Disorder-Induced Stabilization of the Quantum Hall Ferromagnet

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We report on an absolute measurement of the electronic spin polarization of the $\nu = 1$ integer quantum Hall state. The spin polarization is extracted in the vicinity of $\nu = 1$ (including at exactly $\nu = 1$) via resistive NMR experiments performed at different magnetic fields (electron densities) and Zeeman energy configurations. At the lowest magnetic fields, the polarization is found to be complete in a narrow region around $\nu = 1$. Increasing the magnetic field (electron density) induces a significant depolarization of the system, which we attribute to a transition between the quantum Hall ferromagnet and the Skyrmion glass phase theoretically expected as the ratio between Coulomb interactions and disorder is increased. These observations account for the fragility of the polarization previously observed in high mobility 2D electron gas and experimentally demonstrate the existence of an optimal amount of disorder to stabilize the ferromagnetic state.

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Two-dimensional electron gases (2DEGs) under a magnetic field constitute a unique playground to study many-body effects. In a strong enough perpendicular magnetic field, 2D electrons are eventually confined to a single energy level, the lowest Landau level, in which Coulomb interactions can generate a series of collective ground states. When the lowest Landau level is fully occupied, which corresponds to a filling factor ν equal to one, exchange interactions stabilize a ferromagnetic ground state with long-range order known as the $\nu = 1$ quantum Hall ferromagnet (QHF). The lowest energy excitations in this ground state are generally not single spin flips but peculiar textures involving the reversal of several spins, known as Skyrmions [1–4]. Slightly away from the exact $\nu = 1$, charges can be added or removed from the system by forming Skyrmions, which leads to a fast spin depolarization evidenced, e.g., by NMR Knight shift measurements [5]. While early NMR measurements gave substantial information on the Skyrmion formation around $\nu = 1$, an accurate reference for full spin polarization is needed to appreciate the degree of polarization in a more quantitative way. Subsequent absolute measurements of the spin polarization [6,7] have actually revealed an incomplete polarization even at exact filling factor $\nu = 1$, where Skyrmions are *a priori* not expected. More recently, very sharp depolarizations have been observed for small filling factor deviations from $\nu = 1$ and/or nonzero temperatures [8]. The origin of this fragility of the spin polarization of the 2DEG around $\nu = 1$ and the condition for the stability of the QHF are the central focus of our present work.

In this Letter, we present resistive measurements of the NMR Knight shift providing us with an absolute determination of the $\nu = 1$ QHF spin polarization at millikelvin temperatures. Magnetic field-dependent measurements performed by varying the electron density of the 2DEG enable us to probe the spin polarization as a function of the ratio γ_{int} between Coulomb interactions and disorder. For the lowest explored values of γ_{int}, where disorder is significant, the QHF is stabilized in the close vicinity of $\nu = 1$, where the polarization P tends to 1. However, as γ_{int} is increased, a depolarization of the system is observed. We attribute our observation to the theoretically predicted phase transition between the QHF and the quantum Hall Skyrmion glass (QHSG), as interactions are increased with respect to disorder. This demonstrates the existence of an optimal amount of disorder to stabilize the QHF, and in turn accounts for the fragility of the spin polarization in high mobility (high γ_{int}) samples reported in the literature. The effect of the Zeeman energy on the polarization of the Skyrmion phase is finally examined via angular-dependent measurements, and is explained by the theoretically expected changes in the Skyrmion size.

The studied sample is a GaAs 2DEG in which the electron density can be continuously tuned by the application of a top gate voltage. The characteristics of the sample are summarized in Table I. The ^{71}Ga resonance was measured in a dilution fridge inserted in a 16 T superconducting magnet using the recently developed frequency-pulsed resistively detected NMR (f-PRDNMR) technique [9,10]. This technique, a variation of the power-pulsed resistive NMR [14,15], overcomes the limitation of standard continuous wave resistive NMR [16] and has recently allowed the study of various many-body phases in the QH regime [9,17,18]. In the present case, the NMR detection

TABLE I. Characteristics of the 2DEG sample: electron density n, low temperature mobility μ, perpendicular magnetic field B_F corresponding to $\nu = n/(eB_F/h) = 1$, total magnetic field $B_{\rm tot}$, effective Coulomb energy to disorder ratio $\gamma_{\rm int}$, Zeeman to Coulomb energy ratio η (see text for definitions).

