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# Collective spin precession excitations in a two-dimensional quantum Hall ferromagnet

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Using the inelastic light scattering technique we observe the spin excitations for a quantum Hall ferromagnet with charged defects. The lowest energy spin excitation branch behaves as the theoretically predicted collective spin precession ("cyclotron") mode of the spin-texture liquid. A coupling between the spin-exciton and the "cyclotron" mode indicates that the existing theory of noninteracting spin texture liquid does not provide a fully adequate description for the ground state of a quantum Hall ferromagnet with charged defects.

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The ground state of a 2D electron system (2DES) at $\nu = 1$ is a quantum Hall ferromagnet, where all spins occupy the lowest spin sublevel of the zero Landau level. The neutral spin excitation with unit spin and unit spin projection in the magnetic field direction is a spin exciton formed by a hole in the filled spin sublevel and an excited electron in the empty spin sublevel.[1,2] At small in-plane momenta ($ql_B \ll 1$, where $l_B$ is the magnetic length), the dispersion of the spin exciton is $E_{SE} = E_Z + a(ql_B)^2$, where $E_Z$ is the electron Zeeman energy. It has been widely accepted that when the 2DES moves away from the $\nu = 1$ state, the electron spins organize themselves in textures: Skyrmions. Skyrmions (anti-Skyrmions) are vortexlike topological distortions of the electron spins tied to an excess (lack) of electron charge with respect to a filled Landau level.[3] They are a result of competition between the loss of Zeeman energy, when a large number of spins are titled off the magnetic field direction, and the profit of lowering the exchange energy between adjacent spins. In real 2DES based on an AlGaAs/GaAs semiconductor system, the Zeeman term is significant, and Skyrmions shrink to spin-texture quasiparticles (STQs), which are natural generalizations of Skyrmion states.[4] The first experimental evidence in favor of STQs came from nuclear magnetic resonance, where a spin depolarization was measured via the Knight shift.[5] Optical measurements have presented similar evidence.[6] The theoretical mean-field calculations within the Hartree-Fock approximation have reached quantitative agreement with experiment, and completed the proof that STQs are responsible for 2DES depolarization.[7]

It has been further suggested that Skyrmions should condense into a crystalline form.[8] In spite of this pioneering prediction for 2DES systems, experimental evidence for Skyrmion crystallinity has come from 3D science. The formation of a Skyrme crystal has been reported for metallic ferromagnetic MnSi and similar compounds.[9] A real-space observation of the Skyrmion lattice has now been provided by Lorentz TEM imaging in the thin film of a noncentrosymmetric magnetic crystal $Fe_{0.5}Co_{0.5}Si$.[10] It seems that the Skyrmion lattice is a natural phase in magnetic metals lacking inversion symmetry. However, no similarly persuasive evidence has ever been presented for a Skyrme crystal in a Hall ferromagnet with charged defects formed by either the lack or an excess of electron density. In fact, not only the existence of a Skyrme lattice faces a shortage of experimental proofs; the existing theory of STQs is to be reexamined.

It turns out that the 2DES spin depolarization in the vicinity of $\nu = 1$ is well reproduced around $\nu = 3$, where the existence of STQs is debateable even at zero Zeeman energy.[11] The effective number of spin reversals $K$, the characteristics of the inhomogeneity of the spin rotation in space obtained in recent optical experiments, is not consistent with previous experimental findings.[12] Neither is it consistent with the theoretical values. This is surprising, as $K$ should be uniquely defined by the ratio of the Zeeman over the exchange energies. Finally, some of us have come to the conclusion that physical objects similar to STQs exist in the $K = 0$ limit, where STQs are not expected to form.[13] An extra spin mode with a well-defined in-plane momentum has been observed around both $\nu = 1$ and $\nu = 3$, well below the Zeeman energy, suggesting a noncollinear *spin liquid* as the ground state. Those experimental findings revisit the problem of the ground state for a Hall ferromagnet with charged defects. In the present article, we report experimental results supporting the theory of the STQ liquid as the ground state of a Hall ferromagnet with charged defects. When the effective number of spin reversals $K$ extends from 0 to 3, the excitation spectrum of the Hall ferromagnet remains basically unchanged.[14] It maintains a common feature, namely, an extra spin mode similar to that observed at $K = 0$.[15] The energy of the extra mode scales continuously with the density of charged defects. At finite in-plane momenta, this mode couples to the spin exciton. Employing the existing theory of an STQ liquid, we show that the extra spin mode fits the STQ "cyclotron" mode, predicted but before never observed.[16]

