Effects of In-plane Magnetic Fields on Spin Transitions in Bilayer Quantum Hall States

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In a bilayer system, the additional pseudospin degree of freedom in the third direction brings about various phase transitions. In particular, when levels with different Landau indices (N and N') simultaneously approach the Fermi level, the system exhibits an easy-axis or easy-plane quantum Hall (QH) ferromagnetism depending on the spin and subband wave functions of the levels involved [1,2]. Here, we investigate effects of an in-plane magnetic field $B_{\|}$, which couples subband and Landau levels with the same spin [3] and modulate wave functions extended to both layers, on spin/pseudospin transitions of QH states in such a system. As $B_{\|}$ is applied, we observe that crossings between opposite spin levels as well as those between the same spin levels disappear in characteristic sequences. While anticrossings of single-particle levels are sufficient to explain the observed behavior for crossings with $\Delta N \equiv |N - N'| = 1$, the data for $\Delta N = 2$ are not understood in a single-particle picture, and suggest Coulomb induced mixing of different spin levels.

In this work, we measured the magnetoresistance of a sample with the tunneling energy $\Delta_{\rm SAS} = 23 \sim 32\,{\rm K}$ by changing the total electron density of the two layers while maintaining the double-quantum-well potential symmetric throughout. $B_{\|}$ is applied by tilting the sample in the magnetic field. In a bilayer system, level crossings occur at $\Delta N \times \hbar\omega_c + \Delta s \times g^* \mu_B B = \Delta_{\rm SAS}$ (Fig. 1(a)), where $\hbar\omega_c$ and $g^*\mu_B B$ is the cyclotron and Zeeman energies, respectively. $\Delta s = 0$ (± 1) identifies crossings between parallel (antiparallel) spins, which occurs for odd (even) integer fillings. When the sample is tilted, $B_{\|}$ causes subband-Landau-level mixing between the same spin levels, which is first seen as anticrossings for $\nu = 3$ and $\nu = 5$ at $\Delta N = 1$ and $\Delta s = 0$ (Fig. 1(b)). On increasing the tilting angle, the repulsions of the anticrossing levels become large, and then the two crossings with opposite spins for $\nu = 4$ ($\Delta N = 1$ and $\Delta s = \pm 1$) coalesce to disappear (Fig. 1(c) and Fig. 2(a)). For $\Delta N = 2$, on the other hand, the $\Delta s = +1$ and -1 crossings for $\nu = 6$ disappear one by one (Fig. 1(d), (f) and Fig. 2(b)), which is possible only via a mixing of opposite spin levels. Spin-orbit interaction [4] is unlikely to be the sole cause of the mixing, for the observed activation energy of $2\,{\rm K}$ (Fig. 2(b)) seems too large. We suggest that the mixing of different spin levels is caused by Coulomb interactions. When $B_{\|}$ is applied, the difference between the spatial wave functions of the two levels is enhanced, and the direct Coulomb interaction is expected to play more important role. Our results therefore suggest a possibility of easy-plane QH ferromagnetism tuned by the in-plane magnetic field, where the spin polarization continuously changing across the transition.

