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

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Abstract

We observe a dramatic reduction in the degree of spin-polarization of a two-dimensional electron gas in a magnetic field when the Fermi energy moves off the mid-point of the spin-gap of the lowest Landau level, $\nu = 1$. This rapid decay of spin alignment to an unpolarized state occurs over small changes to both higher and lower magnetic field. The degree of electron spin polarization as a function of $\nu$ is measured through the magneto-absorption spectra which distinguish the occupancy of the two electron spin states. The data provide experimental evidence for the presence of Skyrmion excitations where exchange energy dominates Zeeman energy in the integer quantum Hall regime at $\nu = 1$.

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The exchange energy dominates the basic physics in GaAs two-dimensional electron systems (2DES) when the Fermi energy is located between spin-split Landau levels at odd-integral filling factors $\nu$. 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. 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 quanta 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). Evidence of these excitations have been recently observed in NMR and in tilted-field transport measurements. 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. Since each particle sits in a nearly aligned spin neighborhood, the exchange contribution is significantly smaller for the CSTE than for a single flipped spin. The physical size of the CSTE is governed by the relative strength of the Zeeman and Coulomb energies, parameterized by $\tilde{g} \equiv E_Z/E_C = \frac{g\mu_B}{e^2/\epsilon l_0}$, where $l_0 = \sqrt{\hbar/eB}$ is the magnetic length and $\epsilon$ 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 $1.5 \cdot 10^{11} cm^{-2}$, $\tilde{g} \sim 0.015$ at $\nu = 1$. CSTE’s are then expected to be the lowest energy excitations with the change in total spin per flux-quanta significantly greater than one, destroying the spin-polarization of the electron system for small excursions from $\nu = 1$.

In this letter we present 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 figure 1). As we will show, this indicates the spin-up state fills with electrons while the spin-down
state empties, providing a large spin polarization $S_z$ (see inset) which exhibits a pronounced, symmetric decay when $\nu$ deviates from 1. This new technique provides a measurement of the absolute electron spin and has identified saturation in the spin polarization not previously resolved.

The samples were two single-side n-modulation doped AlGaAs - GaAs 250Å single quantum wells (SQW). Sample A had mobility $\mu = 3.2 \cdot 10^6 cm^2/Vs$ and 2DES carrier concentration of $n = 1.5 \cdot 10^{11} cm^{-2}$, and sample B had $\mu = 2.6 \cdot 10^6 cm^2/Vs$ and $n = 1.8 \cdot 10^{11} cm^{-2}$. In transport these wafers exhibited strong fractional Hall minima at $\nu = 1/3$ and $2/3$. The SQWs were chosen to minimize inhomogeneous broadening, and for absorption measurements were mounted strain-free and thinned to $\sim 0.5 \mu m$. Incident power of $\sim 1 mW/cm^2$ yielded typical signal-to-noise ratios of $> 20$ with line widths of 0.2 to 0.5 meV (FWHM). The absorption coefficients $\alpha^+, \alpha^-$, 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 magneto-absorption 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 $\nu = 0.6$ to 1.4 about the spin gap. Representative spectra taken in LCP and RCP polarizations are displayed in the lower left and right of Figure respectively. 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 inter-band 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. With this technique we are able to determine within 10% accuracy the total spin. The inset to figure 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. The total integrated emission was relatively constant, yielding an explanation based on a decrease in the re-combination rate in the lowest energy state due to localization. In the absence of significant non-radiative channels, the minority photo-excited hole must eventually emit a photon on re-combination, 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 inter-band transitions and optical matrix elements. Sub-band energies and wave-functions for electrons and holes were determined self-consistently within the local density approximation. The hole Landau levels were then calculated employing the Luttinger Hamiltonian to take into account the valence band mixing. Figure 2 compares the calculated and measured peak energy positions versus magnetic field about \( \nu = 1 \). The insets display measured and calculated spectra, and the lower right schematic 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 \( m_j = +3/2, +1/2 \) 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. This is corroborated both by 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

\[ S_z = \frac{N_\uparrow - N_\downarrow}{N} = \frac{N_{A_\downarrow} - N_{A_\uparrow}}{N} \]  