For our investigation, several GaAs/AlGaAs quantum wells (QWs) of 18–20 nm with a high-mobility 2DES were used (the dark mobility was between 5 and $7 \times 10^6$ cm$^2$/V s). The electron density for each quantum well was tuned continuously within 0–$10^{11}$ cm$^{-2}$ via the optodepletion effect. The density was measured by means of *in situ* photoluminescence.[17] In the experiment the Zeeman energy was kept constant, whereas the exchange energy was varied by titling the magnetic field relative to the sample surface and tuning the electron density to $\nu = 1$. The experiment ran as follows: Having fixed the total magnetic field and the sample tilt angle, the intensity of the photodepleting laser is changed to adjust the filling factor continuously from slightly above to well below $\nu = 1$. The inelastic light scattering (ILS) experiment was performed at a temperature of 0.3 K. The ILS spectra were obtained using a laser tunable above the fundamental band gap of the QWs.

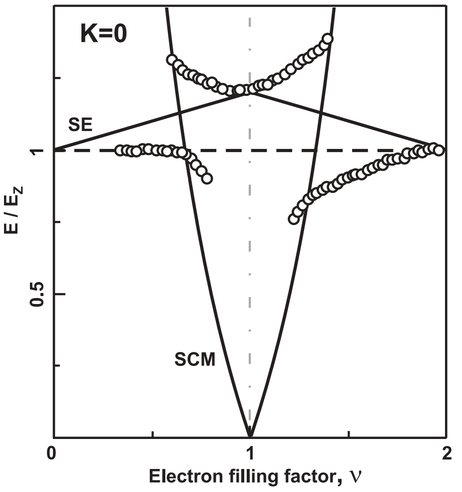

FIG. 1. The energies of ILS lines vs electron filling factor around $\nu = 1$ and $K = 0$ measured at $q = 1.5 \times 10^5$ cm$^{-1}$. The dashed line shows the bare electron Zeeman energy. The solid lines are the theoretical energies for the spin-exciton (Ref. 23) $E_{SE} = E_Z + \gamma \frac{x}{8\pi} q^2 l_B \int_0^\infty V(q) e^{-q^2/2} q^3 dq$ [$V(q) = \frac{e^2}{\varepsilon q} F(q)$, $F(q)$-geometrical form factor (Ref. 18), $\gamma \approx 2$ is the normalization coefficient for equalizing the experimental and theoretical energies] and for the STQ "cyclotron" mode $E_{\mathrm{SCE}} = E_S \frac{2(1-x)}{x}$, where $x = \nu$ for $\nu < 1$ and $x = 2 - \nu$ for $\nu > 1$.

