Charge excitation and transport in pseudospin quantum Hall ferromagnets

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Abstract

Studies on pseudospin quantum Hall ferromagnets involving the $N = 1$ Landau level (LL) of the symmetric state and the $N = 0$ LL of the antisymmetric state in strongly-coupled double quantum wells are presented. Measurements of the charge excitation gap for $\nu = 4$ (3 and 5) reveal easy-axis (easy-plane) anisotropy. Resistance spikes observed for $\nu = 4$ are ascribed to transport along domain walls. We also discuss the effects of potential asymmetry.

Key words: quantum Hall effect; quantum Hall ferromagnet; pseudospin; domain wall

A variety of many-body phenomena in quantum Hall (QH) systems can be understood in a common language of QH ferromagnetism [1]. The key ingredient behind the occurrence of QH ferromagnetism in various systems [2–5] is the coincidence of more than one Landau levels (LLs) at the Fermi level. The resultant additional degrees of freedom, either due to spin, layer, or LL indices, allow the interactions between particles to determine the ground state and low-energy excitations. Specifically, when the degree of freedom is associated with different orbital wave functions, the Coulomb interaction is no longer isotropic in the pseudospin space, leading to a new class, easy-axis and easy-plane, of QH ferromagnets (QHFs) [6] and hence different physics.

In this paper, we study pseudospin QHFs realized in strongly coupled double quantum wells [5]. We focus on the level coincidence between the $N = 1$ LL of the symmetric state (1^{S}) and the $N = 0$ LL of the antisymmetric state (0^{A}), which occurs for LL filling factors of $\nu = 3$, 4, and 5 when the cyclotron energy $\hbar\omega_{\mathrm{c}}$ approaches the tunneling gap Δ_{SAS}. Temperature-dependent magnetotransport measures the activation energy Δ_ν for $\nu = 3$, 4, and 5 as a function of the magnetic field B. Unless specified, the quantum well potential is kept symmetric while changing the total electron density n_s using front and back gates [7].

Figure 1 shows the LL energy diagrams in the double quantum wells and the measured Δ_ν as a function of B. In the vicinity of each crossing, the two nearly degenerate levels, 1^{S}_σ and $0^{\mathrm{A}}_{\sigma'}$, just below and above the Fermi level provide pseudospin degrees of freedom for the electrons in the topmost LL. The relevant LLs for each ν and B-field region are identified by the spin indices, σ and σ', and their energy difference, $h = \epsilon(1^{\mathrm{S}}_\sigma) - \epsilon(0^{\mathrm{A}}_{\sigma'})$, serves as a pseudo magnetic field and its absolute vale the pseudo Zeeman energy, $\delta_{\mathrm{Z}} = |h|$.

In the regions where Δ_ν changes almost linearly with B, the slope, $\partial\Delta_\nu/\partial B$, agrees well with the B dependence of the pseudo Zeeman energy ($\partial\delta_{\mathrm{Z}}/\partial B$) calculated for each ν (solid lines) [5], indicating that the excitation is associated with the pseudospin degrees of freedom [8]. The minima in Δ_ν, at which $\partial\Delta_\nu/\partial B$ changes sign, correspond to the level coincidence, or the zeros in the pseudo magnetic field (i.e., $h = 0$). The sharp reduction of $\Delta_{\nu=4}$ for $h \to 0$ at $B = 1.22$ and 1.52 T, however, is unexpected and is discussed later.

The QH ferromagnetism means that electrons in the topmost LL occupy the single-particle states, $|\psi\rangle_j = \cos(\theta/2)|1^{\mathrm{S}}_\sigma\rangle_j + \mathrm{e}^{i\varphi}\sin(\theta/2)|0^{\mathrm{A}}_{\sigma'}\rangle_j$, characterized by a pseudospin vector $\mathbf{m}_j = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$

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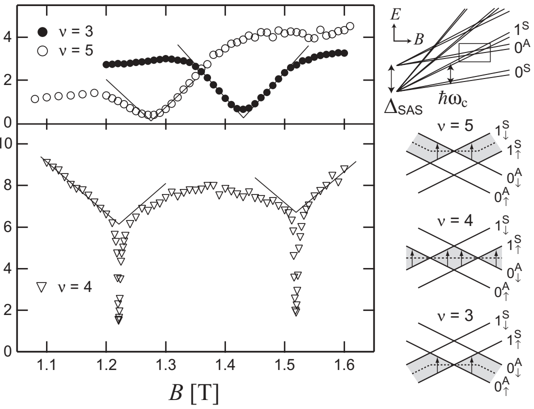

