Nuclear-spin-related resistance enhancements observed over a wide range of magnetic fields

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Slow enhancements in the longitudinal resistance (R_{xx}) due to nuclear spin polarization are studied around Landau-level filling factors of $\nu=2/3$ and 3/5 as functions of both the filling factor and magnetic field. The R_{xx} enhancement appears not only at the $\nu=2/3$ and 3/5 spin transitions observed around magnetic fields of $B=6.9$ and 8.6 T respectively, but also over extended regions at higher and lower magnetic fields along the "flanks" of the $\nu=2/3$ and 3/5 quantum Hall states. Analyses based on the coincidence of spin-split Landau levels for composite fermions provide reasonable account of the R_{xx} enhancements observed in a wide range of magnetic field.

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Fractional quantum Hall effects of a strongly interacting two-dimensional electron system have been successfully interpreted[1–3] by the composite fermion (CF) model.[4,5] In this model, an electron bound to an even number of quantum mechanical vortices forms a CF, which experiences a reduced effective magnetic field $B_{\mathrm{eff}}=|B-B_{\nu=1/2}|$, where B is the externally applied magnetic field and $B_{\nu=1/2}$ is its value at the Landau-level filling factor $\nu=1/2$. A deviation from $\nu=1/2$ quantizes the CF motion and splits their energy spectrum into CF Landau levels, which are split further into spin sublevels by the Zeeman effect of the bare electron. When the CF cyclotron energy is comparable to the Zeeman energy, the CF Landau levels with different spins cross, resulting in spin transitions of the fractional quantum Hall states (FQHSs).[6,7]

Recently, it has been found that the electrons and nuclear spins are strongly coupled around the spin transitions for $\nu=2/3$ (Refs. 8–10) and 3/5.[10] In this regime, the nuclear spin polarization is driven by a source-drain current (I_{ds}) and leads to an enhancement in the longitudinal resistance (R_{xx}). This nuclear spin polarization is interpreted in terms of electronic spin domains with different spin orientations, which are expected to be formed at the spin transitions. When the current passes across the domain wall, the electrons and nuclei are allowed to exchange their spin angular momentum via a simultaneous spin flip-flop process through the contact hyperfine interaction. Thus it is reasonable that the R_{xx} enhancement occurs at the spin transition for $\nu=2/3$ (3/5). However, the R_{xx} enhancement has also been observed in an extended region of magnetic field; for instance in Ref. 11, the data for a single heterostructure show the enhancement at around 5 T, which is much higher than the $\nu=2/3$ spin transition around $B=2.5$ T (Ref. 7) for a single heterostructure. In this paper, we present a systematic study of the R_{xx} enhancement as functions of both filling factor and magnetic field over an extended range, and demonstrate that the R_{xx} enhancements also occur at magnetic fields far away from spin transitions for $\nu=2/3$ and 3/5. Detailed analyses show that all the observed R_{xx} enhancements can be explained by CF level coincidences.

We use a gated GaAs/$Al_{0.3}Ga_{0.7}As$ quantum well structure with a 20-nm-thick well. The gate voltage is used to control the density (N_s) of the two-dimensional electron gas. The mobility is 150 m^2/Vs for $N_s=1.0\times10^{15}$ m^{-2}. The sample is processed into a 50-μm-wide Hall bar with voltage probes at intervals of 200 μm. R_{xx} is measured using a standard low-frequency ac lock-in technique with a current of $I_{ds}=10$ nA unless specified. All measurements are performed at a temperature of $T\sim80$ mK.

Figure 1(a) shows the slow R_{xx} enhancements observed at several magnetic fields. The broken and solid curves are taken by scanning the electron density upwards at *normal* and *slow* rates, which correspond to scanning rates of the filling factor of $\Delta\nu/\Delta t=(0.6\text{–}1.8)\times10^{-1}$ and 2.4×10^{-4} min^{-1}, respectively. The horizontal axis is scaled to the filling factor. At $B=6.75$ T, R_{xx} around $\nu=2/3$ for the slow scan is strongly enhanced from that for the normal scan. Here, the filling factor at which the most pronounced peak appears is about 0.67. The peak position is slightly shifted when the magnetic field is set to higher (7.00 T) or lower (6.58 T) values. At 9.08 T, the R_{xx} enhancement near $\nu=2/3$ becomes weaker, while the one near $\nu=3/5$ becomes stronger. These enhancements vanish at even lower (4.08 T) or higher (12.5 T) values of magnetic field.