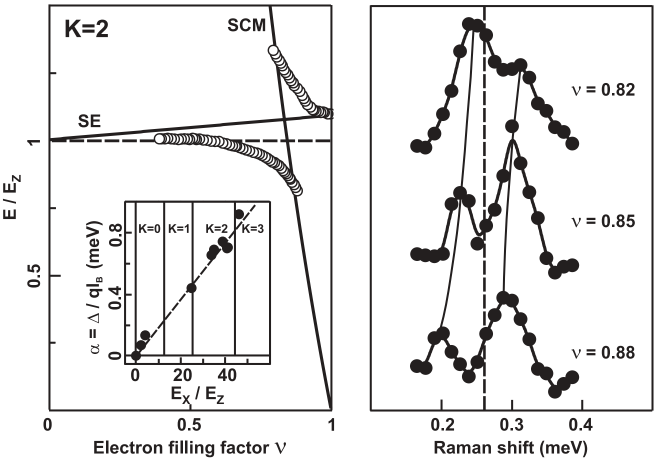

FIG. 2. Right: ILS spectra at $K = 2$ and different electron filling factors. The dashed line shows the bare Zeeman energy. Left: The energies of ILS lines vs electron filling factor at $K = 2$ (dots). The dashed line shows the bare Zeeman energy. The solid lines are the theoretical energies for the spin-exciton and for the STQ "cyclotron" mode $E_{\mathrm{SCE}} = \beta E_S \frac{2(1-\nu)}{\nu}$; $\beta \approx 3$ is the normalization coefficient for equalizing the experimental and theoretical energies. The inset shows the coupling strength between the spin-exciton and the STQ "cyclotron" mode $\alpha = \Delta(q)/ql_B$ vs the electron exchange energy [$\Delta(q)$ is the minimal energy gap between two coupled modes]. The solid lines demonstrate the theoretical boundaries between the adjacent $K$ states calculated as in Ref. 4 with accounting for the geometrical form factor. The dashed line is a guide for the eye.

Scattered light was dispersed by a Raman spectrograph and recorded with a charge-coupled device camera. The overall spectral resolution of the detection system was 0.04 meV.

First, let us reexamine the excitation spectrum of a Hall ferromagnet with charged defects in the $K = 0$ limit, Fig. 1. In spite of the theoretical prediction that STQs should not form in this case, the excitation spectrum agrees qualitatively with the spectrum of an STQ liquid.[16] In fact we observe similar excitation spectra until the full collapse of the exchange energy, a state that could be easily identified with the technique described in Ref. 18. To extend the $K = 0$ limit to larger $K$, where STQs should definitely form, 2DES samples with higher electron densities are employed. At the extended ratio of the exchange over the Zeeman energies, we pass the cases $K = 1,2$ and finally come to the $K = 3$ case. It is a quite tiresome task to reach higher values of $K$ as this implies working with high-density samples ($>3 \times 10^{11}$ cm$^{-2}$), in which the electron mobility unavoidably degrades. In what follows, we will focus on the behavior of holelike defects in a Hall ferromagnet $\nu < 1$, keeping in mind that the properties of the electronlike defects are similar due to the electron-hole symmetry. An extra spin mode is observed at all studied $K$, Fig. 2. In the vicinity of $\nu = 1$, it has an energy below the Larmor gap, whereas it gains in energy when the density of the charged defects increases. The new mode is not a Goldstone mode, as it has finite energy at $q \to 0$.[13] Therefore we consider the STQ liquid as the ground state rather than the STQ crystal, as the latter has a well-defined Goldstone mode.[19]

The theoretical description of the extra spin mode for an STQ liquid is given in Ref. 16. There are two spin modes at $ql_B \ll 1$: the spin exciton acquiring the Larmor gap at $q = 0$, and an additional collective spin mode—the STQ "cyclotron" mode possessing a well-defined in-plane momentum. The meaning of the term "cyclotron" is quite different from the generally accepted one, reserved for standard cyclotron excitations that acquire kinetic energy out of the cyclotron precession of charged particles in a magnetic field. Here, it is related to a collective spin precession in a fictitious magnetic field created by all STQs. As a consequence, the energy of the "cyclotron" mode tends to zero at $\nu = 1$, when the STQ density goes to zero. The "Landau levels" related to the fictitious magnetic field have an energy splitting of $\hbar\omega_c' = E_s 2(1-\nu)/\nu$ at $\nu \leqslant 1$, where $E_s = 4\pi\rho_s = \frac{1}{4} E_x$ is the classic energy for the formation of single Skyrmion, and $E_x$ is the exchange energy in the zeroth Landau level.[20] For the 2DES of zero thickness, $E_x = \frac{e^2}{\varepsilon l_B}\sqrt{\frac{\pi}{2}}$, whereas for the 2DES in GaAs/AlGaAs QWs of finite thickness, one should take into account the nonlocality of the electron wave function in the growth direction.[18] In the Skyrmion-rich limit $\hbar\omega_c' \gg k_B T$ ($T$ is the 2DES temperature), which is our case, the energy of the STQ "cyclotron" mode (SCM) is