n (cm^{-2})	μ (10^6 cm^2/V s)	B_F (T)	$B_{\rm tot}$ (T)	$\gamma_{\rm int}$	η
1.2	0.30	5	5	3.93	0.0123
1.73	0.44	7.2	7.2	4.9	0.0148
1.73	0.44	7.2	14	⋯	0.0287
2.17	0.54	9	9	5.65	0.0165
2.65	0.65	11	11	6.43	0.0182
3.37	0.84	14	14	7.54	0.0206

point, where the longitudinal resistance R_{xx} was measured, was chosen in the flank of the $\nu = 1$ QH state (typically $\nu = 0.8$–0.9). A large delay time between each filling factor acquisition was allowed for to make sure the nuclear system had completely relaxed, and slow sweeps were employed to approach a static response. The electronic temperature was systematically determined from the resistance of the sample and its calibrated temperature dependence, and for the reported scans was essentially current limited to a value of about 0.2 K (currents of about 50 nA were necessary to achieve a sufficient signal-to-noise-ratio to study the weak response close to $\nu = 1$).

In Fig. 1, we report f-PRDNMR signals in a region previously unexplored by conventional resistive NMR [16,19], namely, deep in the QH state where the longitudinal resistance vanishes. The variation of the longitudinal resistance ΔR_{xx} with respect to its off-resonant value R_0 is reported as a function of the relative excitation frequency $(f - f_0)$, where f_0 is the resonance frequency of an unpolarized electron system (zero Knight shift). The f_0 value was determined by using the f-PRDNMR response of unpolarized electron ($P = 0$) domains forming at filling factor $\nu = 2/3$ [9,20]. Because of the coexistence of unpolarized and fully polarized domains at this filling factor, the same measurement could be used to determine the maximal value of the Knight shift $\Delta f_{2/3}$, given by the $P = 1$ response observed at lower frequency. This latter value enables us to locate the expected resonance position for a fully polarized electron system at $\nu = 1$ (vertical dashed lines in Fig. 1) [21]. A peak in the resistive NMR signal generally sits close to the $P = 0$ reference frequency, as previously observed and discussed in Refs. [19,22]. This response, which can be attributed to an unpolarized electronic subsystem, will not be discussed here as we focus on the electronic spin polarization given by the Knight-shifted low frequency response. At low magnetic field, the resistance minimum is close to the dashed lines, showing that the polarization at $\nu = 1$ is nearly complete. As the magnetic field B_F is increased, the position of the minimum shifts to the left because the raw Knight shift is proportional to the electron density. However, the minimum

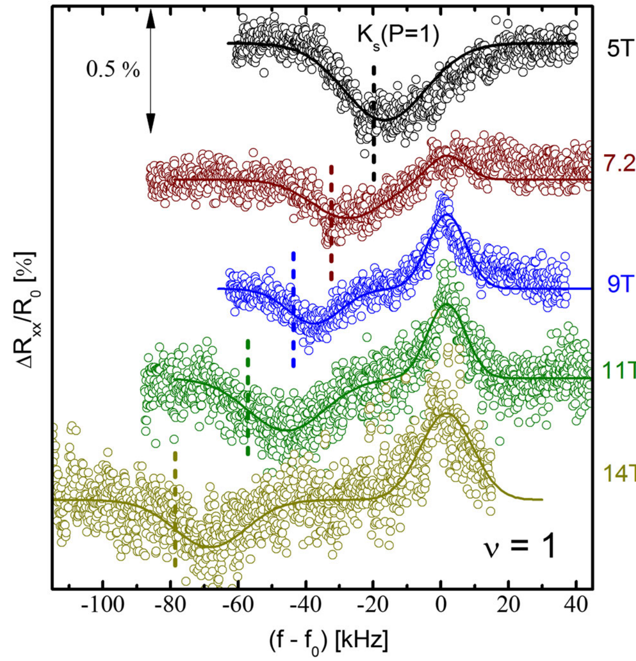

FIG. 1. f-PRDNMR signals at exact filling factor $\nu = 1.000(2)$ for different magnetic fields (circles). $B_F = 5$ (black), 7.2, 9, 11, and 14 T. f_0 is the reference frequency corresponding to an unpolarized electron system (no Knight shift). The vertical dashed lines denote the Knight shift for a fully spin polarized system (see text). The solid lines are simulations of the NMR response [10]. Curves are offset vertically for clarity.

does not shift as far as the dashed line, indicating that the polarization of the system at $\nu = 1$ is diminishing as the magnetic field is increased. This points to a weakening of the QHF phase in higher magnetic fields (higher electron density). This behavior, which is the key result of our studies, can also be evidenced in the vicinity of $\nu = 1$, which we will now discuss.