To clarify the filling factor and magnetic field dependence of the R_{xx} enhancements, we carried out similar measurements at finer increments of the magnetic field. In Fig. 1(b), the white circles indicate the filling factor positions at which the difference between the normal and slow scans becomes a maximum for each magnetic field. Here, we only plotted those points at which the difference exceeds 500 Ω.[12] The radius of the circle denotes the relative magnitude of the R_{xx} enhancement. On the same graph, we also show a gray-scale plot of R_{xx} as functions of both the filling factor and magnetic field, which is taken at the normal speed with $I_{ds}=0.5$ nA. In this condition, one can neglect the effects of the R_{xx} enhancement, since we verified that the current driven R_{xx} enhancement does not occur at $I_{ds}<1$ nA for our sample. Hence, the gray-scale plot reflects the intrinsic configuration of the electronic spin states without the influence from the nuclear spin polarization. The $\nu=2/3$ and 3/5

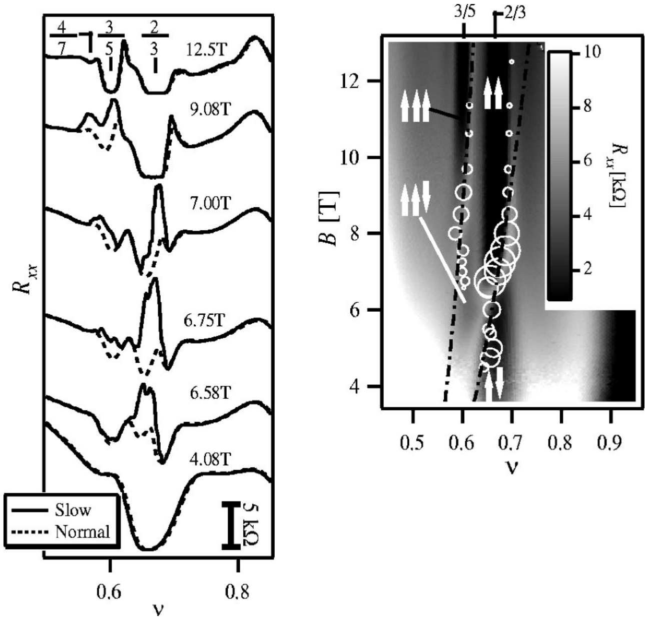

FIG. 1. R_{xx} enhancement at $\nu=2/3$ and 3/5. All data are acquired with the filling factor swept upwards. (a) Magnetic field dependence of R_{xx} enhancements. The broken and solid curves, respectively, show R_{xx} measured at a normal scan rate $[\Delta\nu/\Delta t=(0.6-1.8)\times10^{-1}\ \mathrm{min}^{-1}]$ and at a slow scan rate $(\Delta\nu/\Delta t=2.4\times10^{-4}\ \mathrm{min}^{-1})$. (b) R_{xx} enhancements on the R_{xx} gray scale plot with respect to the filling factor and magnetic field. The circles represent the position of the pronounced R_{xx} enhancement and their radius denotes the relative magnitude of the R_{xx} enhancement. The R_{xx} gray scale plot is obtained with a normal ν scan rate using a current of $I_{ds}=0.5$ nA. The dash-dotted curves represent the fitted level coincidence curves for $\nu=2/3$ and 3/5.

FQHSs can be seen as black areas which indicate R_{xx} minima. The $\nu=2/3$ (3/5) FQHS is separated into two spin phases by the spin transition around $B=6.9$ T (8.6 T). The phases on the lower and higher magnetic field sides of the $\nu=2/3$ (3/5) spin transition correspond to the spin unpolarized (partially spin polarized) and fully polarized states,[6,7] respectively. The R_{xx} enhancements denoted by the white circles can be clearly classified into two series occurring at and near $\nu=2/3$ and 3/5. The pronounced enhancements in each series concentrate around the spin transitions. These enhancements become weaker on either side of the spin transitions, but persist at much lower (higher) magnetic fields along the "flanks" of FQHSs on the lower (higher) filling factor side.