$$E_{\mathrm{SCM}} = \hbar\omega_c'(q) = \hbar\left(\omega_c'^2 + c_1^2 q^2\right)^{1/2},$$

where $c_1 \propto n_s^{1/2} E_s$, and $n_s$ is the STQ density. The weak dispersion of this mode at small $qn_s^{-1/2}$ can be omitted; i.e., $E_{\mathrm{SCM}} \approx \hbar\omega_c'$. The theoretical "cyclotron" mode can be identified with the experimentally observed spin mode having an energy below the Larmor gap, Fig. 2. Thus our results support the theoretical prediction of the STQ liquid's being the ground state of a Hall ferromagnet with charged defects. However, one should not forget that the present theory is too simple to be correct. It completely disregards the interaction of the individual STQs by means of the spin excitons,

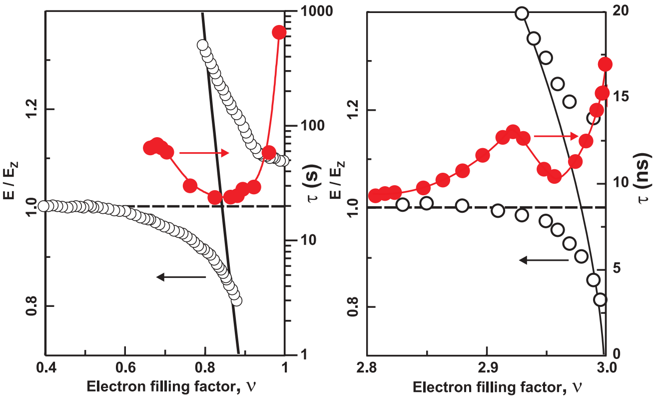

FIG. 3. (Color online) Left: The energies of ILS lines vs electron filling $\nu \leqslant 1$ measured at 6.46 T and the nuclear spin relaxation time measured at 7.05 and 9.39 T taken from Ref. 21. Right: The energies of ILS lines vs electron filling factor $\nu \leqslant 3$ measured at 1.9 T and the electron spin relaxation time measured in the magnetic field range from 2.2 to 2.7 T taken from Ref. 22. The dashed lines show the bare Zeeman energy. The solid lines are guides for the eye.

which is hardly likely to be valid. The importance of the spin-exciton mediated interaction follows from the coupling of the STQ "cyclotron" modes with the spin excitons under energy resonance conditions. This implies physical processes involving the absorption of spin excitons and the creation of STQ "cyclotron" modes, and, vice versa, the absorption of STQ "cyclotron" modes and the creation of spin excitons. Phenomenologically, the energies of the two coupled modes are

$$E_{1,2}(q,\nu) = \tfrac{1}{2}[E_{SE}(q,\nu) + E_{\mathrm{SCM}}(q,\nu)] \pm \sqrt{[E_{SE}(q,\nu) - E_{\mathrm{SCM}}(q,\nu)]^2 + |\Delta(q)|^2},$$

and under resonance conditions, $|E_{SE}(q,\nu) - E_{\mathrm{SCM}}(q,\nu)| \ll |\Delta(q)|$,

$$E_{1,2}(q,\nu) = \tfrac{1}{2}[E_{SE}(q,\nu) + E_{\mathrm{SCM}}(q,\nu)] \pm |\Delta(q)|.$$

The term $\Delta(q)$ is responsible for the interaction between the two modes. It is proportional to the in-plane momentum $\Delta(q) = \alpha q l_B$ at small $q l_B$.[13] The parameter $\alpha$ describes the coupling strength. It is measured over a large range of electron exchange energies and, correspondingly, $K$, Fig. 2. The coupling becomes stronger when the electron exchange energy enhances. This observation emphasizes the importance of the exchange interaction for the energy spectrum of a 2DES and brings to life a completely new picture of an interacting STQ liquid in which the interaction between separate STQs is facilitated by spin excitons. The interacting STQ liquid has not yet been treated theoretically.

