Electrical polarization of nuclear spins in a breakdown regime of quantum Hall effect

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We have developed a method for electrical polarization of nuclear spins in quantum Hall systems. In an odd-integer quantum Hall effect (QHE), electrons are excited to the upper Landau subband with opposite spin polarity dynamically polarizes nuclear spins through the hyperfine interaction. The polarized nuclear spins in turn accelerate the QHE breakdown, leading to hysteretic voltage-current characteristics of the quantum Hall conductor.

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Control of nuclear spins in semiconductor has attracted considerable interests because nuclear spin is one of the most promising elements for implementation of quantum bit. Several techniques have been developed for optical and electrical control of nuclear spins. In quantum Hall (QH) systems, two kinds of approaches for all-electrical manipulation of nuclear spins have been demonstrated. One technique utilized spin-flip scattering of electrons between spin-resolved QH edge channels. One of the most promising elements for implementation of nuclear magnetic resonance (NMR). The relevance of nuclear spins will open a way to find spin-dependent phenomena in QH systems.

In this letter, we demonstrate a method for electrical polarization of nuclear spins in breakdown regime of odd-integer QHE, where the Fermi energy resides in the energy gap of spin-split Landau subbands. In this condition, the lower Landau subband (\( N, \uparrow \)) is fully occupied with up-spin electrons, while the higher down-spin subband (\( N, \downarrow \)) is empty. When a current is transmitted through the conductor, the Landau subbands are tilted due to the Hall electric field as schematically shown in Fig. 1(a). When the current is increased above a critical current \( I_c \), electrons in the lower Landau subband (up-spin) are excited to the higher empty subband (down-spin), giving rise to an abrupt increase of longitudinal voltage \( V_{\text{xx}} \). This phenomenon is referred to as the QHE breakdown. Possible excitation processes of electrons include the Zener-type tunneling (ZT) and the impact excitation (IE) [Fig. 1(a)]. Though the mechanism of the QHE breakdown has been still under debate, it is obvious that the excitation processes are accompanied by up-down spin flips of electrons. Accordingly, we expect that the QHE breakdown can be utilized to polarize nuclear spins, i.e. the up-down spin flips of electrons dynamically polarize the nuclear spins along the external magnetic field \( B \) (\( \langle I_z \rangle > 0 \)) through the counter spin flips of nuclear spins.

FIG. 1: (a) A schematic diagram of spin-split Landau subbands in a breakdown regime of an odd-integer QHE. Electrons are excited to the upper subband through the Zener-type tunneling (ZT) and the impact excitation (IE). In the IE process, electrons in the higher subband are accelerated by the Hall electric field to excite another electron in the lower subband through the electron-electron scattering. (b) A schematic representation of the expected \( V_{\text{xx}}-I \) curves at \( \langle I_z \rangle = 0 \) (solid) and \( \langle I_z \rangle > 0 \) (dashed).
(solid) and negative (dashed) directions at (a) \( \nu = 2.15 \) \( (B = 5.15 \text{ T}) \), (b) \( \nu = 3.10 \) \( (B = 3.58 \text{ T}) \), and (c) \( \nu = 5.11 \) \( (B = 2.17 \text{ T}) \). Inset of (a): A micrograph of the Hall-bar device. Inset of (b): Time evolution of \( V_{xx} \) after the current is changed from \( I = 0.0 \mu \text{A} \) to \( 2.0 \mu \text{A} \) at \( t = 0 \).

FIG. 2: \( V_{xx} - I \) curves taken by sweeping current in positive and negative directions at (a) \( \nu = 2.15 \) \( (B = 5.15 \text{ T}) \), (b) \( \nu = 3.10 \) \( (B = 3.58 \text{ T}) \), and (c) \( \nu = 5.11 \) \( (B = 2.17 \text{ T}) \). The solid and dashed curves are respectively observed hysteretic \( V_{xx} - I \) curves toward the smaller current at \( \nu = 1.0 \mu \text{A} \) and 1.1 \( \mu \text{A} \), and 0.33 \( \mu \text{A} \) for \( \nu = 2.15 \), 3.10, and 5.11, respectively. At \( \nu = 3.10 \) and 5.11 [Figs. 2(b) and 2(c)], the shift of the down-sweep curves toward the smaller current is observed, while no shift is found at \( \nu = 2.15 \) [Fig. 2(a)]. The observed shift of the \( V_{xx} - I \) curves is consistent with our expectation [Fig. 1(b)].

