Vol. **110** (2006) *ACTA PHYSICA POLONICA A* No. 2

Proceedings of the XXXV International School of Semiconducting Compounds, Jaszowiec 2006

Skyrmions in a Hole Gas with Large Spin Gap and Strong Disorder

L. Bryja[a], K. Ryczko[a], A. Wójs[a], J. Misiewicz[a] and M. Potemski[b]

[a]Institute of Physics, Wrocław University of Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
[b]Grenoble High Magnetic Field Laboratory, CNRS
38042 Grenoble Cedex 9, France

In the photoluminescence excitation spectra of two-dimensional valence holes with large spin gap and strong disorder we find evidence for quantum Hall ferromagnetism and small skyrmions around the Landau level filling factor $\nu = 1$. This interpretation is supported by numerical calculations.

PACS numbers: 73.20.Mf, 73.21.Fg, 78.20.Ls, 78.67.De

1. Introduction

Skyrmion [1] is a topological spin excitation of a polarized ground state, energetically favored over a single spin flip due to the tendency for parallel alignment of neighboring spins (i.e., to minimize gradient of the spin projection density). Under certain conditions, it also occurs [2] as an elementary charge excitation in quantum Hall systems, that is in a two-dimensional (2D) system of charge carriers (electrons or holes) in a strong magnetic field B, yielding filling of at most a small number of the Landau levels (LLs).

The LL occupation is conveniently defined by a filling factor $\nu = 2\pi\varrho\lambda^2$, where ϱ is the sheet concentration and $\lambda = \sqrt{\hbar c/eB}$ is the magnetic length. At the exact filling of the lowest spin-polarized LL, corresponding to $\nu = 1$, the ground state is spin polarized even in the absence of the single-particle Zeeman spin splitting $E_{\mathrm{Z}} = g\mu_{\mathrm{B}}B$ (g being the Landé factor). This situation can be described as half-filling of the lowest ($n = 0$) spin-degenerate LL. The reason is the dominant tendency to maximize exchange. The spin-polarized $\nu = 1$ state is an example of quantum Hall ferromagnet. Remarkably, the spin polarization at $E_{\mathrm{Z}} = 0$ is sensitive to the LL filling. In ideal 2D (zero width) it occurs at any integral ν [3] and also at the Laughlin series of fractions $\nu = (2p + 1)^{-1}$ with integral p [4], but not at nearly any other fraction. It also strongly depends on the interaction pseudopotential (interaction among the carriers restricted to the Hilbert subspace defined by the single-particle quantization). Similar behavior occurs in a half-filled atomic shell, polarized according to the Hund rule, but the opposite results for a half-filled 2D Hubbard lattice.

An extra reversed-spin carrier e_R added to the polarized ground state can have little effect on the underlying ferromagnet, but it can also induce and capture a number (K) of additional spin flips (e_R−h pairs, where h denotes a vacancy in the filled majority-spin level) [5]. Such bound $(K+1)e_R + K$h state is precisely a K-size skyrmion. In analogy, the $Ke_R + (K+1)$h state formed from an h is called a K-size antiskyrmion.

Whether skyrmions form or not in a given ferromagnet depends on the competition between the cost to create a spin flip and the gain to bind it to the free carrier. For example, in ideal 2D (and for sufficiently low E_Z) skyrmions occur in the lowest LL but not in higher LLs (even at $E_Z = 0$). At $\nu = 1$ the criterion for the occurrence and size of skyrmions can be expressed through the ratio $\tilde{g} = E_Z/E_C$, with $E_C = e^2/\lambda$ being the characteristic Coulomb energy. An early prediction for $K = 1$ was $\tilde{g} \leq 0.054$ [2], though even more severe estimates can be found in literature.

A striking consequence of the skyrmion formation is that addition (or removal) of each carrier to (from) the ferromagnet causes K additional spin flips. Especially, if K is large, this leads to a rapid depolarization as a function of B moving away in either direction from, e.g., $\nu = 1$.

Though skyrmions in quantum Hall systems were reported in several experiments with small $\tilde{g}$ (using NMR [6], transport [7], and optics [8]), their stability at significant spin gaps remains an open question. The effect is generally believed to be relatively subtle, with observation requiring special experimental conditions, including superior quality structures. In this paper we report the photoluminescence excitation (PLE) experiment on a 2D hole gas with rather large spin gap and strong disorder. Combined with realistic calculations, it demonstrates that, in contrast to earlier expectations, spin depolarization due to emergence of skyrmions is a robust phenomenon characteristic of the Hall systems even in the absence of perfect translational symmetry or spin degeneracy.

