Local Dynamic Nuclear Polarization Using Quantum Point Contacts

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We have used quantum point contacts (QPCs) to locally create and probe dynamic nuclear polarization (DNP) in GaAs heterostructures in the quantum Hall regime. DNP is created via scattering between spin-polarized Landau level electrons and the Ga and As nuclear spins, and it leads to hysteresis in the dc transport characteristics. The nuclear origin of this hysteresis is demonstrated by nuclear magnetic resonance (NMR). Our results show that QPCs can be used to create and probe local nuclear spin populations, opening up new possibilities for mesoscopic NMR experiments.

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It is well known that spin-polarized electrons can be used to create and detect nuclear spin populations in solids [1]. An electron spin **S** and a nuclear spin **I** interact through the contact hyperfine Hamiltonian:

$$\mathcal{H}_{\text{hyperfine}} = A\mathbf{I} \cdot \mathbf{S} = \tfrac{1}{2}A[I_+S_- + I_-S_+] + AI_zS_z\,,$$

where A is the hyperfine constant. The first term represents the simultaneous flip-flop of an electron spin ("flip") and a nuclear spin ("flop"). The second term is the effective Zeeman interaction between the electron and nuclear spins. Electron spin-flip scattering can be used to flop nuclear spins and change the net nuclear polarization $\langle I_z \rangle$, a process referred to as dynamic nuclear polarization (DNP). Conversely, electron transport is affected by the presence of DNP, and can therefore be used to probe the nuclear spin population. For example, this has been demonstrated for two dimensional electron gas (2DEG) systems in the quantum Hall regime by the recent work of Dobers *et al.* [2] and Kane, Pfeiffer, and West [3].

Quantum point contacts (QPCs) can be used to manipulate electron spin-flip processes in a 2DEG on a *submicron* scale [4]. These devices can selectively probe the spin-resolved edge channels of a 2DEG that form in high magnetic fields where the Landau levels bend up at the edges of the sample (see Fig. 1). This makes it possible to generate nonequilibrium spin populations in the edge channels and measure the subsequent spin-flip scattering that occurs when the electrons equilibrate. While these spin-flip processes have been studied previously [4,5], no experimental results have been reported on the effects of *electron-nuclear* scattering [6].

In this work, we explore the effects of nuclear spins on electron transport in these systems. First, we observe hysteresis in the dc transport characteristics of single and multiple QPC devices, and demonstrate the nuclear origin of this hysteresis by performing electrically detected nuclear magnetic resonance (NMR). Then, we discuss the ways in which the nuclear spins affect and are affected by the transport currents, concluding that electron-nuclear spin-flip scattering is the most important mechanism. Finally, we present experimental evidence for the effects of nuclear spin diffusion and the electron-nuclear Zeeman interaction on interedge state scattering.

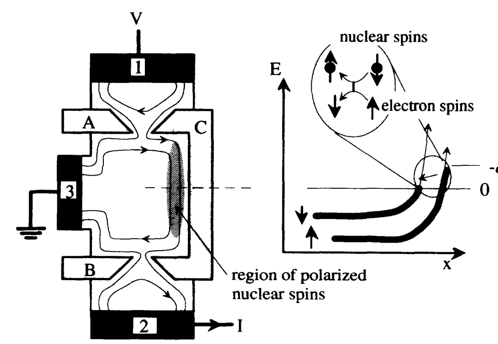

FIG. 1. Left: Schematic of a double QPC device at a bulk filling factor $\nu = 2$. Lightly shaded regions A, B, C are gates. The dark regions 1, 2, 3 are Ohmic contacts. The spin-resolved edge channels are represented by the curved lines; each QPC transmits only the lower edge channel. Right: Edge state energy level diagram through cross section along dashed line in left figure, for $V < 0$. Heavy lines denote filled electron states. The electron-nuclear flip-flop scattering process is discussed in the text.