The inset of Fig. 2(b) shows time evolution of \( V_{xx} \) at \( \nu = 3.10 \) after the current is changed from \( I = 0.0 \mu \text{A} \) to \( 2.0 \mu \text{A} \). The value of \( V_{xx} \) increases slowly with a relaxation time over 300 s \( \times 2^{12} \) which is a typical time scale for the nuclear spin relaxation. The increase in \( V_{xx} \) indicates the acceleration of the QHE breakdown due to the reduction of the spin-splitting energy \( E_S \).

The relevance of DNP to the shift of the \( V_{xx} - I \) curves is unambiguously confirmed by the NMR measurements described below. A rf magnetic field parallel to the 2DES is applied after \( V_{xx} \) is completely saturated at \( I = 2.0 \mu \text{A} \). The value of \( V_{xx} \) decreases at the NMR frequencies of \( ^{75}\text{As} \), \( ^{69}\text{Ga} \), and \( ^{71}\text{Ga} \) as shown in Figs. 3(a), 3(b), and 3(c). The detection of NMR shows that the shift of the \( V_{xx} - I \) curves are caused by the DNP and that the nuclear spins are polarized in the QHE breakdown regime.

The shift of the \( V_{xx} - I \) curves is prominent in the odd-integer QHE plateaus of \( \nu = 3 \) and 5 [Figs. 2(b) and 2(c)] when the nuclear spins are polarized in the QHE breakdown regime. The polarized nuclear spins \( \langle I_z \rangle > \langle I_z \rangle \) are changed from \( I = 0.0 \mu \text{A} \) to \( 2.0 \mu \text{A} \) at \( t = 0 \).

FIG. 3: NMR spectra for (a)\(^{75}\text{As} \), (b)\(^{69}\text{Ga} \), and (c)\(^{71}\text{Ga} \) detected by measuring \( V_{xx} \). The sweep rate of rf magnetic fields is 13 kHz/min.

When the nuclear spins are polarized in the QHE breakdown regime, the polarized nuclear spins \( \langle I_z \rangle > \langle I_z \rangle \) reduce the spin-splitting energy \( E_S = |g| \mu_B B - A \langle I_z \rangle \), where \( g \) is the g factor of electrons \( (\approx -0.44 \text{ in GaAs}) \) and \( \mu_B \) is the Bohr magneton. Since the odd-integer QHE is stabilized by \( E_S \), the reduction of \( E_S \) is expected to accelerate the QHE breakdown, leading to the shift of voltage-current \( (V_{xx} - I) \) curves toward the smaller current as shown in Fig. 1(b). Thus, the \( V_{xx} - I \) curve is expected to show hysteresis depending on the sweep direction of the current. Nachtwei et al. observed hysteretic \( V_{xx} - I \) curves in InGaAs/InAlAs systems, but they excluded the relevance of nuclear spins and interpreted the hysteresis in terms of quantum Hall ferromagnet. Song and Omling also reported hysteretic magnetotransport in the regime close to the QHE breakdown. They found an unexpected huge differential resistance peak with a very slow relaxation time and suggested the influence of nuclear spins on it. However, the relationship between the nuclear spins and the QHE breakdown has been unclear.

A Hall-bar device with a channel width of 20 \( \mu \text{m} \) was fabricated by photolithography from a wafer of GaAs/AlGaAs single heterostructure [inset of Fig. 2(a)]. The mobility and sheet carrier density of the 2DES are \( \mu = 60 \text{ m}^2/\text{Vs} \) and \( n = 2.7 \times 10^{15} \text{ m}^{-2} \), respectively. The longitudinal voltage \( V_{xx} \) was measured by a standard dc four-terminal method in a dilution refrigerator with a base temperature of 20 mK. A single-turn coil around the device was used to irradiate radio-frequency (rf) magnetic fields.