The above results clearly show that the nuclear spins are polarized not only at the $\nu=2/3$ and 3/5 spin transitions, but also over the extended regions of higher and lower magnetic fields. To quantitatively understand the filling factor and magnetic field dependence of the nuclear spin polarizations, we carry out the following analysis based on the coincidence of the spin-split CF Landau levels, which would lead to the electronic domain structure and therefore allow the nuclear spin polarization. The level coincidence around $\nu=2/3$ is highlighted in the energy diagram of the CF Landau levels in Fig. 2. The energy levels illustrated as a function of the filling factor are compared at three different magnetic fields.

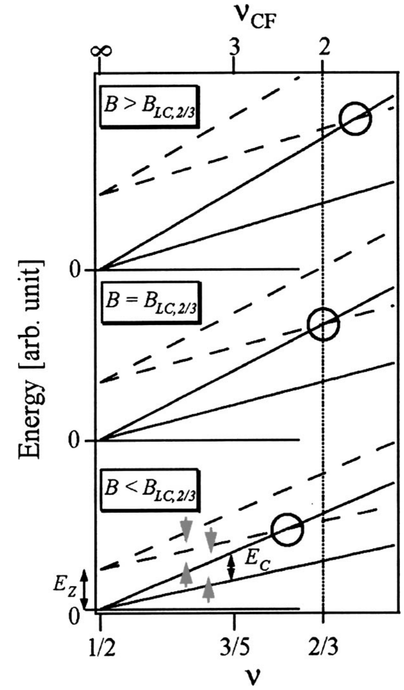

FIG. 2. Schematically drawn energy diagram of the first and second CF spin-split Landau levels at three different magnetic fields. Each diagram is drawn as a function of filling factor for a constant magnetic field. The first and second Landau levels are separated by the CF cyclotron energy, E_C. The Landau fans for the spin-up (solid line) and spin-down (broken line) levels are separated by the Zeeman energy E_Z. The level coincidence points are marked by circles, where the spin-up branch of the second CF Landau level crosses the spin-down branch of the first CF Landau level. $B_{LC,2/3}$ is the specific magnetic field at which the level coincidence happens exactly at $\nu=2/3$.

The first and second CF Landau levels are separated by CF cyclotron energy defined by $E_C=e\hbar B_{\mathrm{eff}}/m^*$, or

$$E_C=\frac{2e\hbar}{m^*}B\left|\nu-\frac{1}{2}\right|, \tag{1}$$

where $\hbar=h/2\pi$ (h is Planck's constant) and m^* is the effective mass of CFs. The Landau fans for the different spin directions are separated by the Zeeman energy

$$E_Z=|g^*|\mu_B B, \tag{2}$$

where g^* is the effective g factor and $\mu_B=e\hbar/2m_0$ is the Bohr magneton. The level coincidence occurs when the Zeeman energy of CFs is equal to a multiple of the CF cyclotron energy, $E_Z=jE_C$, where $j=1$ and 2 for $\nu=2/3$ and 3/5, respectively. The middle diagram in Fig. 2 depicts the situation when the level coincidence (LC) occurs exactly at $\nu=2/3$. This happens at a specific magnetic field, $B_{LC,2/3}$. When $B>B_{LC,2/3}$, the level coincidence occurs at a higher filling factor. On the other hand, when $B<B_{LC,2/3}$, it occurs at a lower filling factor.

We can obtain a quantitative expression for the condition of the level coincidence. By considering that the CF cyclotron energy is expected to be proportional to the Coulomb energy and also a function of filling factor, $E_C \propto (e^2/\varepsilon l_0)|1-2\nu|$,[5] Eq. (1) defines the effective mass m^* which scales as $\sqrt{B}$, so that

$$m^*/m_0 \equiv \alpha \sqrt{B}. \tag{3}$$

Here, ε is the dielectric constant and $l_0 = \sqrt{\hbar/eB}$ is the magnetic length. Thus, the level coincidence occurs when

$$B = \left| \frac{4j}{\alpha g^*}\left(\nu - \frac{1}{2}\right)\right|^2. \tag{4}$$