In Figs. 2(a) and 2(b) we present the extracted filling factor dependence of the spin polarization for different magnetic fields. The spin polarization of the system [21] at a filling factor ν is obtained by

$$P_\nu = (\Delta f_\nu / n_\nu)(W_\nu / \mathcal{A}), \tag{1}$$

where $\Delta f_\nu = f_r - f_0$, with f_r the frequency corresponding to the R_{xx} minimum, W_ν is the physical width of the electron system, and $\mathcal{A}$ is the hyperfine coupling constant. The ratio $(W_\nu/\mathcal{A})$ is determined from $\nu = 2/3$ calibration experiments, such that the determination of P_ν is absolute and involves only measured quantities.

At $B = 7.2$ T, the polarization of the system tends to be full only in a narrow filling factor region around $\nu = 1$, similarly to recent observations made in optical absorption experiments [8]. Away from $\nu = 1$, the polarization drops due to the well-established formation of Skyrmions in the system [5,6]. As the magnetic field is increased [Fig 2(b)],

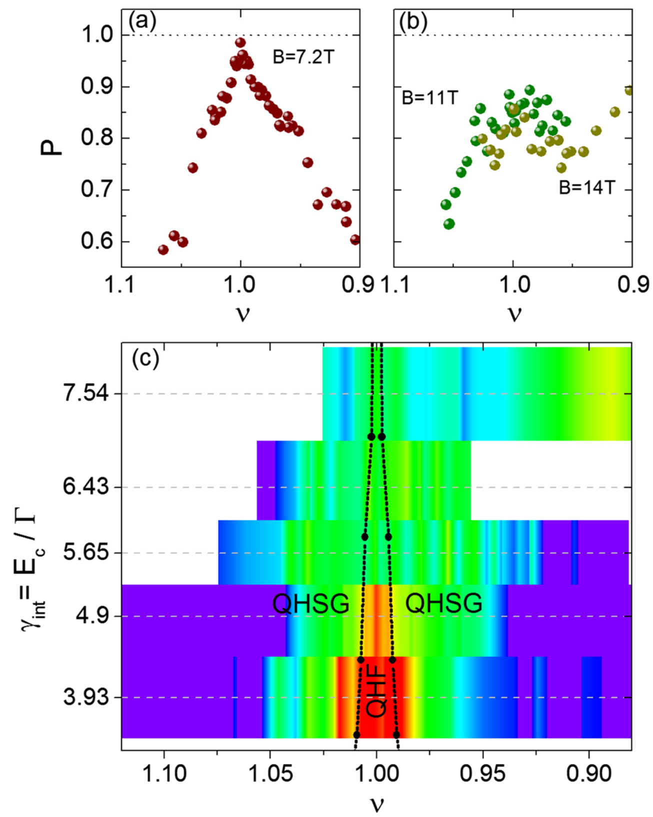

FIG. 2. Spin polarization P around filling factor 1 at magnetic fields of 7.2 T (a) and 11 and 14 T (b). (c) Polarization color map and phase diagram of the QHF. Color code: $P \leq 0.7$ (purple), $P = 0.7$ (blue) to $P = 1$ (red). The horizontal axis is the filling factor, and the vertical axis is the interaction parameter γ_{int} (see text). The horizontal dashed lines represent γ_{int} values for which sets of data were taken. The black dotted line and full circles materialized the phase boundaries between QHF and QHSG calculated in Ref. [23].

the spin polarization drops and is incomplete even in the close vicinity of $\nu = 1$. In the highest magnetic fields studied, the average polarization around $\nu = 1$ is about 0.75–0.8. The field-induced depolarization globally observed around $\nu = 1$ is not expected from simple *a priori* considerations, since in an ideal system the Coulomb interaction $e^2/(4\pi\epsilon_0\epsilon_r\ell_B)$ (where the magnetic length $\ell_B = \sqrt{\hbar/eB_F}$) should become stronger in high fields and favor the ferromagnetic state. This is not expected from Zeeman energy considerations either, since the increase in the Zeeman to Coulomb energy ratio $\eta = (|g^*|\mu_B B_{tot})/[e^2/(4\pi\epsilon_0\epsilon_r l_B)]$ with the magnetic field should lead to unfavorable conditions for the Skyrmion formation, and thus a repolarization of the system. This latter effect is actually observed in the 0.85–0.95 filling factor region for $B = 14$ T [partially visible in Fig 2(b)], but absent when going closer to $\nu = 1$.

