Observation of skyrmions in a two-dimensional hole system

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We present magnetoreflectivity results indicating the observation of skyrmions in a two-dimensional hole system. The structure is chosen so that the complex valence-band structure causes a crossing of the lowest two spin-split Landau levels at fields near $\nu=1$. This reduces the Zeeman energy with respect to the Coulomb energy sufficiently to allow the formation of skyrmions. The formation of antiskyrmions at higher fields is rapidly suppressed due to the rapid divergence of the Landau levels at these magnetic fields.

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The existence of skyrmion excitations at small deviations in filling factor from the quantum Hall ferromagnet (at $\nu=1$) in two-dimensional systems was predicted a decade ago.[1] These excitations are observed in the situation of a full Landau level consisting of electrons of one particular spin orientation being perturbed by additional electrons of the opposite spin at sufficiently small ratios of the Zeeman energy to Coulomb energy ($\tilde{g}=E_z/E_c$). A skyrmion consists of a single reversed spin surrounded by spins that gradually tilt over until at the edge they are aligned with the external magnetic field. The effect of varying the Zeeman energy was studied theoretically and showed that skyrmion excitations would only be present at very small $\tilde{g}$.[2,3] This then prompted experimental studies. Magnetotransport methods in which the collapse of the spin gap was measured for different g-factors (altered either by tilting the sample or by applying pressure) have been used to study skyrmion formation in addition to a resistively detected nuclear magnetic resonance technique.[4–6] Heat capacity measurements have also been performed.[7] However, the most successful techniques for studying skyrmions have involved measuring the polarization of the system. Such experiments were first performed by Barret *et al.*[8] in which the deviation from near 100% polarization around $\nu=1$ was measured *via* the Knight shift as a function of filling factor. These experiments were followed by Aifer *et al.*[9] where they used magnetoabsorption to measure the polarization around $\nu=1$. Both works concluded that the size of the skyrmions was relatively small, with *additional* spin-flips of $A=S=2.6$ (Ref. 8) and $A=S=1.5\rightarrow 2.7$ (Ref. 9) per flux quantum. More recently Zhitomirsky *et al.*[10] have shown that if the electron Zeeman energy is reduced by the use of narrower quantum wells values of A and S of order 9 can be observed.

No studies of skyrmions, either optical or transport, have yet been reported in two-dimensional hole systems to our knowledge. To a large extent the study of hole systems in the quantum Hall regime has been thwarted so far by poor sample quality, the complex nature of the valence band interfering with interpretation of results and, in the case of optical experiments, strong density depletion under illumination.[11] Most of these problems have now been overcome or circumvented and in this paper we present new magnetoreflectivity results demonstrating the existence of skyrmions around the $\nu=1$ quantum Hall ferromagnet in the lowest heavy-hole Landau level. This is in fact a consequence of the complex nature of the valence band in this system, causing these spin-split Landau levels to cross at magnetic fields near $\nu=1$ thus reducing the Zeeman energy sufficiently to allow skyrmion formation.

We use reflectivity spectroscopy to measure the polarization of two-dimensional holes in a $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well and find that the system adheres to the skyrmion picture for filling factors $\nu>1$ and to the single-particle picture for $\nu<1$.

It has been demonstrated theoretically that reflectivity is a valid probe of the unoccupied density of states. The measurement is obtained from the excursion of the reflectivity signal around the transition energy *via* the Kramers-Kronig relations.[13] By selecting either of the two circular polarizations of reflected light, polarized reflectivity gives an absolute measure of the polarization of the system and has already been used to investigate further the precise nature of the ground state of the quantum Hall ferromagnet at $\nu=1$ in electron systems[10] and the composite fermion effective mass.[12]

The systems investigated consist of a p-type single-side Si modulation-doped GaAs quantum wells of width 100 or 150 Å within $Al_{0.3}Ga_{0.7}As$ barriers, grown on (311)A oriented substrates. The undoped spacer layer between the well and doped layer is 200 Å. The density and mobility of both systems was measured in the dark to be 2.1×10^{11} cm^{-2} and 4×10^{5} cm^{2}(V s)$^{-1}$, respectively. The density has been shown to be relatively unaffected by illumination in these narrow spacer width systems, and the light is carefully filtered so as to consist solely of energies between that of the GaAs and $Al_{0.3}Ga_{0.7}As$ band gaps.[11] Care was taken to exclude all light outside the investigated reflectivity energy band, nevertheless a small increase in the density of the sample is still observed due to an inevitable contamination with below GaAs band gap energy light.[15]