Using Eq. (4), we fit the level coincidence curve to the $\nu = 2/3$ and 3/5 spin transitions at which the pronounced R_{xx} enhancements are observed. The fitting curves are shown by dash-dotted curves in Fig. 1(b). The best fit yields $\alpha \sim 0.58$ for the $\nu = 2/3$ spin transition and 0.61 for the $\nu = 3/5$ spin transition, assuming $|g^*| = 0.44$. These values are consistent with the "polarization mass," $m_p^*/m_0 = 0.60\sqrt{B}$ calculated from the Coulomb energy difference between the FQHSs with different spin polarizations,[13] and is larger than the "activation mass," $m_a^*/m_0 = 0.07\sqrt{B}$ calculated from the energy required to create a far separated CF particle hole pair.[5]

We now compare the fitted curves with the plotted circles in Fig. 1(b). The fitted curve for the $\nu = 2/3$ (3/5) spin transition in the magnetic field region, 4.5–9.1 T (6.5–11.4 T), agrees with the plotted circles even at the flanks of the FQHS away from the spin transition. If level coincidence is the only requirement for nuclear spin polarization, the magnitudes of the R_{xx} enhancements at the spin transitions are expected to be preserved even at the flanks of FQHSs. The R_{xx} enhancements at these flanks are, however, much smaller than those at the spin transitions. This can be understood as follows. A slight deviation from the exact filling factor of 2/3 creates a small number of quasiparticles, which are localized and therefore do not significantly affect the general features of domain morphology. The quasiparticles at the flanks of the FQHS are, however, delocalized,[14] and therefore facilitates the domain walls to move and fluctuate. As a result, the nuclear spin polarization due to the flip-flop process inside the domain walls, are smeared out. At even higher or lower magnetic fields, the level coincidence curves deviate from the flanks of FQHSs and, simultaneously, the R_{xx} enhancement vanishes (except for the higher magnetic field side of $\nu = 2/3$, which we discuss later). This is because, beyond the flanks of $\nu = 2/3$ (3/5) FQHS, the neighboring FQHS becomes dominant, and therefore the $\nu = 2/3$ (3/5) level coincidence does not contribute to the flip-flop process. As for the comparison between the two series of R_{xx} enhancements, the magnitude of the R_{xx} enhancement around the $\nu = 3/5$ spin transition is about two times smaller than that around the $\nu = 2/3$ spin transition. This lower nuclear spin polarization for $\nu = 3/5$ may be due to the smaller CF cyclotron gap, which would result in a high density of thermally activated delocalized quasiparticles.

Finally, we examine a feature of the R_{xx} enhancement far away from the spin transition. On the high magnetic field side, the R_{xx} enhancement persists up to 12.5 T, i.e., 5.9 T away from the $\nu = 2/3$ spin transition, while on the low magnetic field side it disappears at 4.5 T, only 2.1 T away from the spin transition. The large difference in the magnetic field region (5.9 T − 2.1 T = 3.8 T) may suggest that the effective level coincidence curve favors sticking to the flank of the FQHS on the high magnetic field side. A possible and interesting cause for this is that the effective mass is enhanced by the finite exchange interaction between CFs (Ref. 15) exactly at $\nu = 2/3$. A deviation from the exact filling factor of 2/3 increases the number of quasiparticles and therefore the exchange interaction becomes weaker, leading to a reduction of the effective mass.[15] Considering that the enhancement of the effective mass is included in the coefficient α [see Eq. (3)], the coefficient of the quadratic function of ν, $(4j/\alpha g^*)^2$ [see Eq. (4)], increases as the level coincidence curve deviates from the exact filling factor of 2/3. This causes the effective level coincidence curve to approach the flanks of the FQHS on the high magnetic field side of the spin transition. We also note that, at lower fields, the FQHS is not well developed because of the reduced electron mobility, which may also account for the rapid quenching of the R_{xx} enhancement on the lower field side.

In conclusion, we have shown the occurrence of the nuclear-spin-related R_{xx} enhancement at $\nu = 2/3$ and 3/5 over a wide range of magnetic fields. The B-ν position and strength of the R_{xx} enhancement can be, respectively, explained by the CF level coincidence and the effects of quasiparticles on the domain structure.

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