Another important parameter in our experiment is the significant amount of disorder [24]. It is well known that in the high disorder limit, the $\nu = 1$ QH state (and thus the QHF) collapses [23,25–27]. While being larger than in the most recent QHF studies, the disorder in our sample is still small enough compared to the Coulomb interaction to ensure that the long-range order can develop and stabilize the QHF. This is theoretically expected for a ratio γ_{int} between Coulomb energy and disorder larger than ~2 [26]. On the other hand, a less intuitive effect of disorder can occur as the 2DEG is slightly taken away from the $\nu = 1$ filling factor. In this situation, charges are introduced into the system by forming Skyrmions. In the presence of disorder, fluctuations of the impurity potential generate random potential wells which establish an optimal Skyrmion size [23,28]. The QHF can resist until the Skyrmions are numerous enough to overlap, which occurs for a sufficient deviation $\delta\nu$ from $\nu = 1$ determined by the Skyrmion size, and, thus, the strength of disorder. These considerations led Rapsch *et al.* to build a phase diagram where the QHF dominates the QHSG over a small optimal window of γ_{int} and $\delta\nu$ values (Fig. 2 in Ref. [23]). Increasing γ_{int} at a fixed $\delta\nu$ brings the system to the Skyrmion glass phase, leading to the peculiar prediction that the QHF could be destabilized in a more interacting and/or less disordered system [23,26].

In the following, we show that we are here experimentally probing this so-far unexplored part of the phase diagram and the associated transition between the QHF and the Skyrmion glass phase with increasing γ_{int}. Figure 2(c) shows a color plot of the spin polarization, as a function of the filling factor for different values of interaction ratio γ_{int} obtained by performing experiments at magnetic fields of 5, 7.2, 9, 11, and 14 T. The effective Coulomb energy in our system has been estimated by performing thermal activation transport experiments at $\nu = 1$, taking into account the contribution of Zeeman energy and disorder. This enables us to come up with a realistic value of the Coulomb interaction, about $10\sqrt{B}$ K, taking into account its large reduction in a nonzero thickness system. Disorder, more precisely, the Landau level FWHM Γ, has been estimated by Shubnikov–de Haas (SdH) measurements. These estimations lead us to an interaction ratio $\gamma_{int} = (10\sqrt{B})/\Gamma$ varying from about 4 to 7.5 in our experiments [29]. The theoretical phase diagram of Ref. [23] is also reported in Fig. 2(c), where the QHF phase and the QHSG phase are separated by black dotted lines and full circles. We make a quantitative comparison between our data and theory by defining the high disorder phase boundary at $\delta\nu = 0$ in Ref. [23] to match the one in Ref. [26], which occurs for a value of $\gamma_{int} = 1.6$. In Fig. 2, the QHF phase appears as a stripe, which sharpens with increasing γ_{int}. As can be seen, a realistic estimation of γ_{int} in our sample shows that our experiment sits at low magnetic fields in the optimal window of the phase diagram where the QHF is stable and the spin polarization is complete close to $\nu = 1$. Increasing γ_{int} leads to a depolarization in the $\nu = 1$ vicinity, as experimentally observed. These observations also explain why the QHF is surprisingly more fragile in higher mobility samples [5,6,8,15], where the higher value of $\gamma_{\rm int}$ confines the QHF to an even narrower stripe around $\nu = 1$.