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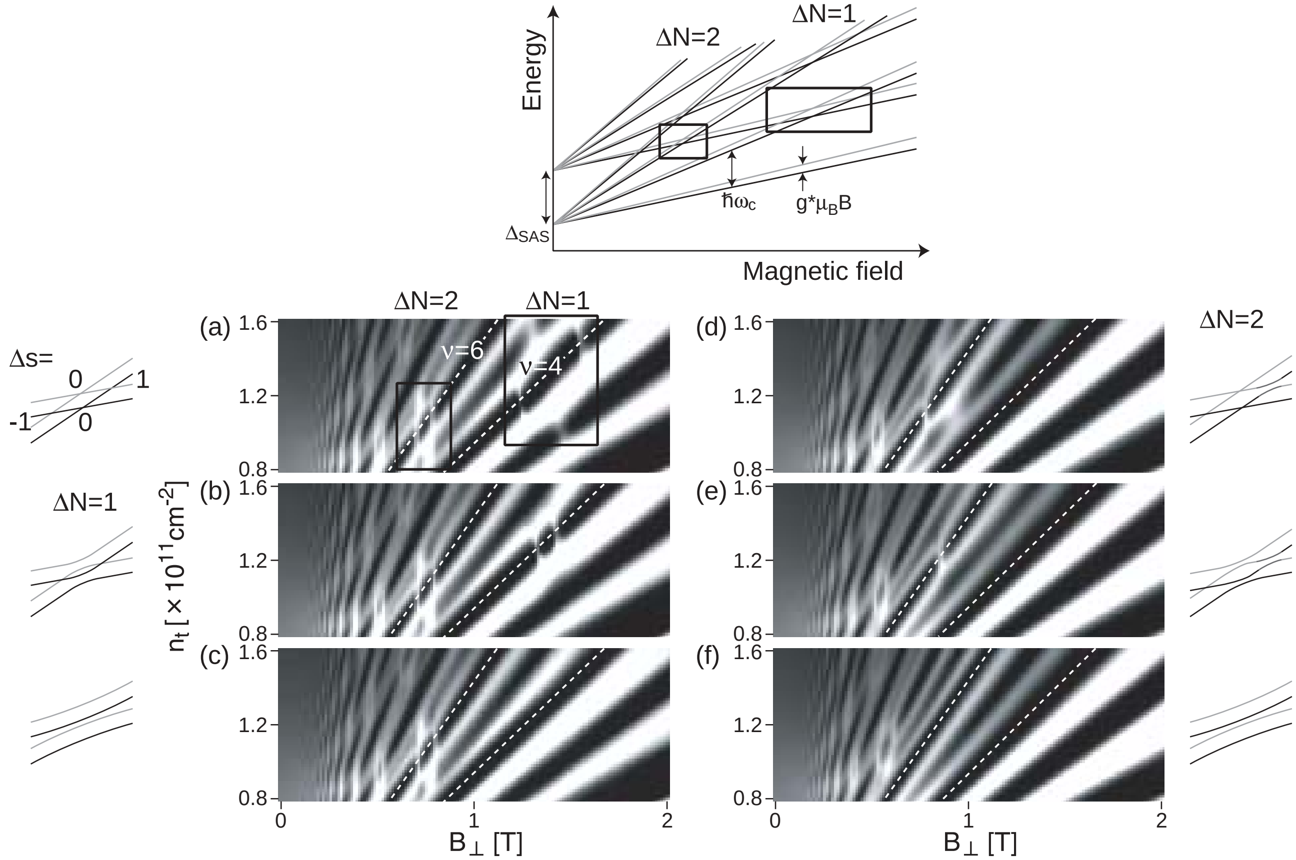

Figure 1: Gray-scale plot of the magnetoresistance R_{xx} in the $\Delta_{\rm SAS} = 23 \sim 32\,$K sample at the balanced density point at the tilting angle (a) $\theta = 0°$, (b) 15°, (c) 30°, (d) 50°, (e) 55° and (f) 60°. The gray scale is proportional to R_{xx}: R_{xx} is small and a QH state is realized in the black region, while R_{xx} is large in the white region. The horizontal and vertical axes are the perpendicular magnetic field $B_\perp$ and the total electron density n_t of the two layers, respectively. At the top, we illustrate energy levels in a bilayer system. The black and gray lines represent levels with up and down spins, respectively. The level crossings in the squares correspond to those in (a). We also illustrate the behavior of the disappearance of the crossing points.

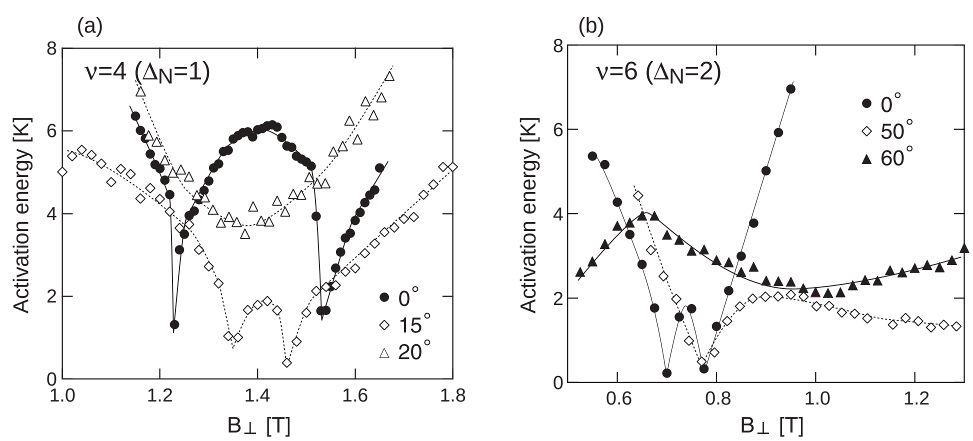

Figure 2: Activation energy of (a) $\nu = 4$ and (b) $\nu = 6$ for several tilting angles measured along the dashed line in Fig. 1. The two minima of the activation energy of $\nu = 4$ ($\nu = 6$) at $\theta = 0°$ correspond to the level crossing points at $\Delta N = 1$ and $\Delta s = \pm 1$ ($\Delta N = 2$ and $\Delta s = \pm 1$).