The experiments were performed in a 21.5 T superconducting magnet, with the sample placed in the Faraday geometry inside a rotary-pumped ^{3}He jacket which was in turn placed in a variable temperature insert. Sample temperatures

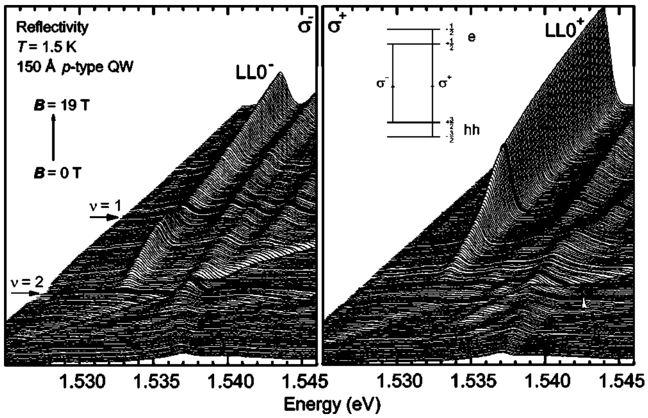

FIG. 1. Raw reflectivity spectra as a function of magnetic field for both of the two circular polarizations, taken in steps of 0.1 T. Inset, optical transitions in the high field limit.

as low as 0.4 K could be achieved. Light from a filtered Halogen lamp was transmitted to the sample *via* a single fiber optic; a fiber bundle was used for light collection. Polarization analysis of the reflected light was carried out using *in-situ* circular polarizers (the incident light remained unpolarized at the sample), reversing the direction of the magnetic field allows us to select σ^- or σ^+ optical transitions. The light was dispersed and the spectra aquired using a 1 m focal length single-grating spectrometer and CCD detector combination with a resolution of 0.12 meV.

Figure 1 shows waterfall plots of raw reflectivity spectra taken at $T=1.5$ K in each of the two circular polarizations as a function of magnetic field from 0 T (bottom) to 19 T (top) for the 150 Å quantum well. Here we are only interested in the main peak, labelled LL0 in both sets of spectra. This feature is absorption into the lowest heavy-hole Landau level (see inset to Fig. 1). The other peaks are related to other correlated states and the light-hole band and are dealt with elsewhere.[14,16]

Landau levels in a two-dimensional system are only observed in absorption experiments once their energy is greater than the Fermi energy (E_F). In the single-particle picture, the upper and lower spin branches of the lowest Landau level (LL0) should begin to appear in the reflectivity spectra in different polarizations when they begin to empty at $\nu=2$ and $\nu=1$, respectively. However, it is clear from the spectra in Fig. 1 that peaks appear in both polarizations at magnetic fields above $\nu=2$, thus indicating a loss of polarization between $\nu=2$ and $\nu=1$. To quantify this, we plot the polarization as a function of filling factor at various temperatures in Fig. 2. It is calculated using

$$P = \frac{N^- - N^+}{N^- + N^+}, \qquad (1)$$

where, for the experimental data, N^- (N^+) is the magnitude of the excursion of the reflectivity signal for the lower (upper) spin-split landau level. For the theoretical curves (discussed next) N^- and N^+ are given by the calculated fractional occupancies of the lower and upper levels, respectively.

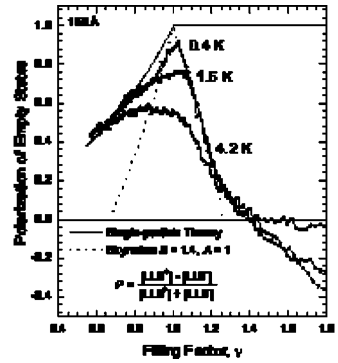

FIG. 2. Polarization as a function of filling factor for the 150 Å quantum well at three different temperatures.