Voltage-current curves in QHE regimes were taken by sweeping the current between \( -2.5 \mu \text{A} \) and \( 2.5 \mu \text{A} \) at various Landau-subband filling factors \( \nu \). Figures 2(a)-2(c) show the \( V_{xx} - I \) curves in QHE regimes at \( \nu = 2.15 \) \( (B = 5.15 \text{ T}) \), \( \nu = 3.10 \) \( (B = 3.58 \text{ T}) \), and \( \nu = 5.11 \) \( (B = 2.17 \text{ T}) \). The solid and dashed curves are respectively obtained by sweeping the current at a rate of 0.012 \( \mu \text{A/s} \) in positive and negative directions. The value of \( V_{xx} \) starts to increase at \( I = 1.0 \mu \text{A} \), 1.1 \( \mu \text{A} \), and 0.33 \( \mu \text{A} \) for \( \nu = 2.15 \), 3.10, and 5.11, respectively. At \( \nu = 3.10 \) and 5.11 [Figs. 2(b) and 2(c)], the shift of the down-sweep curves toward the smaller current is observed, while no shift is found at \( \nu = 2.15 \) [Fig. 2(a)]. The observed shift of the \( V_{xx} - I \) curves is consistent with our expectation [Fig. 1(b)].
The longitudinal resistance $R_{xx}$ for the excitation process in the QHE breakdown. Within plateaus of $2(c)$, while it is almost absent in the even-integer QHE dashed curves.

FIG. 4: Shift of $V_{xx}I$ curves between up- and down-sweeps at $V_{xx} = 2$ mV as a function of the Landau-subband filling factor in the QHE plateau regions of (a) $\nu = 3$ and (b) $\nu = 5$. The longitudinal resistance $R_{xx}$ is plotted together by the dashed curves.

[2(c)], while it is almost absent in the even-integer QHE plateaus of $\nu = 2, 4, \text{and} 6$ [Fig. 2(a)], where the cyclotron energy $\hbar \omega_c \gg g \mu_B B$ is the relevant energy gap for the excitation process in the QHE breakdown. Within the QHE plateaus of $\nu = 3$ and 5, the shift of the $V_{xx}I$ curves ($\Delta I$) at $V_{xx} = 2$ mV increases monotonically with increasing the filling factor of Landau subbands as shown in Figs. 3(a) and 3(b), i.e. the hysteresis is more prominent when the Fermi energy locates closer to the upper Landau subband.

In a breakdown regime of QHE ($I > I_c$), current flows mainly in the inner bulk region of the 2DES. However, in the Hall-bar geometry, edge channel transport may contribute to the DNP. To know whether the bulk region is polarized, we studied another device with Corbino geometry, where the edge-channel transport is completely absent. We observed the similar shift of $V_{xx}I$ curves in breakdown regimes of odd-integer QHE ($\nu = 1, 3, \text{and} 5$) and detected the NMR signals. These results definitely show that the nuclear spins in the bulk region of the 2DES are polarized and detected in this technique. Details of the Corbino geometry experiment will be described elsewhere.

To summarize, we have demonstrated a method for electrical polarization of nuclear spins in the inner bulk region of a quantum Hall conductor. In a breakdown regime of odd-integer QHE, the excitation of electrons to the upper Landau subband with opposite spin polarity polarizes nuclear spins through the hyperfine interaction. The dynamic nuclear polarization in turn reduces the spin-splitting energy of Landau subbands, accelerating the QHE breakdown.

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21. In the heterostructure used in the present study, the value of $I_c$ is proportional to the width of conduction channel.
22. When a current with opposite polarity $I = -2.0 \mu A$ is applied, $|V_{xx}|$ increases slowly as well.
23. Because the QHE breakdown develops along the current direction, the DNP may have spatial distribution along the channel.