2. Experiment and results

We report low-temperature ($T = 1.8$ K), high-field ($B \leq 23$ T), circular--polarization-resolved PLE studies of a 2D valence hole gas in a rather narrow ($w = 8$ nm) $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well. The low-temperature sheet concentration and mobility of the holes were $p = 3\times10^{11}$ cm^{-2} and $\mu = 3.3\times10^{3}$ cm^2/(V s). Polarized PLE indirectly measures absorption of circularly polarized light ($\sigma^{\pm}$). Due to the simple spin/polarization selection rules (see Fig. 1) combined with the Pauli phase space blocking, it probes occupation of LLs by the electrons with a given spin, i.e., spin polarization.

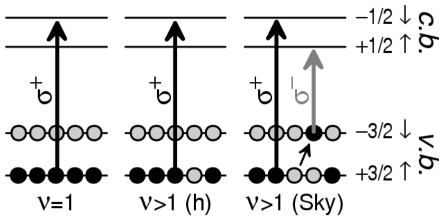

Fig. 1. Schematic LL diagrams for the 2D hole gas at $\nu = 1$ (ferromagnet) and at $\nu > 1$ with and without skyrmions. Full and shaded dots mark electrons and holes; vertical arrows show polarized optical transitions; spins are marked on the right.

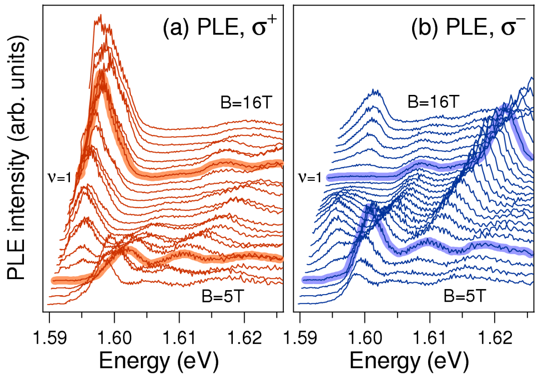

Fig. 2. Field evolution of PLE in both polarizations. Thick lines: $\nu = 1$ and 2.

In Fig. 2 the spectra for both polarizations are compared. Their field dependence is completely different, especially for the lowest-energy line, corresponding to optical excitation from the highest LL in the valence band (lowest heavy-hole LL) to the lowest electron LL. This "$n = 0 \to 0$" line appears in σ^+ at $B = 6.5$ T ($\nu = 2$) and then gradually gains intensity with the increase in B. In σ^- PLE it also appears around $B = 6.5$ T, but it only gains intensity up to $B = 9$ T. Then, it gradually weakens to disappear completely at $B = 13$ T ($\nu = 1$), beyond which reappears and regains intensity. This is clearly visible in a 2D contour map in Fig. 3.

This behavior is consistent with the skyrmion picture. At $\nu = 2$, the "$0 \to 0$" transition is not possible at either polarization for the lack of electrons. At $\nu = 1$, complete spin polarization allows for a strong signal in σ^+, but it forbids the σ^- transition. 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-↑ LL with holes, but also (uniquely for the skyrmion scenario) puts electrons in the spin-↓ LL, allowing their interband excitation observed in the σ^- PLE (see Fig. 1). When B *increases* from $\nu = 1$, each consecutive vacance (electron) in the spin-↓ hole LL becomes an

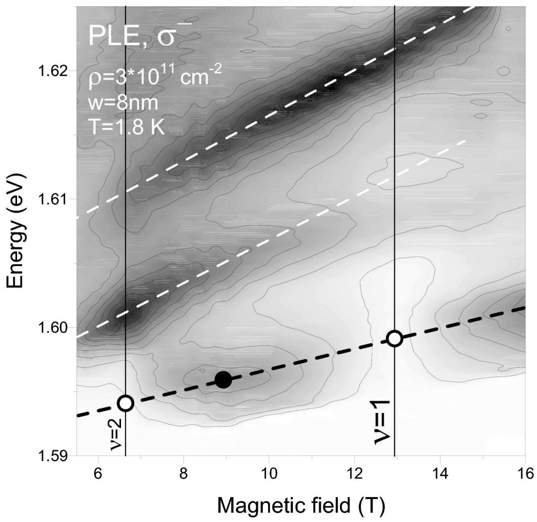

Fig. 3. Polarized PLE spectrum of the 2D hole gas as a function of magnetic field B. Open dot at $\nu = 1$ marks forbidden absorption region attributed to quantum Hall ferromagnetism. Emergence of intensity at lower and higher B is due to skyrmions.

