

Electrical Readout of the Local Nuclear Polarization in the Quantum Hall Effect: A Hyperfine Battery

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It is demonstrated that the now well-established “flip-flop” mechanism of spin exchange between electrons and nuclei in the quantum Hall effect can be reversed. We use a sample geometry which utilizes separately contacted edge states to establish a local nuclear spin polarization—close to the maximum value achievable—by driving a current between electron states of different spin orientation. When the externally applied current is switched off, the sample exhibits an output voltage of up to a few tenths of a mV, which decays with a time constant typical for the nuclear spin relaxation. The surprising fact that a sample with a local nuclear spin polarization can act as a source of energy and that this energy is well above the nuclear Zeeman splitting is explained by a simple model which takes into account the effect of a local Overhauser shift on the edge state reconstruction.

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The recent interest in nuclear spin polarization in semiconductor-based electronic structures arises mainly from their possible application for quantum information storage and processing [1]. As a consequence, experimental and theoretical emphasis has been put on the electrical controllability of the nuclear spin polarization, with the aim to realize both write-in and readout schemes.

One way to locally manipulate and detect nuclear spins makes use of the spin-polarized channels formed at the edges of a two-dimensional electron system (2DES) in the quantum Hall regime. The spin-flip associated with transport between two edge states of different spin orientation can be mediated by a reverse “spin-flop” in the nuclear spin system, which over time leads to a buildup of a nuclear spin polarization [2,3]. A number of experiments have demonstrated such electrically pumped nuclear spin polarization and how it affects electronic transport in high magnetic fields [4–10].

Here we introduce an experimental approach which makes use of separately contacted, spin-polarized edge channels and allows us not only to induce a local nuclear spin polarization at a predefined site [9]. It also provides for a simple and accurate means to determine the local hyperfine field. We find that the nonequilibrium state associated with the spatial variation of the nuclear polarization can serve as an internal source of energy. So the nuclear system in the sample, after being energized by the flip-flop mechanism, can be viewed as a “hyperfine battery.” By measuring the voltage between the edge channels, we can directly determine the Overhauser shift as a function of time. We find clear evidence that the flip-flop mechanism is most effective for establishing a nuclear spin polarization when the electrons are transferred resonantly, i.e., when the applied bias corresponds to the electronic Zeeman gap.

The samples are fabricated from two different GaAs/Al_xGa_{1-x}As heterostructures (*A* and *B*), grown by molecular-beam epitaxy. They contain a 2DES, located

70 nm and 110 nm below the surface, respectively. The mobilities and carrier densities at 4.2 K are 8×10^5 cm²/Vs and 3.7×10^{11} cm⁻² for sample *A*, and 2.2×10^6 cm²/Vs and 1.35×10^{11} cm⁻² for sample *B*. Different samples prepared from both heterostructures exhibit the same behavior. For consistency, only results from sample *A* are presented in the following.

To separately contact single edge channels of different spin orientation, we use an etched, quasiring-shaped mesa

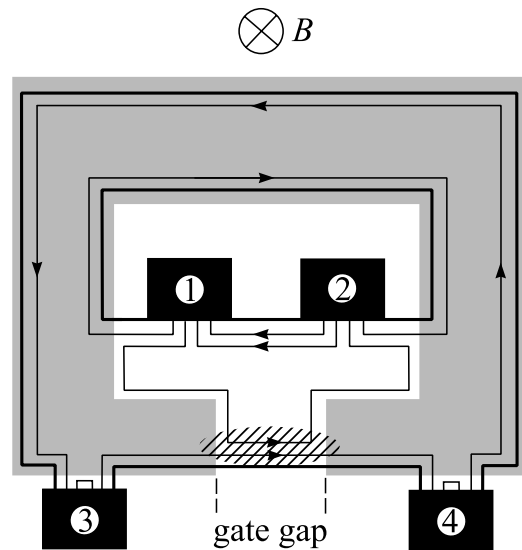


FIG. 1. Schematic of the sample geometry. Contacts (1)–(4) are positioned along the etched edges (thick lines) of the ring-shaped mesa. The gray area represents the gate electrode, the hatched area indicates the interaction region of the edge states, where the nuclear spin polarization is induced. Arrows indicate the direction of electron drift in the edge states for the chosen magnetic field direction. The filling factors are $\nu = 2$ in the ungated regions and $g = 1$ under the gate. The gate gap width is $2 \mu\text{m}$.

geometry [11,12], as shown in Fig. 1 (thick lines). Two Ohmic contacts (1 and 2) are located in the interior, two others (3 and 4) on the outside of the mesa. A horseshoe-shaped gate electrode (shaded gray) covers most of the sample, leaving uncovered only the narrow gate gap region on the outer sample edge, which determines the location where the nuclear spin polarization will be induced and detected. An external magnetic field is applied so that the filling factor ν in the ungated regions of the sample is $\nu = 2$ ($\nu = n/n_B$, with n being the electron density and $n_B = eB/h$ the degeneracy of each Landau level). A negative voltage is applied to the gate electrode to adjust the local filling factor under the gate to $g = 1$.