(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

\[ I_{ij} = C \cdot f_{ij} N_{A_j} \]  

(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 \( i, j \) label the initial and final states respectively. The constant of proportionality \( C \) may be found using the sum-rule

\[ \frac{N_{A_\downarrow} + N_{A_\uparrow}}{N} = \frac{(N_B - N_\uparrow) + (N_B - N_\downarrow)}{N} = \frac{2 - \nu}{\nu} \]  

(3)

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

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

(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 of \( \nu = 0.6 \) to 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 inset to Fig. 1.). Since the \( 0H^- \) and the \( 2H^- \) 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. Finally, the matrix elements themselves are varying relatively slowly over the filling factor range of interest $\nu = 0.6$ to $1.4$, 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 figure 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 exchange enhanced $g$-factor that modulates the overlap of the two electron spin levels [8]. $g$ is the self-consistent solution of

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

where

$$N_{\uparrow(\downarrow)} = \frac{2B}{\Gamma \sqrt{\pi}} \int f(E, E_f) \cdot e^{-\left(\frac{E \pm \mu B/2}{\Gamma/2}\right)^2} dE \tag{6}$$

$f(E, E_f)$ is the Fermi distribution function, and $\Gamma = \Gamma_0 \sqrt{B}$ is the field dependent level width. The exchange coefficient $\epsilon_{\text{xc}}^0$ in (5), was chosen to satisfy $g = 7.3$ at $\nu = 1$, as determined from activated transport measurements in [11], leaving $\Gamma_0$ 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 $\sim \frac{2\nu}{\nu^2} = N_{A_\downarrow}/N$ for $\nu > 1$, in contrast to the measured polarization which decays symmetrically about $\nu = 1$ at a much more rapid rate.

The changes in polarization do adhere however, to a treatment which includes Skyrmion excitations (see solid line fit figure 3). In the model proposed by Barret 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 flux quanta $|N_B - N|$, above (below) $\nu = 1$. In this model the spin polarization is
\[ S_z = \begin{cases} 
S \left( \frac{2-\nu}{\nu} \right) - (S - 1) & \nu > 1 \\
\frac{1}{\nu} - (2A - 1) \left( \frac{1-\nu}{\nu} \right) & \nu < 1 
\end{cases} \] (7)

Particle-hole symmetry requires that the size of the Skyrmion be the same as the Anti-Skyrmion, \( S = A \), giving a rapid quasi-symmetric 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 figure 3 gives a skyrmion size of 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 size is somewhat smaller, only 2.5 flipped particles per flux quanta.

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 figures 3 and 4). The saturation could be due to the finite level width with the result of non-vanishing overlap of the spin-states at \( \nu = 1 \), consistent with our measured line-widths.

In conclusion, we have demonstrated a novel method of extracting 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 technique. The measured size of the charged spin-texture excitations is consistent with a spin of \( \sim 3 \) flips per unpaired flux quanta.

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I. FIGURE CAPTIONS

**Figure 1**: 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 calculated spin-polarization is plotted as a function of filling factor $\nu$ 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.

**Figure 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 12T are plotted versus 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.

**Figure 3**: The calculated spin-polarization $S_z$ displayed as a function of filling factor $\nu$ for 1.4 and 0.5K. The solid line fit assumes a macroscopic spin of $\sim 3.7$ per flux quanta, while the dashed, dotted, and dash-dot fits assume a single particle self-consistent exchange-enhanced $g$-factor model with appropriate ranges of broadening and temperature.

**Figure 4**: Spin-polarization as a function of temperature in sample A with a carrier density of $n = 1.5 \times 10^{11} \text{cm}^{-2}$. 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.
FIG. 1.

E. H. Aifer, et al. Figure 1.
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FIG. 3.

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FIG. 4.

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