The three devices [7] we used were fashioned from gated GaAs/AlGaAs heterostructures; an example is shown schematically in Fig. 1. The bulk filling factor is $\nu = 2$, and the conductance of each QPC is set at e^2/h. A dc voltage is then applied to contact 1, and the current is measured at contact 2; contact 3 is grounded. In this configuration, the upper QPC injects current into

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the spin up edge channel, which is then detected with the lower QPC. If electrons traveling between the QPCs scatter from the spin up channel to the spin down channel, they will not make it to contact 2, but will instead drain into contact 3, and the measured current will decrease. Similar selective injection and detection schemes have been widely used to probe edge channel scattering [4,5,8].

Figure 2(a) shows a lock-in measurement of dI/dV taken at $T \cong 50$ mK and $B = 4$ T ($\nu = 2$) for device I, a double QPC with a 1 μm separation, set up in the configuration of Fig. 1. For small $|V|$, dI/dV of the two QPCs in series is $\sim e^2/h$; this indicates that the spin up edge channel is adiabatically transmitted, with little spin-flip scattering. (The broad minimum near the origin is a result of a voltage dependent contact resistance.) When $|V|$ reaches about 0.2 mV, dI/dV drops, indicating that scattering is occurring between the spin up channel and the spin down channel. At large $|V|$, interedge channel scattering completely equilibrates the two channels, and dI/dV is reduced to approximately half its original value.

A number of mechanisms may be contributing to the observed interedge channel scattering, including spin-orbit coupling [5] and acoustic phonon emission [8]. The new result here is the *hysteresis* in the two sweep directions, which, as we discuss below, is evidence for electron-nuclear scattering. This hysteresis is reproducible and systematic, and depends on the sweep rate and history of the device, as we discuss later. This hysteresis is a general feature of our measurements in this magnetic field regime. For instance, single QPCs also displayed hysteresis. Examples are shown in Figs. 3(a) and 3(b) for device II, where gate A was grounded.

We attribute the hysteresis in Figs. 2 and 3 to the differing nuclear polarizations created by the transport currents when sweeping V up versus sweeping V down, and the resultant difference in flip-flop scattering. Before discussing these data in detail, however, we first verify the nuclear origin of these effects by means of electrically detected NMR. To do this, we fix V in a region of large hysteresis, and monitor dI/dV as a function of frequency of an rf voltage applied to one of the gates. The rf signal generates an ac magnetic field that couples to the nuclei, and when the rf frequency matches the NMR frequencies, nuclear spin-flop transitions erase the nuclear polarization. Such a trace, measured on a single QPC from device III, with the rf applied to gate B, is shown in Fig. 4. dI/dV is seen to dip sharply at the NMR frequencies of the ^{75}As and ^{69}Ga nuclei [9], followed by slow recoveries thereafter. These data clearly demonstrate that nuclear spins are affecting transport.

The slow recoveries of dI/dV that follow the NMR dips in Fig. 4 are manifestations of the slow repolarization of the nuclei. In the inset to Fig. 4, we show the time dependence of the repolarization of the ^{75}As line. This plot indicates a roughly exponential time dependence with a time constant of $\cong 40$ sec. This repolarization time scale is consistent with, although somewhat longer than,