The spectrum of an STQ liquid helps to explain the remarkable experiments on the relaxation of nuclear and electron spins in GaAs 2DES.[21,22] Figure 3 shows the nonmonotonic behavior of the spin relaxation on the electron filling factor around $\nu = 1$ and $\nu = 3$. It can be understood by taking into account the STQ "cyclotron" modes. When the STQ "cyclotron" energy lies below the Larmor gap, both the rates of the nuclear and of the electron spin relaxation enhance dramatically. In this case, the relaxation rate is defined by emitting the STQ "cyclotron" modes. As soon as the STQ "cyclotron" energy exceeds the Larmor gap, the relaxation rate starts to decrease. When the energy of the STQ "cyclotron" mode is far above the Larmor gap, the relaxation rate is defined by the low-energy spin excitons, and the dependence of the relaxation rate on the STQ density becomes monotonic. No similar arguments for a nonmonotonic relaxation behavior are presented by the theory of the Skyrme crystal, as the spin Goldstone mode with zero energy should exist at all defect densities. Therefore there is no obvious reason for the relaxation rate to be a nonmonotonic function of the STQ density.[19]

In conclusion, we outline briefly the physical issues of the reported results. The concept of the Skyrme crystal is not just a theoretical invention to describe the nontrivial spin polarization behavior of GaAs 2DES; it is a new state of matter observed experimentally in chiral magnets. Yet the very existence of the Skyrme crystal does not prove its relevance to the two-dimensional electron systems. It had already happened once that the 2DES chose liquid ground states—Laughlin liquids—notwithstanding numerous preliminary theoretical predictions of the Wigner crystal's being the ground state. Our data demonstrate that something similar is happening with the Skyrme crystal. The excitation spectrum of a Hall ferromagnet with charge defects appears to be the spectrum of an STQ liquid rather than that of the Skyrme crystal,[24] but not exactly the STQ liquid described by the theory. The real STQ liquid possesses a number of properties not discussed before. First, it seems that the effective number of spin reversals $K$ is not a good quantity for describing the STQ liquid. There is no significant difference in the excitation spectrum of an STQ liquid when $K$ changes successively from 0 to 3. This may indicate that the fluctuations in $K$ are so strong that there are no definite boundaries between neighboring states with different $K$. Second, the STQ liquid exists not only at $\nu = 1$, but also at $\nu = 3$, and most probably even at $\nu = 5$.[22] Third, two branches of spin excitations, the STQ "cyclotron" and the spin exciton, are coupled: a phenomenon that is neither predicted nor satisfactorily understood. We hope that our observations can facilitate the creation of a reasonable theory of the STQ liquid in a 2DES.

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[1] Y. A. Bychkov, S. V. Iordanskii, and G. M. Eliashberg, JETP Lett. **33**, 143 (1981).

[2] C. Kallin and B. I. Halperin, Phys. Rev. B **30**, 5655 (1984).

[3] S. L. Sondhi, A. Karlhede, S. A. Kivelson, and E. H. Rezayi, Phys. Rev. B **47**, 16419 (1993).

[4] M. Abolfath, J. J. Palacios, H. A. Fertig, S. M. Girvin, and A. H. MacDonald, Phys. Rev. B **56**, 6795 (1997).