Electronic transport between the inner (1, 2) and outer contacts (3, 4) is only possible in the gate gap region, where the edge channels are running parallel in close proximity. For the chosen filling factor combination, the edge channel connected to contacts 1 and 2 is spin-down (antiparallel to the external magnetic field), whereas the one connected to contacts 3 and 4 is spin-up (parallel to the external magnetic field). This way, four-probe transport measurements are possible between spin-polarized electron states [9,11].

The experiments shown here are performed in a ^3He cryostat at a temperature of $T = 240$ mK and a magnetic field of $B = 9.1$ T. First, a stable nuclear polarization is established in the gate gap region by driving a constant current $|I_{\text{pump}}| \leq 500$ nA between the edge states in the gate gap. It is well established [2,3,6,7] that charge transfer between electron reservoirs of opposite spin requires an electronic “spin-flip” which can be mediated by a nuclear “spin-flip” in the opposite direction. Because nuclear spin relaxation times are typically several tens to thousands of seconds, a net nuclear spin polarization builds up at the location where the electron spin-flip is induced. This process of “dynamic nuclear polarization” (DNP) will in turn affect the energetic structure of the electron system through the hyperfine interaction. The Hamiltonian of the hyperfine interaction is given by

$$AI \cdot S = \frac{1}{2}A(I^+S^- + I^-S^+) + AI_zS_z, \quad (1)$$

where $A > 0$ is the hyperfine constant, I is the nuclear, and S is the electron spin. The final term accounts for the contact-hyperfine interaction between the z components of the nuclear and the electron spin (I_z and $S_z = \pm 1/2$), respectively.

In general, a stable nuclear polarization is established within a few minutes [6,7]. In the present setup, this can be confirmed *in situ* by 4-probe measurements of the resistance between inner and outer contacts [9]. To polarize the nuclear spin system, we apply I_{pump} for 10 minutes, until a constant voltage drop has established between inner and outer contacts. This procedure provides for a reproducible initial state of the system with a nuclear polarization, depending on the sign and magnitude of I_{pump} [9].

When the DNP has been established and I_{pump} is switched off, the voltage between the inner and outer contacts does not vanish. This is somewhat surprising, since it indicates that there is a source of energy present in the sample. Figure 2 shows that the output voltage V_{out} is dependent on the magnitude of I_{pump} in a nonmonotonic fashion and that it exhibits a slow exponential decay as a function of time. From the dependence of the output voltage on I_{pump} (both sign and magnitude), a number of spurious effects can be excluded as explanations for this striking observation: thermal effects, e.g., caused by local heating of the sample should be independent of the current direction. A transient charging of the highly resistive bulk region of the 2DEG should exhibit a positive V_{out} for a positive I_{pump} .

On the other hand, there is strong evidence that the internal source of energy which gives rise to the output voltage is related to the nuclear spin system. The output voltage exhibits a time dependence that is similar to the one observed when the nuclear polarization is established [9], with a decay time that is typical for nuclear depolarization [6,7]. Flip-flop scattering of the nuclear spin system is expected to be most efficient at the sample edge. The reconstruction of the edge potential [13,14] results in a high density of electron states at the Fermi energy and provides for a continuous energy dispersion so that energy conservation is easily fulfilled during flip-flop scattering (cf. also the discussion of Fig. 3, below). It is therefore expected that the decay of the nuclear polarization will take place by an inverse flip-flop process and that this process will lead to a population imbalance between the spin-polarized edge states. At first glance, however, it seems impossible that this process can generate a voltage

