Quantum Hall skyrmions in a hole gas with large spin gap and strong disorder

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Abstract. Photoluminescence excitation spectra of two-dimensional holes are investigated in high magnetic fields. Despite large spin gap and strong disorder, quantum Hall ferromagnetism and small skyrmions are identified around the Landau level filling factor $\nu = 1$, based on the field dependence of polarized emission. This interpretation is supported by realistic numerics.

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INTRODUCTION

Concentration ρ of a two-dimensional electron (or hole) gas in a high magnetic field B is conveniently expressed by the Landau level (LL) filling factor $\nu = 2\pi\rho\lambda^2$, where $\lambda = \sqrt{\hbar c/eB}$ is the magnetic length. Even in the absence of Zeeman spin splitting E_Z, exchange interaction between the carriers causes their complete spin polarization at $\nu = 1$ [1]. Even small deviation from $\nu = 1$ makes such "quantum Hall ferromagnet" unstable [2]. Each additional vacancy or reversed-spin particle in the majority- or minority-spin LL, respectively, induces and binds K spin flips to become a *skyrmion* [3]. The skyrmion size K depends on the ratio of Zeeman and Coulomb energies, $\tilde{g} = E_Z/(e^2\lambda^{-1})$. At $\tilde{g} \to 0$, K diverges and skyrmions carry macroscopic spin per unit charge [4].

Though skyrmions were demonstrated in several experiments [5], the effect has been believed to be relatively subtle, observable only in the superior quality structures. In this work we demonstrate skyrmions in a hole gas with both significant disorder and large spin gap. This proves that, contrary to earlier expectation, skyrmions are a robust feature of quantum Hall systems, requiring neither spin degeneracy nor translational symmetry.

RESULTS AND DISCUSSION

We report low-temperature polarization-resolved photoluminescence excitation (PLE) studies of a p-doped $w = 8$ nm GaAs/Al$_{0.3}$Ga$_{0.7}$As quantum well grown by MBE on the (001) semi-insulating GaAs substrate and modulation C-doped in the barrier on one side. The low-temperature concentration and mobility of the holes were $\rho = 3 \cdot 10^{11}$ cm^{-2} (yielding $\nu = 1$ at $B = 13$ T) and $\mu = 3.3 \cdot 10^3$ cm^2/Vs. The spectra were recorded at low temperatures ($T = 1.8$ K), in magnetic field $B \leq 23$ T, in Faraday configuration, for different σ^+ and σ^- helicities of both the excited and emitted light.

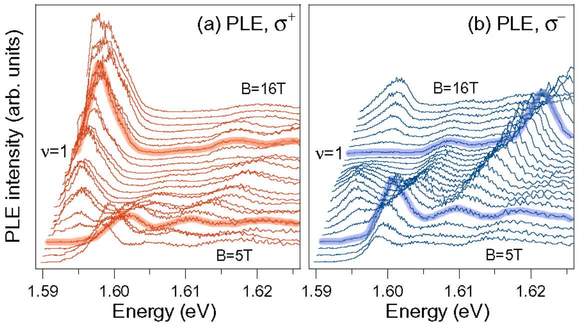

FIGURE 1. Quasi-continuous field evolution of PLE spectra in both σ^+- and σ^- polarizations. Thick lines: $\nu = 1$ and 2.

The polarization-resolved PLE is an indirect measure of the absorption of circularly polarized light ($\sigma^{\pm}$). Due to the simple spin/polarization selection rules combined with Pauli phase space blocking, polarized PLE is a probe of the occupation of LL's by the electrons with a given spin, i.e., to the spin polarization.

In Fig. 1 the spectra for both polarizations are compared. Their field evolution is completely different, especially in the lowest-energy signals, corresponding to the interband optical excitation from the highest LL in the valence band (lowest heavy-hole LL) to the lowest electron LL (i.e., to the $n = 0 \to 0$ transitions). The "$0 \to 0$" line appears in the σ^+ PLE spectra at $B = 6.5$ T and then gradually gains intensity with the increase of B. The same feature in the σ^- PLE also appears around $B = 6.5$ T, but it gains intensity with increasing field only up to $B = 9$ T. When the field grows further, the σ^- line first gradually weakens to disappear completely at $B = 13$ T, and then reappears and regains intensity.

This behavior is consistent with the skyrmion picture.