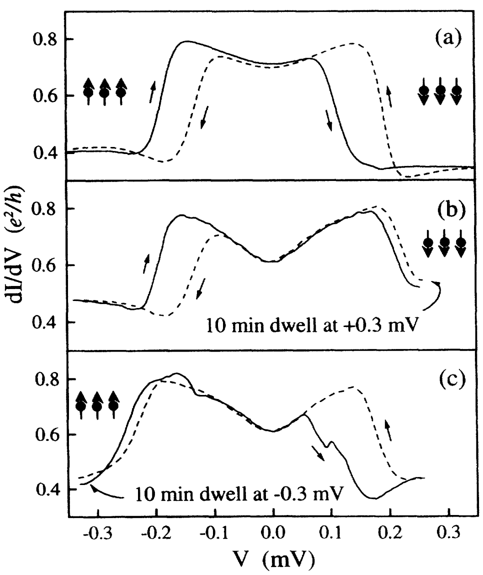

FIG. 2. (a) Differential conductance dI/dV versus voltage V for device I, set up in the configuration illustrated in Fig. 1, for $T \cong 50$ mK and $B = 4$ T ($\nu = 2$). Solid curve: sweep up, dashed curve: sweep down. The round-trip sweep time is 200 sec. The nuclear spin polarizations are schematically indicated. (b) and (c) Same as (a), except taken after dwelling for 10 min at $V = +0.3$ and -0.3 mV, respectively.

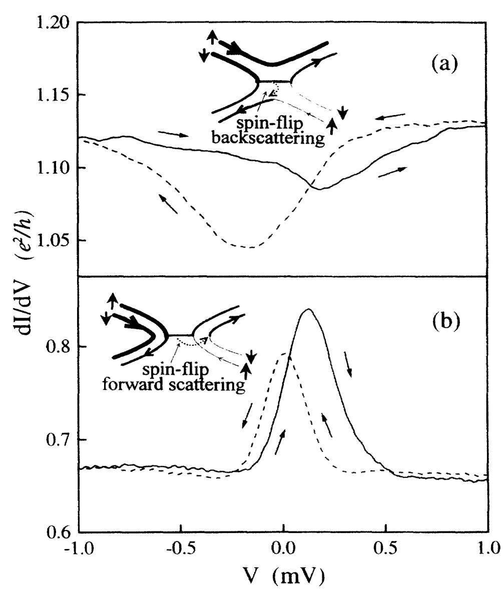

FIG. 3. Differential conductance dI/dV versus voltage V for (a) $dI/dV > e^2/h$, (b) $dI/dV < e^2/h$. Measured on device II, a single QPC formed by gates B and C (with gate A grounded) at $T \cong 50$ mK and $B = 5.4$ T ($\nu = 2$). Solid curve: sweep up, dashed curve: sweep down. Round-trip sweep time for each trace is 200 sec. Insets depict flip-flop scattering processes discussed in the text. Heavy lines denote electron states filled up to higher electrochemical potentials.

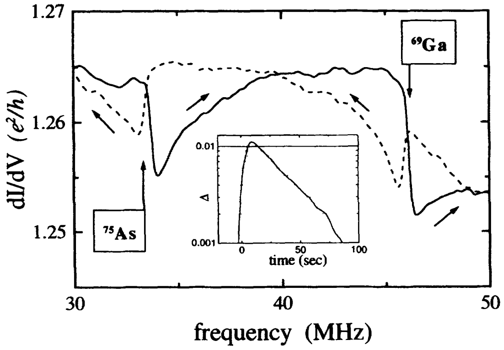

FIG. 4. Differential conductance dI/dV versus rf frequency applied to gate B of a single QPC from device III (gate A is grounded) at $T \cong 50$ mK and $B = 4.7$ T ($\nu = 3$). Solid trace: increasing frequency. Dashed trace: decreasing frequency. Inset: Repolarization of ^{75}As line vs time. $\Delta \equiv |dI/dV - 1.265e^2/h|$.

that obtained from optically pumped nuclear polarization studies [10]. From the repolarization time and the magnitude of the currents, we estimate that $\sim 6 \times 10^{10}$ nuclear spins are flopped during repolarization. This corresponds to a volume of $\sim 1.5\ \mu\text{m}^3$. Since this is many times larger than the width of the edge channel wave functions, we suspect that nuclear spin diffusion [10–13] is important, which together with flip-flop scattering determines the repolarization dynamics.

