particularly sensitive to the carrier density or the precise value of the zero-field splitting; these parameters have been varied with no significant change in the final spin polarization S_z.

In Fig. 3, spin polarization versus filling factor is plotted for samples A and B, and compared with both a single-particle and a Skyrmion-based model. The single-particle model is based on an exchange enhanced g factor that modulates the overlap of the two electron spin levels [11]. g is the self-consistent solution of

$$g = g_0 + \frac{\epsilon_{\rm xc}^0 (N_\uparrow - N_\downarrow)}{\mu_B B}, \tag{5}$$

where

$$N_{\uparrow(\downarrow)} = \frac{2B}{\Gamma\sqrt{\pi}} \int f(E, E_F) \times \exp\left[-\left(\frac{E \pm g\mu_B B/2}{\Gamma/2}\right)^2\right] dE, \tag{6}$$

$f(E, E_F)$ is the Fermi distribution function, and $\Gamma = \Gamma_0\sqrt{B}$ is the field-dependent level width. The exchange coefficient $\epsilon_{\rm xc}^0$ in (5) was chosen to satisfy $g = 7.3$ at $\nu = 1$, as determined from activated transport measurements in [12], leaving Γ_0 the only adjustable parameter. Clearly the single-particle model does not capture the behavior of S_z. The polarization quickly saturates to unity for $\nu < 1$ and goes as $\sim\frac{2-\nu}{\nu} = N_{A_\downarrow}/N$ for $\nu > 1$, in contrast to the measured polarization which decays symmetrically about $\nu = 1$ at a much more rapid rate. A spin-wave model which includes interactions [13] would provide depolarization for $\nu < 1$, though with a weaker

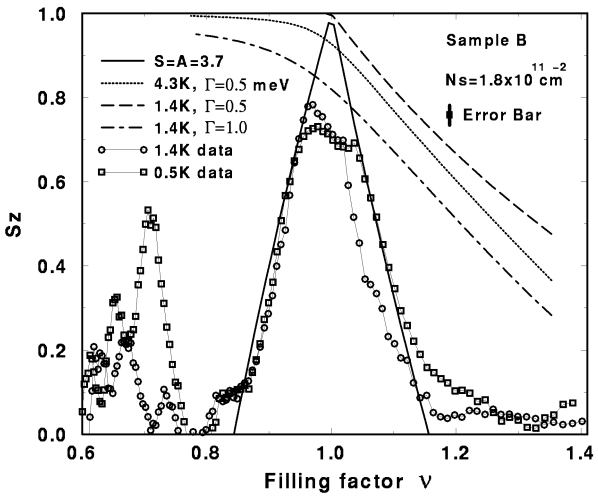

FIG. 3. The calculated spin polarization S_z displayed as a function of filling factor ν for 1.4 and 0.5 K. The solid line fit assumes a macroscopic spin of ~3.7 per flux quantum, while the dashed, dotted, and dash-dotted fits assume a single-particle self-consistent exchange-enhanced g-factor model with appropriate ranges of broadening and temperature.

temperature dependence than the data [4]. Recent theoretical work has also indicated that a spin-wave model is insufficient [14].

The changes in polarization do adhere, however, to a treatment which includes Skyrmion excitations (see solid line fit in Fig. 3). In the model proposed by Barrett *et al.* [4] the one-particle available densities of states are scaled by a parameter S (A) that gives the number of spin flips per unpaired quantum of flux $|N_B - N|$ above (below) $\nu = 1$. In this model the spin polarization is

$$S_z = \begin{cases} S\left(\frac{2-\nu}{\nu}\right) - (S-1), & \nu > 1, \\ \frac{1}{\nu} - (2A-1)\left(\frac{1-\nu}{\nu}\right), & \nu \le 1. \end{cases} \quad (7)$$

Particle-hole symmetry requires that the size of the Skyrmion be the same as that of the anti-Skyrmion, $S = A$, giving a rapid quasisymmetric loss in polarization about $\nu = 1$ for $S > 1$. When $S = A = 1$ the single-particle model is recovered (modulo overlap effects). The fit for sample B in Fig. 3 gives a Skyrmion spin of 3.7 which is near the theoretically predicted value for a 2DES in GaAs of 3.5 [2,3]. For sample A the Skyrmion spin is somewhat smaller, only 2.5 flipped particles per flux quantum.

A feature of our technique is that it allows a quantitative determination of the total spin. The data display a marked saturation in the peak spin polarization at $\nu = 1$ for decreasing temperature (see Figs. 3 and 4). The saturation could be due to the finite level width with the result of nonvanishing overlap of the spin states at $\nu = 1$, consistent with our measured linewidths, as well as the observation of absorption into the lower spin state for $2 > \nu > 1$.

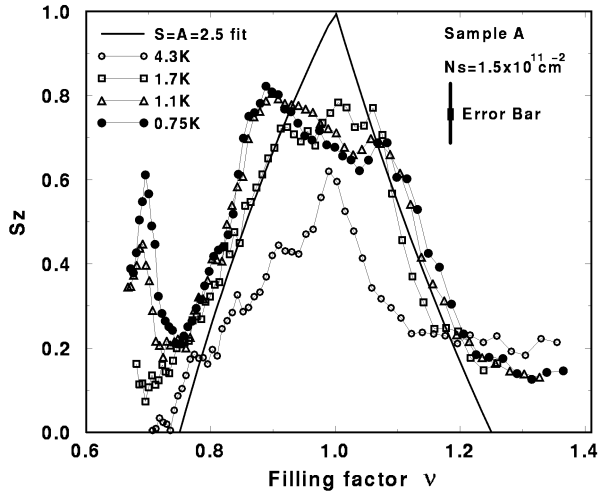

FIG. 4. Spin polarization as a function of temperature in sample A with a carrier density of $n = 1.5 \times 10^{11}$ cm^{-2}. The peak of the spin polarization increases to 0.8 for decreasing temperature where it saturates. Most notable is the increase in width of the region of spin polarization, which may be due to a relatively wide $\nu = 1$ integral Hall plateau in this sample, and the resultant effect of increased carrier localization on local exchange.

In conclusion, we have demonstrated extraction of the spin polarization from interband absorption spectroscopy. Self-consistent checks of the subband and matrix element calculations, as well as an adherence of the raw data to a simple sum rule, provide confidence in our analysis. The measured loss in spin polarization is consistent with charged spin-texture excitations of $\sim$3 flipped spins per unpaired quantum of flux.

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