Metamorphosis of the Quantum Hall Ferromagnet at ν = 2/5

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We report on the dramatic evolution of the quantum Hall ferromagnet in the fractional quantum Hall regime at ν = 2/5 filling. A large enhancement in the characteristic timescale gives rise to a dynamical transition into a novel quantized Hall state. The observed Hall state is determined to be a zero-temperature phase distinct from the spin-polarized and spin-uncorrelated ν = 2/5 fractional quantum Hall states. It is characterized by a strong temperature dependence and puzzling correlation between temperature and time.

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In two-dimensional electron systems under strong transverse magnetic field, transitions to quantum Hall ferromagnets occur when two degenerate quantum Hall states coincide within some configurational space. The correlation between the two degenerate quantum Hall phases can be treated theoretically - in analogy to isospin degeneracy in nuclear physics - through a pseudospin representation of the relevant quantum numbers. Easy-axis quantum Hall ferromagnets have been shown to emerge in systems in which two degenerate quantum Hall states that differ primarily in the spin part of the wave function. Near a crossing between two spin levels, competition between the two degenerate quantum Hall states produces a correlated ground state termed a quantum Hall ferromagnet (QHF). Experimental studies in a number of systems have shown that Ising quantum Hall ferromagnets are characterized by metastability and hysteresis.

Of the various examples of easy-axis QHFs, the ν = 2/5 fractional quantum Hall effect (FQHE) state in the crossover regime between the spin-uncorrelated and spin-correlated states demonstrates the transport signatures associated with the Ising quantum Hall ferromagnetism. Realized under the conditions of reduced g-factor arising from application of hydrostatic pressure in excess of 10 kbar, the transport in proximity of ν = 2/5 filling exhibits strong hysteresis and anomalous logarithmic time-dependence. The path-dependent order parameter of an Ising QHF provides an elegant explanation for the hysteretic behavior. Local frustration of the pseudospin domains gives rise to a glassy behavior and the associated logarithmic time-dependent transport. Competition between the local interaction energy of the ferromagnetic domains and the configurational entropy of the domains walls is thought to be responsible for the large enhancement in the characteristic timescale. An important unresolved question concerning the glassy dynamics of the QHF at ν = 2/5 involves the nature of its ground state in the t → ∞ limit.

In this paper, we report on a novel phase transition of the QHF at ν = 2/5 in the crossover regime between the spin eigenstates of the ν = 2/5 FQHE. After an extensive duration of annealing, the time-dependent aging features previously attributed as the relaxation of QHF domains culminates with a quantized Hall state at ρ_xy = 5h/2e^2. Due to large enhancement in the characteristic time associated with the QHF at ν = 2/5, we are able to capture the progressive evolution into a highly correlated quantum Hall phase. This phase differs from the spin-singlet and spin-polarized ν = 2/5 FQHE states in that (1) initially there is no quantum Hall state at ν = 2/5 under ~13.5 kbar of pressure, (2) the quantized Hall state only appears after ~2 days of annealing, (3) it exhibits hyper-sensitivity to changes in temperature with an increase of ~10mK sufficient to destabilize the quantum Hall state, and (4) it demonstrates an anomalous correlation of magnetoresistance as a function of temperature and time. Based on these findings, we conclude that the quantized Hall state obtained via annealing is a zero temperature correlated phase distinct from the spin-singlet and the spin-polarized FQHE states at ν = 2/5.

High-quality GaAs/AlGaAs heterostructure was placed under large hydrostatic pressure inside a miniature copper-beryllium pressure clamp. The detail of the pressure apparatus has been described elsewhere. Application of large hydrostatic pressure reduces the magnitude of the Lande g-factor and the consequent reduction in the Zeeman energy. E_Zeeman = gμ_B B_total, enhances the spin-reversals of electrons. In order to optimize the competition between the spin-polarized and spin-uncorrelated ν = 2/5 FQHE states, the pressure was tuned to the crossover pressure of ~13.5 kbar. The density of the sample under 13.5 kbar of pressure is n = 1.2 × 10^{11} cm^{-2} with mobility of μ = 1.8 × 10^6 cm^2/Vs. Typical annealing run lasted ~2 days prior to subsequent magnetic field sweeps. The pressure inside the pressure-cell remained stable at low temperatures and no change could be detected even after several months of experiment. All 4 samples studied during the course of the experiment exhibited the reported effect.