We note that, even though theories [23,26] do not predict any depolarization in the ideal $\nu = 1$ and $T = 0$ K cases (the phase boundary tends to $\delta\nu = 0$ for infinite values of $\gamma_{\rm int}$), a depolarization is observed experimentally at exact $\nu = 1$, as already reported in Fig. 1. We attribute this effect to the small but nonzero inhomogeneity (fluctuations) in the electron density, which makes the filling factor not perfectly equal to 1 in the physical space, and consequently pushes the system away from of the $\delta\nu = 0$ condition. Even with density inhomogeneities $\delta n/n$ of less than $\pm 0.5\%$ (an upper bound estimated from low field Hall and SdH measurements), we are probing at $\nu = 1$ a stripe of width $\delta\nu = \pm 0.005$ which extends out of the narrow QHF theoretical stripe at $\gamma_{\rm int} \sim 6$. This is precisely in the region where we experimentally observe the $\nu = 1$ depolarization. An additional loss of spin polarization is induced by the finite (nonzero) temperature of our experiment. The above point illustrates the sharpness of the QHF phase, which can only be stabilized by low temperatures, closeness to $\nu = 1$ (implying high electron density homogeneity), and, as we demonstrated, with the help of disorder. We recall that a too high amount of disorder will induce a transition to a QHSG paramagnetic state for $\gamma_{\rm int} < 1.6$ [23,26,27], which defines an optimal amount of disorder to stabilize the QHF.

Finally, we would like to comment on the role of the Zeeman energy. As we mentioned above, the increase in η at higher perpendicular magnetic fields (quantified in Table I) leads to a repolarization of the system seen in the top right-hand corner of Fig. 2(c). To further enhance the effect of the Zeeman energy, we have performed tilted field experiments where the Coulomb energy is limited by the magnetic field perpendicular to the sample, while the Zeeman energy scales with the (larger) total magnetic field. This enables us to boost the value of η up to about ∼0.03 (the electronic g factor is $g^* = -0.44$). In Fig. 3, we report the spin polarization around $\nu = 1$ in the two cases $\eta = 0.0148$ [data of Fig. 2(a)] and $\eta = 0.0287$. In the first case, the depolarization away from $\nu = 1$ lies very close to the theoretical expected behavior due to the formation of Skyrmions (anti-Skyrmions) of size $S\ (A) = 3.5$ for $\eta = 0.014$ (dashed lines) [1]. In the second case, the polarization drop away from $\nu = 1$ is much less pronounced, showing that Skyrmions are destabilized by the large value of η, again, in agreement with theoretical predictions. More precisely, for $\nu > 1.1$, the spin polarization follows the single-particle spin polarization with single spin flip excitation ($S = 1$), theoretically expected for $\eta = 0.03$ [32], very close to our experimental conditions. Quantitatively recovering the single-particle spin polarization is an additional confirmation of the accuracy of our absolute polarization measurement. For $\nu < 0.95$, very small size ($A = 1.5$) anti-Skyrmions are observed.

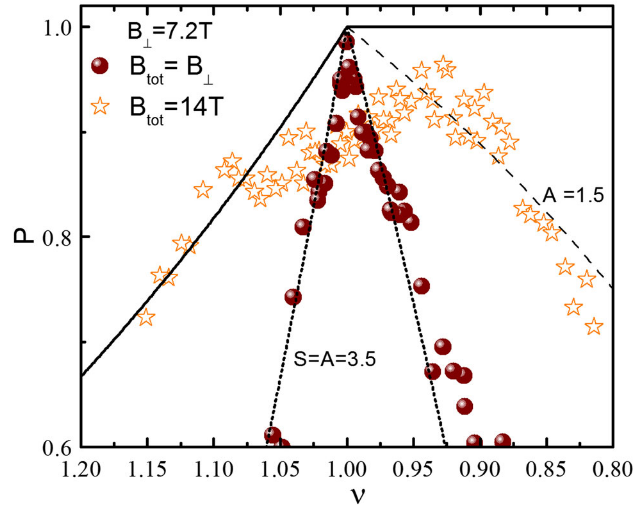

FIG. 3. Effect of the Zeeman energy. Spin polarization P for $\eta = 0.0148$ (dots) and $\eta = 0.0287$ (stars). Dotted (dashed) lines are theoretical expectation for a macroscopic spin of 3.5 (1.5) per flux quantum, while the solid lines are the single-particle spin polarization.

To conclude, we have reported absolute low temperature spin polarization measurements of the quantum Hall ferromagnet by employing state-of-the-art resistive NMR technique. Our results show that an optimal amount of disorder can stabilize the fully polarized QHF on a narrow temperature or filling factor window by preventing Skyrmions from expanding in the 2DEG. This accounts for the surprising fragility of this phase in high-quality 2D systems, and opens up new ways to generate robust 2D quantum Hall ferromagnets.

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