The solid line in Fig. 2 is a theoretical curve for the polarization behavior for a single particle system. Note, however that absorption experiments probe the polarization of the *empty* states of the system. The polarization of the empty states in the single-particle picture is

$$P = 1, \quad \nu \geqslant 1, \qquad (2)$$

$$P = \frac{\nu}{2-\nu}, \quad \nu < 1. \qquad (3)$$

For small filling factors $\nu<1$ the experimental polarization data in Fig. 2 fits the single particle picture very well. However, for $\nu>1$ it clearly bears no relation to this picture. Instead we invoke the concept of skyrmions. In this case each decrease (increase) of a single flux quantum away from $\nu=1$ is accompanied by $S(A)$ *additional* spin-flips, which are the tilted spins of the skyrmion. As a result the polarization, which is still 1 (fully polarized) at $\nu=1$, decreases rapidly as the filling factor deviates. For the empty states the polarization in the skyrmion picture is

$$P = \frac{(2-\nu) - 2(\nu-1)S}{2-\nu}, \quad \nu \geqslant 1, \qquad (4)$$

$$P = \frac{\nu - 2(1-\nu)A}{2-\nu}, \quad \nu < 1. \qquad (5)$$

which reverts back to the single particle case when A or S $=0$.

As noted above, our experimental data fits the single-particle case extremely well for small filling factors $\nu<1$. For $\nu>1$ it is necessary to use the skyrmion picture with S $=1.4$. This fit is drawn in Fig. 2. The decrease in polarization (from nearly 94% at $T=0.4$ K to approximately 55% at T $=4.2$ K) is due to the thermal excitation of carriers across the spin gap. By contrast a similar study of the 100 Å well is described well by single particle behavior and shows no evidence of skyrmion formation.

The size $S(A)$ of the skyrmion depends upon the competition between the electron Coulomb interactions which try to maximize $S(A)$, and the Zeeman energy which tries to minimize it. This is characterized by

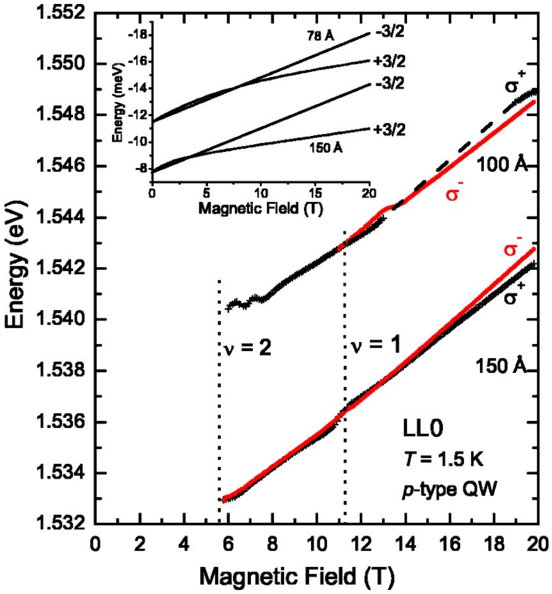

FIG. 3. (Color online) Transition energy of the reflectivity signal as a function of magnetic field for both polarizations for both of the quantum wells. The absence of the σ^- signal for the 100 Å well at filling factors $\nu > 1$ clearly indicates that the system is fully polarized between $\nu = 1$ and $\nu = 2$. The 100 Å sample presents some difficulties for data fitting since higher Landau level bulk lines pass through the quantum well features, causing some oscillations in the line positions. Inset, data taken from Cole *et al.* (Ref. 17) showing calculated Landau level energies (relative to the bottom of the well).

$$\tilde{g} \equiv \frac{E_Z}{E_C} = \frac{g\mu_B B}{e^2/\epsilon l_0}, \tag{6}$$

where $l_0 = \sqrt{\hbar/eB}$ is the magnetic length. Theoretically it has been found that for $\tilde{g} \geqslant 0.02$, the skyrmion diameter reduces to a value such that it is indistinguishable from a single spin-flip excitation.[2,3]

We attribute the existence of skyrmions in our system to Landau level mixing which is a result of the complex valence band structure in GaAs quantum well systems. In these systems the close energy proximity of the heavy- and light-hole bands causes the bands to become nonparabolic with anisotropic effective masses. These systems have been modelled theoretically in the axial approximation by Cole *et al.*[17] and our experimental values for the light-heavy hole splitting and other features agree well with their predictions.[16] In the calculations one effect of this mixing is to introduce a crossing of the two lowest spin-split Landau levels at about 3 T for the 150 Å well and 8 T for a 78 Å well (see inset to Fig. 3), caused by the close proximity of the next two-dimensional subband. These crossings are expected to move to significantly higher fields when full level mixing is taken into account. The energy dispersions as a function of magnetic field have been largely confirmed by cyclotron resonance experiments in which only a single broad resonance is observed for the 150 Å well near the crossing point with two individual resonances becoming resolved only at fields above 12 T.[17] Calculations for a 100 Å well are not available but the crossing point can be expected to lie between those of the