Fig. 1 illustrates the representative hysteresis in mag-
magnetoresistance and Hall effect that appears at $\nu = 2/5$ filling under 13.5 kbar of pressure. Although no quantum Hall state at $\nu = 2/5$ is found, there is a prominent hysteresis as both magnetoresistance and Hall effect depend on the direction and sweep rate of the applied magnetic field. Fig. 1 compares the magnetoresistance and Hall effect of a specimen before and after approximately $\sim 2$ days annealing at 30mK. Fig. 1 illustrates the time dependence of the magnetoresistance at $\nu = 2/5$ under temperature of 30mK and 11.6 tesla of magnetic field. The resistance initially increases until it reaches a maximum around $\sim 1 \times 10^4$ seconds. Subsequent resistance decay is slow but persistent even after 2 days of annealing. Magnetic field sweeps performed after annealing reveal an unexpected quantum Hall state as evidenced from the pronounced minimum in the magnetoresistance and the quantized Hall plateau with $\rho_{xy} = 5h/2e^2$. This shows that the preferential ground state after an extensive period annealing of the QHF at $\nu = 2/5$ is a quantized Hall state.

Fig. 2 illustrates the time dependence of the magnetoresistance obtained through annealing at $\nu = 2/5$. The time dependent magnetoresistance for different temperatures can be separated into two distinct behaviors before and after the resistance peak found near $t_o \approx 1 \times 10^4$ seconds. In the initial part of annealing during $t < t_o$, magnetoresistance is weakly temperature dependent and increases slightly between 30 to 50mK. For $t > t_o$, the $R_{xx}$ at $\nu = 2/5$ exhibits a strong temperature dependence associated with the formation of the quantized Hall state at $\nu = 2/5$. A resistance decrease of $\sim 75\%$ by the end of the annealing run at $1.5 \times 10^5$ seconds is found at 30mK. Raising the temperature beyond 50mK removes the resistance downturn above $t > t_o$ and produces the

FIG. 1: History dependent transport of the quantum Hall ferromagnet at $\nu = 2/5$. The data was obtained under 13.5 kbar of pressure. (a) Hysteresis in magnetotransport associated with the quantum Hall ferromagnet at $\nu = 2/5$. (b) Comparison of the magnetotransport before (red) and after (blue) annealing of $1 \times 10^5$ seconds. Only the down field sweeps are shown for clarity. (c) Time dependence of magnetoresistance at $\nu = 2/5$ from annealing at temperature of 30mK.

FIG. 2: Magnetoresistance at $\nu = 2/5$ as a function of temperature and time. (a) Time dependence of magnetoresistance for annealing at different temperatures. From top to bottom, the traces correspond to 50 (red), 47, 43, 40, 35, 34, and 30 mK (blue) from top to bottom. (b) Scaling analysis of the change in magnetoresistance above $2 \times 10^5$ seconds from (a). The change in magnetoresistance, $\Delta R_{xx}$, for different temperatures can be collapsed onto a universal curve of the form $b(T)\Delta R_{xx} \sim (T_0 − T)/t$. $b(T)$ is the the size of $\Delta R_{xx}$ and $T_0$ is the characteristic temperature of $\sim 50 mK$. (c) Magnetoresistance in the lowest Landau level obtained after different duration of annealing. From top to bottom, the annealing duration corresponds to 0 (red), 36700, 65700, 94300, 132700, and 162900 seconds (blue). (d) Magnetoresistance obtained after $\sim 1.5 \times 10^5$ seconds for temperatures of 50 (red), 47, 43, 40, 34, 30 mK (blue).
The characteristic temperature, $T_R$, is a universal curve of the form $b(T)\Delta R_{xx} \sim (T_0 - T)/t$, where $b(T)$ is the temperature dependent prefactor that is equivalent to the size of $R_{xx}$ reduction. The characteristic temperature, $T_0$, of $\sim 50\text{mK}$ provides a measure of the energy scale of the phase. This inverse correlation between time and temperature demonstrates a remarkable interplay of the dynamics and thermodynamics of the annealed, low temperature phase.

Fig. 2a shows the quantitative relationship between time and temperature in the annealed quantum Hall state at $\nu = 2/5$. The change in magnetoresistance, $\Delta R_{xx}$, for $t > 10^4$ seconds from Fig. 2a can be collapsed onto a universal curve of the form $b(T)\Delta R_{xx} \sim (T_0 - T)/t$, where $b(T)$ is the temperature dependent prefactor that is equivalent to the size of $R_{xx}$ reduction. The characteristic temperature, $T_0$, of $\sim 50\text{mK}$ provides a measure of the energy scale of the phase. This inverse correlation between time and temperature demonstrates a remarkable interplay of the dynamics and thermodynamics of the annealed, low temperature phase.

Fig. 2a provides a sequence of snapshots of the quantum Hall phase at $\nu = 2/5$ with increasing annealing time. The quantum Hall state becomes stronger as longer annealing is applied. Emergence of the new Hall state is possible as long as the annealing is performed in proximity of $\nu = 2/5$. From the onset of $R_{xx}$ minimum at $\nu = 2/5$, we estimate the characteristic time of the transition to be $\sim 1 \times 10^5$ seconds, enormously enhanced compared to the single electron relaxation time of $\sim 10^{-12}$ seconds. Fig. 2b shows the representative traces at different temperatures attained after $\sim 1.5 \times 10^5$ seconds of annealing. The annealed Hall state at $\nu = 2/5$ exhibits an uncharacteristically strong sensitivity to temperature compared to the neighboring FQHE states. Raising the temperature to $\sim 50\text{mK}$ is sufficient to displace the quantized Hall state at $\nu = 2/5$. Interestingly, the temperature dependence of magnetoresistance is nearly a mirror-image of the time-dependence measurement of Fig. 2a with temperature acting similar to inverse time. This presumably reflects the scaling relation between temperature and time established in Fig. 2b.