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At $\nu = 2$, there are no electrons with either spin in the $n = 0$ LL in the valence band. This forbids the "$0 \to 0$" interband transition for either spin, and causes vanishing of the lowest PLE line for either polarization. At $\nu = 1$, the hole gas is spin-polarized. In this case, the σ^- transition is forbidden, while σ^+ remains strong. When B is decreased from $\nu = 1$, each consecutive hole forced to reverse its spin due to shrinking LL degeneracy invokes additional K spin flips to become a skyrmion. This not only fills the spin-$\uparrow$ LL with holes, but also puts electrons in the spin-$\downarrow$ LL, allowing their interband excitation observed in the σ^- PLE. When B increases from $\nu = 1$, each consecutive vacancy (electron) in the spin-$\downarrow$ hole LL becomes an (anti)skyrmion, and the additional spin flips give rise to additional enhancement of the σ^- PLE.

Note that skyrmions occur in our sample despite strong disorder (with the mean free path shorter by 2–3 orders of magnitude than in high-quality electron systems). This is due to the local nature of the PL/PLE probe, sensitive to the presence of skyrmions regardless of their localization (in contrast to a transport experiment requiring mobile skyrmions acting as charge carriers).

Let us now estimate E_Z. From the comparison of σ^+ and σ^- PL spectra (not shown) we determined the spin splitting of the recombination energy as a function of B. It contains the (known) electron and (unknown for arbitrary w and B) hole Zeeman gaps, and the splitting due to spin-asymmetric exchange of the recombining hole with the hole gas of varying spin polarization. The latter, oscillatory term vanishes whenever the holes are paramagnetic, so it is easily eliminated. From the remaining, nearly quadratic dependence (and by taking $g_e = -0.15$ for the electron Landé factor), we obtain for the holes $E_Z = 0.55$ meV and $\tilde{g} = 0.034$ (at $\nu = 1$).

Let us turn to the skyrmion size K at $\tilde{g} = 0.034$. The smallest valence skyrmion $S_1^+ = 2h + e$ is a bound state of two reversed-spin ($\uparrow$) valence holes ($2h$) and one electron (e) in the majority-spin ($\downarrow$) valence level. It forms spontaneously from h when the Coulomb binding energy $\mathscr{E}_1$ between h and eh exceeds E_Z. Analogously, skyrmions $S_K^+ = (K+1)h + Ke$ with $K > 1$ are formed when the binding $\mathscr{E}_K$ between S_{K-1}^+ and eh exceeds E_Z.

The skyrmion binding energies for $K = 1$ and 2 were calculated by exact numerical diagonalization of realistic $2h + e$ and $3h + 2e$ hamiltonians. Significant enhancement of $\mathscr{E}_K$ compared to the earlier estimates $\mathscr{E}_1 = 0.0545 E_C$ [3] and $\mathscr{E}_2 = 0.03 E_C$ [6] was found when the finite well width and LL mixing were included. The plots of $\mathscr{E}_1$ and $\mathscr{E}_2$ as a function of B, are shown in Fig. 2. The binding enhancement through LL mixing is significant, from $\mathscr{E}_1 = 0.89$ to 1.35 meV (by 50%) and from $\mathscr{E}_2 = 0.49$ to 0.78 meV (by 60%) at $B = 13$ T. These values (recall $E_Z = 0.55$ meV), lead to the prediction of $K = 2$ for the skyrmion size at $\nu \sim 1$ in our experiment.

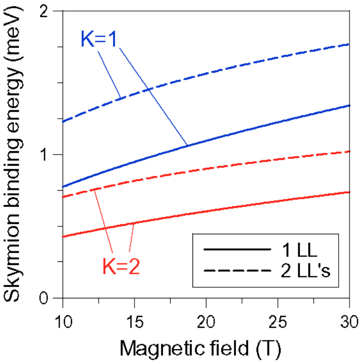

FIGURE 2. Magnetic-field dependence of Coulomb binding energies of small ($K = 1$ and 2) skyrmions calculated with and without inclusion of higher LL's.

CONCLUSION

In conclusion, in the PLE spectra of the 2D hole gas we found evidence for quantum Hall ferromagnetism and small skyrmions at $\nu \approx 1$. The skyrmions occur despite large Zeeman spin gap E_Z (too large, according to earlier theoretical estimates) and significant disorder (probably causing their localization). Realistic calculations confirm this interpretation, predicting skyrmion size $K = 2$.

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