Dynamic nuclear polarization induced by the breakdown of fractional quantum Hall effect

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Abstract. Dynamic polarization of nuclear spins has been studied in the breakdown regime of fractional quantum Hall effect using a Corbino-disk device. We find that nuclear spins are polarized in the Corbino disk in the breakdown regime of fractional quantum Hall effect. Since edge channel is completely absent in the Corbino disk, the demonstration of dynamic nuclear polarization in the Corbino disk shows that nuclear spins are polarized and detected in the bulk channel of the quantum Hall conductor.

Breakdown phenomena of quantum Hall effect (QHE) has been a subject of research interest not only for developing a QHE resistance standard but also for understanding fundamental physics of electron transport in quantum Hall (QH) systems ever since the discovery of the QHE[1, 2]. The QHE breakdown has attracted a renewed interest because of the recent development of dynamic nuclear polarization technique in the breakdown regime of odd-integer QHE[3, 4]. It was demonstrated that nuclear spins at the interface of GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructure was dynamically polarized via the hyperfine interaction when the two-dimensional electron system (2DES) located at the interface was driven to the breakdown regime of odd-integer QHE. The DNP technique makes it possible to detect nuclear magnetic resonance (NMR) signals by simply measuring the transport properties of the 2DES. The dynamic nuclear polarization (DNP) technique has been utilized for the initialization procedure of the nuclear spin quantum bits[5, 6, 7]. Because of its extremely high sensitivity, the resistively detected NMR has been also utilized to investigate electron spin properties of the QH conductors[8, 9, 10], which had not been explored otherwise.

In our earlier work[11], we found that DNP is also induced by the breakdown of fractional QHE. We found that the voltage-current characteristics strongly depend on current-sweep rates at Landau-level filling factors $\nu = 2/3$ and $1/3$, and that the value of $V_{xx}$ decreased slowly over 600 s after a sudden increase in the bias current from 0 to 30 nA. The relevance of DNP in the sweep-rate dependent $V_{xx} - I$ characteristics and slow evolution of $V_{xx}$ was confirmed by resistive detection of NMR signals under irradiation of rf-magnetic field. However, the demonstration of DNP in the breakdown regimes of fractional QHE was conducted using Hall-bar devices, in which both edge and bulk channels coexist. Therefore, it has not been clarified yet which
channel is relevant to the DNP. In order to understand the mechanism of the DNP induced by the fractional QHE breakdown, it should be clarified experimentally which channel is relevant to the DNP.

In this paper, we report dynamic nuclear polarization in a Corbino-disk device in the breakdown regime of fractional QHE. We detected nuclear magnetic resonance signals by measuring the current flowing between the inner and outer electrodes of the Corbino disk in the breakdown regime of fractional QHE. Since edge channel is completely absent in the Corbino disk, the demonstration of the DNP in the Corbino-disk device shows that nuclear spins are polarized and detected in the bulk channel of the QH conductor.

Experiments were conducted using a device with Corbino disk geometry fabricated photolithographically from a wafer of GaAs/Al_{0.3}Ga_{0.7}As single heterostructure with a 2DES at the interface. The mobility and carrier density of the 2DES at 4.2 K are 115 m^2/Vs and 2.27 \times 10^{15} m^{-2}, respectively. The inner and outer diameters of the Corbino disk are 120 and 180 \mu m, respectively, as shown in Fig. 1(a). All the measurements were performed in a dilution refrigerator with a base temperature of 20 mK. An external magnetic field \( B \) was applied perpendicular to the 2DES plane by using a superconducting solenoid. The current flowing between the inner and outer electrodes was measured using standard dc method, unless otherwise mentioned. A single-turn coil around the device was used to apply radio-frequency (rf) magnetic fields for NMR measurements.

Figure 1(b) shows the magnetic field \( B \) dependence of the two-terminal conductance between the outer and inner electrodes of the Corbino disk. The data were obtained using a standard lock-in technique with an excitation voltage 10 \mu V and a frequency 18 Hz. The zero conductance plateaus are clearly seen at around Landau level filling factors \( \nu = 4 \) (\( B = 2.34 \) T), \( \nu = 3 \) (\( B = 3.14 \) T), \( \nu = 2 \) (\( B = 4.68 \) T), \( \nu = 1 \) (\( B = 9.36 \) T), and \( \nu = 2/3 \) (\( B = 14.05 \) T). The \( \nu = 2/3 \) fractional QH state observed in the present experiment belongs to the spin polarized phase because the applied magnetic field of \( B = 14.05 \) T is much higher than the typical magnetic field for the spin phase transition in \( \nu = 2/3 \)[12].

Figure 2(a) shows the current (\( I \)) - voltage (\( V \)) characteristic curves obtained at \( \nu = 2/3 \) (\( B = 14.05 \) T) by sweeping the bias voltage in the positive and negative directions at a sweep rate of 1 mV/s. Hysteresis is clearly observed in the \( I-V \) curves. Hysteretic transport properties are observed in the breakdown regime of odd-integer QHE where DNP occurs[4]. Therefore the
Figure 2. (a) I-V characteristic curves obtained at $B = 14.05$ T. The directions of the voltage sweep are indicated by arrows. (b) Evolution of $I$ after a rapid increase of the bias voltage from 0 mV to 30 mV at $t = 0$. (c) Responses of $I$ to the rf-magnetic field as a function of frequency. The data were obtained at $B = 14.05$ T and $V = 30$ mV.

observation of hysteresis in the present study suggests the occurrence of DNP in the Corbino disk in the breakdown regime of the $\nu = 2/3$ QHE. Figure 2(b) shows the time evolution of $I$ at $\nu = 2/3$ after a rapid increase of the bias voltage from $V = 0$ mV to $V = 30$ mV. The value of $I$ increased slowly over more than 60 s. The long relaxation time over 60 s is typical to the nuclear spin-related phenomena.

Involvement of nuclear spins to the hysteresis of the I-V curves and the slow evolution of $I$ is directly shown by the NMR measurements, as shown in Fig. 2(c). The data shown in Fig. 2(c) were obtained by measuring $I$ at bias voltage $V = 30$ mV under irradiation of continuous wave rf-magnetic field with input power of -15 dBm at the top of the cryostat. As the frequency $f$ of the rf-magnetic field was scanned, the value of $I$ dropped at 102.012 MHz which coincides with the NMR frequency of $^{75}$As (gyro magnetic ratio $\gamma = 45.82$ rad-MHz/T) at $B = 14.05$ T. The detection of NMR signals by measuring the current flowing through the 2DES indicates that nuclear spins are dynamically polarized and detected in the Corbino disk in the breakdown regime of the $\nu = 2/3$ QHE. Since there is no edge channel in the Corbino-disk device, the occurrence of the DNP directly indicates that nuclear spin polarization occurs in the bulk part
of the QH conductor. The occurrence of DNP in the bulk part of the QH conductor has been also reported in the case of DNP induced by the breakdown of odd-integer QHE[13]. This similarity may suggest the common underlying origin of DNP occurring in the breakdown regimes of both fractional and odd-integer QHE.

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