(anti)skyrmion, and the additional spin flips give rise to additional enhancement of the σ^- PLE.

Remarkably, skyrmions occur in our sample despite strong disorder (mean free path shorter by 2–3 orders of magnitude than in high-quality electron systems). This is explained by local nature of the PL/PLE probe, sensitive to the presence of skyrmions regardless of their localization.

With increasing ν from 1 to 2, the number of skyrmions grows. Being charged, they interact with one another. Close to $\nu = 1$, the size K of each of the very few skyrmions is governed by $\tilde{g}$. However, further away from $\nu = 1$ (i.e., above certain skyrmion concentration), the size must shrink to $K = 1$ to accomodate all skyrmions in the limited space of a LL. Beyond some critical ν there is enough $K = 1$ skyrmions to cause complete spin depolarization. Indeed, our experiment shows the merger of σ^+ and σ^- intensities (vanishing of PLE polarization) below $B = 9$ T, corresponding to $\nu \approx 1.4$ (fairly close value to $\nu = \frac{4}{3}$ obtained from a simple single-electron phase-space filling argument).

Let us now estimate E_Z. From comparison of the polarized PL spectra (not shown) the spin splitting of the recombination energy was determined 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. The latter term vanishes whenever the holes are paramagnetic, so it was easily eliminated. From the remaining, nearly quadratic dependence (and using $g = -0.15$ for the electrons), 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 this $\tilde{g}$. The smallest valence skyrmion $S_1^+ = 2\mathrm{h_R} + \mathrm{e}$ is a bound state of two reversed-spin ($\uparrow$) valence holes and one electron in the majority-spin ($\downarrow$) valence level (let us note that we adjusted notation going from electron to hole gas: $\mathrm{e_R} \rightarrow \mathrm{h_R}$ and $\mathrm{h} \rightarrow \mathrm{e}$). It forms spontaneously from $\mathrm{h_R}$ when the Coulomb binding energy $\mathcal{E}_1$ between $\mathrm{h_R}$ and $\mathrm{eh_R}$ exceeds E_Z. Analogously, skyrmions $S_K^+ = (K+1)\mathrm{h_R} + K\mathrm{e}$ with $K > 1$ are formed when the binding $\mathcal{E}_K$ between S_{K-1}^+ and $\mathrm{eh_R}$ exceeds E_Z.

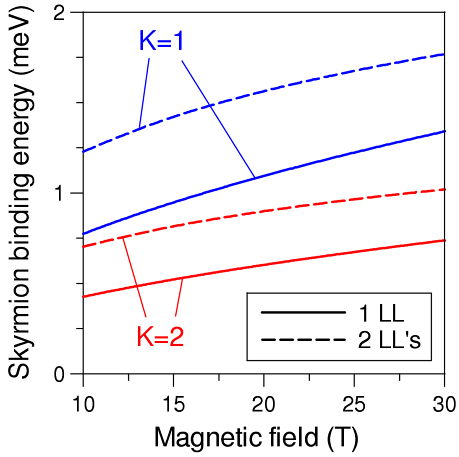

Fig. 4. Dependence of the Coulomb binding energies of small ($K = 1$ and 2) skyrmions on the magnetic field, calculated with and without inclusion of one higher LL.

$\mathcal{E}_1$ and $\mathcal{E}_2$ were calculated by exact numerical diagonalization of $2\mathrm{h}+\mathrm{e}$ and $3\mathrm{h}+2\mathrm{e}$ Hamiltonians (more realistic than studied previously [9]). The field dependence is shown in Fig. 4. Significant enhancement caused by LL mixing was found, from $\mathcal{E}_1 = 0.89$ to 1.35 meV (by 50%) and from $\mathcal{E}_2 = 0.49$ to 0.78 meV (by 60%) at $B = 13$ T. These values (recall $E_\mathrm{Z} = 0.55$ meV) yield skyrmion size $K = 2$ at $\nu \approx 1$ in our experiment.

3. Conclusion

In conclusion, in PLE 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 and significant disorder. Realistic calculations confirm this interpretation, predicting skyrmion size $K = 2$.

Acknowledgments

We thank L. Gravier for his input in the initial stage of this work and A. Fisher and K. Ploog for providing the structures used in experiment. Support from grants RITA-CT-2003-505474 from EC and N20210431/0771 from MENiS (Poland) is also acknowledged.

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