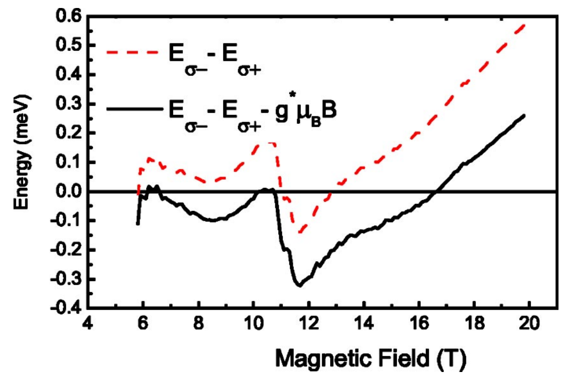

FIG. 4. (Color online) The transition energy splitting $(E_{\sigma_-} - E_{\sigma_+})$ and the estimated heavy hole splitting $(E_{\sigma_-} - E_{\sigma_+} - g*\mu_B B)$ for the 150 Å sample.

78 Å well and 150 Å well. This picture is also supported by photoluminescence experiments[18] which showed that, for the 150 Å well, the behavior at $\nu = 1$ is different from that at other odd integer filling factors implying that the Landau levels cross at magnetic fields between $\nu = 2$ and $\nu = 1$. No such anomaly occurs for the 100 Å well indicating that a crossing has yet to occur in magnetic fields up to at least 10 T. These results are consistent with our present interpretation.

In the 150 Å sample the two-dimensional hole density is such that the crossing is accidentally in the magnetic field region below $\nu = 1$. The most reliable estimate is that this is at $\nu \simeq 1.4$ (8 T), where the net polarization in the single particle regime is close to zero and temperature independent (Fig. 2). The field dependence of the hole Zeeman splitting may be estimated from the splitting of the reflectivity peak positions, the estimated electron Zeeman energies which are calculated using a value of $g* = 0.27$ (Refs. 10 and 19) and the assumption of the same excitonic binding energy for both transitions. This is shown in Fig. 4 where both the peak splitting $(E_{\sigma_-} - E_{\sigma_+})$ and the estimated hole Zeeman energy $(E_{\sigma_-} - E_{\sigma_+} - g_e * \mu_B B)$ are shown. With the exception of a small anomaly in the region very close to $\nu = 1$ where the transition energies may be affected by exchange interactions[18,20] the data suggests that the hole Zeeman splitting is essentially constant from 8 to 15 T $(1.4 < \nu < 0.75)$, with an estimated value of order 0.15 ± 0.15 meV corresponding to a value of $\tilde{g} \leqslant 0.01$. Formation of a skyrmion with $A = 1.4$ may take place for values of $\tilde{g}$ as large as 0.025, taking into account finite thickness effects.[3] Thus the Zeeman energy is still sufficiently small at $\nu = 1$ (11.3 T) for the formation of skyrmions to be energetically favorable. At higher magnetic fields the Landau levels begin to diverge rapidly (Fig. 3) and the Zeeman energy is too large for antiskyrmions to form, while in the region $0.75 < \nu < 1$ the polarization behavior is neither single particle nor does it fit a particular antiskyrmion size (Fig. 2), indicating that the antiskyrmions are rapidly becoming smaller with decreasing filling factor until they finally break apart completely at $\nu = 0.75$. Below $\nu \leqslant 0.75$ the behavior is entirely single particle.

The picture for the 100 Å well is different. In Fig. 3 a feature for the σ^- transition is only observed for filling factors $\nu < 1$ indicating that between $\nu = 2$ and $\nu = 1$ the system is fully polarized. Skyrmions are not present in this system. This can be explained by the large heavy-light hole energy splitting[16,17] which means that the Landau levels are more linear and do not cross ensuring that the effective Zeeman energy, $\tilde{g}$, is too large at all filling factors for the formation of skyrmions to be possible.

In summary, we have shown data indicating the first observation of skyrmions in a two-dimensional hole system. By using a wide (150 Å) well, heavy-light hole mixing is sufficiently strong to cause the lowest spin-split Landau levels to cross. By choosing a structure where this occurs in the magnetic field region near $\nu = 1$, it is possible to make the effective Zeeman energy, $\tilde{g}$, sufficiently small to allow skyrmions to form but with a relatively small size.

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