[5] S. E. Barrett, G. Dabbagh, L. N. Pfeiffer, K. W. West, and R. Tycko, Phys. Rev. Lett. **74**, 5122 (1995); P. Khandelwal, A. E. Dementyev,

N. N. Kuzma, S. E. Barrett, L. N. Pfeiffer, and K. W. West, *ibid.* **86**, 5353 (2001).

[6] E. H. Aifer, B. B. Goldberg, and D. A. Broido, Phys. Rev. Lett. **76**, 680 (1996).

[7] L. Brey, H. A. Fertig, R. Côtè, and A. H. MacDonald, Phys. Rev. Lett. **75**, 2562 (1995).

[8] R. Côté, A. H. MacDonald, L. Brey, H. A. Fertig, S. M. Girvin, and H. T. C. Stoof, Phys. Rev. Lett. **78**, 4825 (1997).

[9] S. Mühlbauer, B. Binz, F. Joinetz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni, Science **323**, 915 (2009).

[10] X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa, and Y. Tokura, Nature (London) **465**, 901 (2010).

[11] N. R. Cooper, Phys. Rev. B **55**, 1934 (1997); Y.-Q. Song, B. M. Goodson, K. Maranowski, and A. C. Gossard, Phys. Rev. Lett. **82**, 2768 (1999).

[12] P. Plochocka, J. M. Schneider, D. K. Maude, M. Potemski, M. Rappaport, V. Umansky, I. Bar-Joseph, J. G. Groshaus, Y. Gallais, and A. Pinczuk, Phys. Rev. Lett. **102**, 126806 (2009).

[13] I. K. Drozdov, L. V. Kulik, A. S. Zhuravlev, V. E. Kirpichev, I. V. Kukushkin, S. Schmult, and W. Dietsche, Phys. Rev. Lett. **104**, 136804 (2010).

[14] The effective number of spin reversals $K$ is not directly measurable quantity. It is obtained theoretically from the ratio of $E_z/E_c$ as in Ref. 4.

[15] The low energy spin mode is also observed in Y. Gallais, J. Yan, A. Pinczuk, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **100**, 086806 (2008).

[16] J. P. Rodriguez, Europhys. Lett. **42**, 197 (1998).

[17] L. V. Kulik, S. Dickmann, I. K. Drozdov, A. S. Zhuravlev, V. E. Kirpichev, I. V. Kukushkin, S. Schmult, and W. Dietsche, Phys. Rev. B **79**, 121310 (2009).

[18] A. B. Van'kov, L. V. Kulik, I. V. Kukushkin, V. E. Kirpichev, S. Dickmann, V. M. Zhilin, J. H. Smet, K. von Klitzing, and W. Wegscheider, Phys. Rev. Lett. **97**, 246801 (2006); A. S. Zhuravlev, A. B. Van'kov, L. V. Kulik, I. V. Kukushkin, V. E. Kirpichev, J. H. Smet, K. von Klitzing, V. Umansky, and W. Wegscheider, Phys. Rev. B **77**, 155404 (2008).

[19] R. Côté, A. H. MacDonald, L. Brey, H. A. Fertig, S. M. Girvin, and H. T. C. Stoof, Phys. Rev. Lett. **78**, 4825 (1997).

[20] The real spin stiffness $\rho_s$ may depend on the electron filling factor; however, within the present theoretical approach it is assumed to be a constant in the vicinity of $\nu = 1$.

[21] R. Tycko, S. E. Barrett, G. Dabbagh, L. N. Pfeiffer, and K. W. West, Science **268**, 1460 (1995).

[22] D. Fukuoka, K. Oto, K. Muro, Y. Hirayama, and N. Kumada, Phys. Rev. Lett. **105**, 126802 (2010).

[23] I. V. Kukushkin, J. H. Smet, D. S. L. Abergel, V. I. Falko, W. Wegscheider, and K. von Klitzing, Phys. Rev. Lett. **96**, 126807 (2006).

[24] Our experimental setup does not allow us to measure ILS spectra below $T = 0.3$ K. Therefore we could not reject a hypothesis of solid phase formation at lower temperatures. In the temperature range from 0.3 to 1.5 K the low energy spin mode persists.