Fig. 1. Left: Activation energy Δ_ν vs. magnetic field B. The sample has 20-nm GaAs quantum wells separated by a 1-nm $Al_{0.3}Ga_{0.7}As$ barrier. The tunneling gap is a function of n_s, varying from $\Delta_{SAS} = 29$ to 24 K with increasing n_s from 1.2 to $2.0 \times 10^{15}\,m^{-2}$. The electron mobility is $80\,m^2/Vs$ for $n_s = 1.5 \times 10^{15}\,m^{-2}$. Right top: LL energy diagram in double quantum wells. The LL crossings for $\nu = 3$, 4, and 5 are shown in the box. Right bottom: Close-up of the LL crossings. Dotted lines show the Fermi level for $\nu = 3$, 4, and 5. Arrows represent excitations associated with the pseudospin degrees of freedom.

common to all Landau orbital center coordinates j, such that the order parameter $\langle \mathbf{m}_j \rangle$ does not vanish for $h \to 0$. The small but finite $\Delta_{\nu=3,5}$ for $h = 0$ is due to pseudospin exchange energies, indicating that $\langle \mathbf{m}_j \rangle \neq 0$. The smooth minima of Δ_ν indicate a continuous rotation of the magnetization $\langle \mathbf{m}_j \rangle$ from $\theta = 0$ to π upon sweeping the pseudo field from $h < 0$ to $h > 0$. This happens only when the anisotropy energy, $K \equiv \partial E_{\rm int}/\partial(\cos 2\theta)$, is positive, indicating the easy-plane anisotropy [4,6] ($E_{\rm int}$: total interaction energy).

For $\nu = 4$, the relevant LLs have opposite spin, and the total spin changes upon crossing. Hence, the level crossing can be seen as a first-order phase transition between spin-unpolarized and partially polarized states [9]. In the context of QHFs, the first-order transition means a discontinuous rotation of the magnetization $\langle \mathbf{m}_j \rangle$ upon sweeping h across zero. This occurs for $K < 0$, corresponding to the easy-axis anisotropy.

The first-order phase transition alone, however, cannot account for the sharp reduction of $\Delta_{\nu=4}$ for $h \to 0$. If $\langle \mathbf{m}_j \rangle$ is reversed at once in the entire region of the sample, the gap should exhibit a 'V'-shaped dependence on B [10]. Rather, coexistence of domains with opposite magnetization and low-energy excitation modes associated with their boundaries, i.e., domain walls (DWs), are suggested to be the cause of the reduced gap. Excitations inside DWs have been theoretically discussed in terms of a Hartree-Fock quasiparticle [11] and a topological defect [12]. The latter is a kink in the in-plane component of $\langle \mathbf{m}_j \rangle$, and is topologically equivalent to a Skyrmion trapped at a DW [4,5].

These modes carry charge along DWs and give rise to

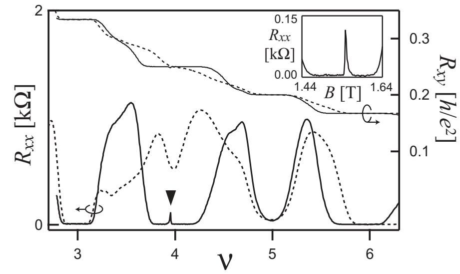

Fig. 2. Longitudinal (R_{xx}) and Hall (R_{xy}) resistance at 100 mK for (i) symmetric (solid) and (ii) asymmetric (dotted) potentials. For each case, $n_s =$ (i) 1.48 and (ii) $1.90 \times 10^{15}\,m^{-2}$ is chosen so that the $1^S_\uparrow$-$0^A_\downarrow$ crossing occurs at $\nu = 4$. For case (ii), the nominal density ratio of the two wells is 1.1 : 0.8. Inset: Close-up of the resistance spike for the symmetric potential.

a sharp resistance spike (Fig. 2) [4,5,9], similar to those reported in Ref. [3]. The resistance spike gets broader with increasing potential asymmetry, and eventually evolves into a broad feature as shown by the dotted line [9]. The excitation modes in DWs should be sensitive to the width of the walls, which is determined by the anisotropy energy and the pseudospin stiffness. The effect of the potential asymmetry is to increase the Hartree contribution and hence reduce the easy-axis anisotropy [6]. This opens a possibility to tune the widths of the DWs and modify the transport properties with gates, which deserves further investigations.

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