Having demonstrated the nuclear origin of the hysteresis, we can explain our results in more detail by considering (1) how the nuclei are polarized during the measurements, and (2) how the electrons flip-flop scatter off these polarized nuclei. We will address the possible effects of the electron-nuclear Zeeman interaction later. Consider again the measurement in Fig. 2(a). First, note that, at large $|V|$, flip-flop scattering is occurring in the region between the QPCs [14], and the nuclei are becoming polarized. At large positive (negative) biases, the nuclei in the vicinity of the scattering are polarized downward (upward). To understand the hysteresis that results from this nuclear polarization, let us follow Fig. 2(a) in sequence, starting from the left. During the sweep from -0.5 to -0.2 mV (solid curve), interedge channel scattering is occurring, but with little flip-flop scattering, because most of the nuclei are already polarized in the up direction. When V reaches about -0.2 mV, interedge channel scattering ceases, but the net upward nuclear polarization remains. dI/dV then remains essentially flat until V is swept up to positive voltages. At this point, electrons must flip the other way, from down to up, to equilibrate. Since there is a large population of up nuclear spins available to flop, interedge scattering occurs more efficiently than it would in the absence of polarized nuclei, diminishing dI/dV when V reaches about $+0.1$ mV. As we sweep V the rest of way up, flip-flop scattering slowly erases any remaining upward nuclear polarization, and begins to polarize the nuclei in the down direction. The entire process then repeats in reverse as we sweep V back down. The hysteresis thus results from the *increased flip-flop scattering off polarized nuclei* when changing the direction of the current; i.e., *when V changes sign.*

In addition to the flip-flop process that we have been discussing so far, we have also seen evidence of the importance of nuclear spin diffusion. Such measurements are shown in Figs. 2(b) and 2(c), where we strongly pumped the DNP by dwelling at large $|V|$ for approximately 10 min before taking sweeps. Consider Fig. 2(b), where we dwelled at large positive V. As we sweep V down through negative values, and then back towards the origin, we observe hysteresis, as in Fig. 2(a). However, in contrast to Fig. 2(a), as we continue to sweep through the origin back to positive V, there is very little hysteresis. We interpret this behavior as a manifestation of nuclear spin diffusion. The initial dwell at positive V builds up a large region of downward polarized nuclear spins. When we sweep down to negative V, the electron current plows out a trench of upward nuclear polarization, but the surrounding region of downward nuclear polarization remains. On the sweep back up, as soon as flip-flop scattering ceases, the surrounding region of downward polarized nuclear spins diffusively fills in the trench of upward nuclear polarization. Thus there is little flip-flop scattering and therefore little hysteresis back at positive V. Similar arguments explain the data in Fig. 2(c) [15]. These measurements, together with the NMR repolarization measurement, show that nuclear spin diffusion into and out of the regions of electron current flow has important effects on transport.

We now turn to the single QPC data of Fig. 3. Similarly to Fig. 2(a), the hysteresis in these data can be understood in terms of flip-flop scattering processes [16]. Consider Fig. 3(a). Here the QPC was set such that $dI/dV > e^2/h$, with the spin up edge channel fully transmitted, and the spin down channel partially transmitted (see inset). Electrons in the spin down edge channel approaching the QPC can flip-flop *backscatter* (dashed arrow) into the spin up channel, thus being reflected away from the QPC. (Flip-flop forward scattering is not allowed, as there are no empty final states.) Flip-flop scattering thus *decreases* dI/dV. Recall that flip-flop scattering occurs mostly when V changes sign. Therefore dI/dV should display hysteresis following smaller values after crossing the origin. This is what we observe in the data in Fig. 3(a). On the other hand, in Fig. 3(b) the QPC was set such that $dI/dV < e^2/h$ (see inset). In this case, electrons in the spin up edge channel approaching the QPC can flip-flop *forward scatter* (dashed arrow) into the spin down channel, thus being transmitted through the QPC. (Flip-flop backscattering is not allowed, as there are again no empty final states.) Flip-flop scattering thus *increases* dI/dV, and the hysteresis should follow larger values after crossing the origin. Again, we observe this experimentally in Fig. 3(b). Thus the differing hysteresis in the single QPC data can be explained in terms of flip-flop scattering processes.