The time dependence of $R_{xx}$ in Fig. 2a can be phenomenologically modeled in terms of two competing processes related to the motion of QHF domains, in analogy to the slow dynamics found in systems such as structural glass\[11\] and spin glass\[12\]. Within the framework of the droplet scaling theory of spin glasses\[13\], domain growth in glassy systems involves overcoming the barriers whose height grows with increasing lengthscale. The early, temperature-independent part of annealing may be explained in terms of coarsening of QHF domains. The initial rise of resistivity may be due to novel one-dimensional excitations responsible for the dissipation within the domains walls of QHF\[14\]. The latter stage of annealing appears to be dominated by the second, slower process that reduces dissipation and eventually leads to the quantized Hall phase. The $R_{xx}$ peak at $t = t_s$ may involve formation of a critical state in which a QHF domain with some preferential pseudospin vector percolates throughout the sample. This would greatly accelerate the growth of the domains along with reduced dissipation as the total length of the domain wall is decreased.

Appearance of the low temperature quantum Hall phase will continue until the domain size becomes comparable to the sample dimension.

An unusual feature of this phase involves its extreme sensitivity to temperature. While it may take a day or more of annealing to realize the quantum Hall state at $\nu = 2/5$, it is remarkable that raising the temperature by $\sim 10\text{mK}$ is sufficient to destabilize the Hall phase. Such an uncharacteristically strong effect of temperature can be understood if the annealed QHF is a zero temperature phase whose quantum mechanical coherence is readily destabilized by finite temperature. In terms of the QHF domains, thermal excitations produce local reversal of pseudospin magnetization and nuclear domains that destroy the underlying long range coherence achieved through annealing. This apparent ease of destabilization at low temperature points to smallness of its gap associated with its unique correlated origin.

In Fig. 3 we show the effect of in-plane magnetic field on the annealed phase at $\nu = 2/5$ at a temperature of $40\text{mK}$. With increasing tilt-angle, the annealed phase grows weaker as the $R_{xx}$ minimum for $18^\circ$ is about factor of 2 larger than the minimum for $0^\circ$. The weakening of the annealed quantum Hall phase at $\nu = 2/5$ can be interpreted as reduction in its energy gap under a larger Zeeman energy, suggesting that the spin-polarization of the annealed phase may be a spin-singlet. However, such an interpretation is complicated by the fact that presence of an in-plane magnetic field creates an imbalance between
the energies of the spin-polarized and spin-unpolarized states at \( \nu = 2/5 \) and this may produce a different annealing path at finite tilt angles compared to 0°. While the question regarding its spin polarization cannot be unambiguously answered, the tilted field study nonetheless shows that in-plane magnetic field tends to destabilize the annealed quantum Hall phase at \( \nu = 2/5 \).

In the context of spin transitions within the composite fermion model of the FQHE, it has been proposed that a new type of charge and spin density wave states can arise at \( \nu = 2/5 \) at intermediate values of Zeeman coupling. An admixture of two spin bands of composite fermion Landau levels at \( \nu = 2/5 \) can give rise to a partially polarized density wave (PPDW) state. Unlike the \( \nu = 2/5 \) FQHE state which can be either polarized or unpolarized, a PPDW possesses a spin polarization at half the value of the maximal polarization. Since PPDW states are stabilized under the conditions - of zero temperature and vanishing Zeeman energy - realized in our experiment, a possible consequence of annealing may involve a phase transition to a PPDW state. In addition, the angular dependence shown in Fig. 2 is also consistent with presence of a PPDW. A larger Zeeman energy increases the spin-polarization of a PPDW from the half of maximum polarization, leading to its eventual destabilization at large tilt angles. However, as discussed earlier, the effect of in-plane field on the annealing process needs to be properly accounted.

In summary, we have observed a transition into a novel quantum Hall phase at \( \nu = 2/5 \) in the limit of small \( g \)-factor and large time domain. Found at the level crossing between spin-polarized and spin-unpolarized \( \nu = 2/5 \) FQHE state, previously reported metastable state associated with the quantum Hall ferromagnetism evolves into a zero temperature correlated phase. This phase is distinguished by large enhancement of the characteristic time, a bizarre correlation between temperature and time and its high sensitivity to thermal fluctuations. Within the coarsening picture of QHF domains, the observed quantum Hall state may represent a QHF state with long range spatial coherence. Alternatively it may be the postulated partially polarized density wave or some other type of quantum Hall state.

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