As a final note, we examine the effects of the Zeeman term in the hyperfine Hamiltonian. The Zeeman term can also be expected to influence transport, since it leads to an additional electronic splitting for fully polarized nuclei ($\sim$0.12 meV) that can be as large as the bare spin splitting [1,2]. However, the exchange-enhanced electronic splitting is expected to be much larger (up to $\sim$1 meV in the bulk), so the nuclear Zeeman effect is likely a relatively minor perturbation. In the double QPC measurements of Fig. 2, the nuclear Zeeman splitting would influence transport by changing the edge channel separation, and hence the interedge channel scattering. At positive (negative) V, the downward (upward) polarized nuclei would increase (decrease) the Zeeman splitting, increasing (decreasing) dI/dV. Indeed, we note a slightly enhanced conductance after a long dwell time at +0.3 mV [Fig. 2(b)], and the slightly suppressed conductance after a long dwell time at −0.3 mV [Fig. 2(c)]. Analogous effects of the Zeeman term were observed by Kane, Pfeiffer, and West [3]. However, the major *hysteresis* in Fig. 2 cannot, we believe, be explained by Zeeman effects. The Zeeman term leads to "asymmetric" hysteresis, with dI/dV enhanced after time at $+V$ and diminished after time at $-V$, as described above. However, the hysteresis in Fig. 2(a) is symmetric, i.e., dI/dV always *decreases* when the current changes sign, *regardless of the sign of V.* We therefore believe that the flip-flop scattering is the origin of this hysteresis, through the mechanism described in the preceding paragraphs. In the case of the single QPC data, we have not been able to definitively rule out the Zeeman effect as the source of hysteresis, but simply note that flip-flop scattering can account for these observations.

In conclusion, we have used quantum point contacts to create and detect nuclear spin polarization in quantum Hall conductors. We have performed electrically detected NMR on a micron size scale, and studied the effects of flip-flop scattering, nuclear spin diffusion, and the Zeeman interaction on edge state transport. This work both extends the techniques of nuclear spin manipulation to the submicron scale and demonstrates the direct relevance of electron-nuclear flip-flop scattering in transport. Although we have discussed here QPCs, it is clear that our results are relevant for any mesoscopic system where a spin-polarized dc current flows, e.g., quantum dots, magnetic scanning tunneling microscopy tips, etc. These results should thus pave the way for new classes of experiments on mesoscopic nuclear spin systems.

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[15] In Fig. 2(c), additional features are observed in the data, one near −0.15 mV and the other near +0.1 mV. Their origin is not yet clear.
[16] For a discussion of the overall nonlinearity of single QPCs see L.P. Kouwenhoven, B.J. van Wees, C.J.P.M. Harmans, J.G. Williamson, H. van Houten, C.W.J. Beenakker, C.T. Foxon, and J.J. Harris, Phys. Rev. B **39**, 8040 (1989).

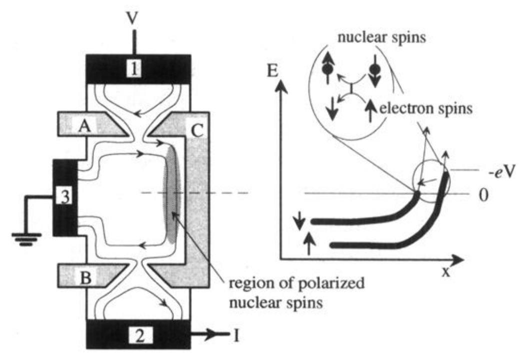

FIG. 1. Left: Schematic of a double QPC device at a bulk filling factor $\nu = 2$. Lightly shaded regions A, B, C are gates. The dark regions 1, 2, 3 are Ohmic contacts. The spin-resolved edge channels are represented by the curved lines; each QPC transmits only the lower edge channel. Right: Edge state energy level diagram through cross section along dashed line in left figure, for $V < 0$. Heavy lines denote filled electron states. The electron-nuclear flip-flop scattering process is discussed in the text.