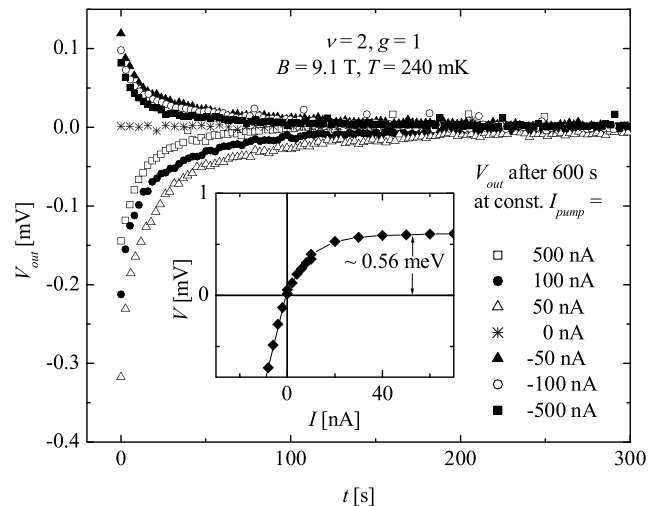


FIG. 2. Time-dependent output voltage between inner and outer contacts after establishing a nuclear polarization for ten minutes at different currents I_{pump} . The filling factors are $\nu = 2$ and $g = 1$ in the ungated and gated regions, respectively. The inset shows the nonlinear I - V characteristic used to determine ΔE_z (see text).

in the millivolt range, since the energy gain from a nuclear spin-flip is approximately 3 orders of magnitude smaller.

To account for our experimental observation, we will introduce in the following a simple model, based on the local energy shift of the spin-resolved edge states. The required energy of a few 100 μeV is supplied by the interaction energy between electrons and nuclei rather than the nuclear Zeeman energy alone. Loosely speaking, the energy is taken out of the Overhauser field.

Figure 3(a) shows a sketch of the local energy for the spin-down (dashed line) and the spin-up electron system (solid line) as it would develop if the local spin polarization was present in the bulk of the sample: in the unpolarized regions (left and right side of the figure), the energy gap between the different spin systems corresponds to the bare Zeeman splitting $\Delta E_z = |g^*|\mu_B B$, where g^* is the effective electronic Landé factor (including exchange effects [14]). In the region where nuclear spin polarization is present (middle, shaded area), the hyperfine interaction will cause an additional Overhauser shift ΔE_{Ov} .

In the presence of the edge potential, however, current-carrying edge channels will develop, which—in local equilibrium—share a common chemical potential (see bottom of Fig. 3 for sketches of the edge reconstruction in the representation given by Chklovskii *et al.* [13]). In the present sample structure, the edge channels can only interact in the very same region where the nuclear polarization is present (hatched area in Fig. 1). Therefore, the energies of the two spin systems will be aligned, but only inside the

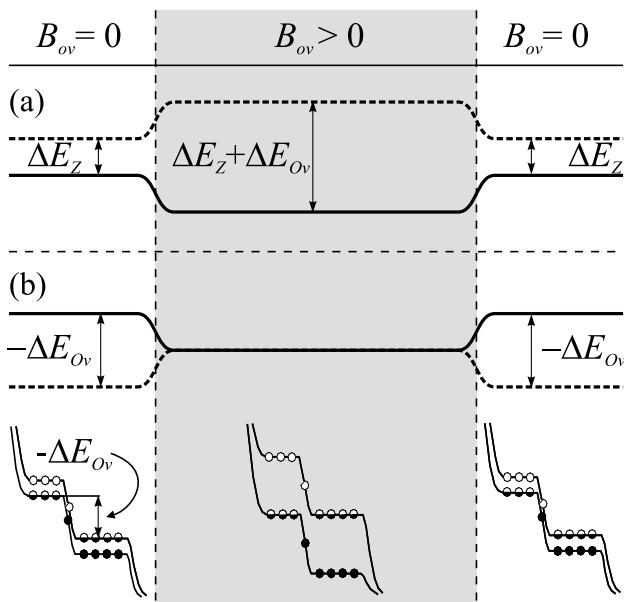


FIG. 3. Schematic representation of the local energy structure of (a) noninteracting electron states and (b) edge states in local equilibrium. The gray area indicates the gate gap region with polarized nuclear spins, where an Overhauser field $B_{Ov} > 0$ is present. The bottom inset shows the edge reconstruction inside (center) and outside (left and right) of the gate gap region. Half filled circles represent electronic states at the Fermi energy.

gate gap region [15]. Everywhere else, particularly at the location of the voltage probes, the shift by $-(\Delta E_z + \Delta E_{Ov})$, induced by the equilibration in the gate gap region, will result in an energy difference of $-\Delta E_{Ov}$ [see Fig. 3(b)].

To understand the polarity of the output voltage with respect to the sign of the pumping current, we analyze how I_{pump} affects the Overhauser field B_{Ov} . Assuming the inner current contact to be grounded, a positive I_{pump} corresponds to electrons flowing from the inner to the outer edge channel. This requires an electron spin-flip from down to up. The corresponding nuclear spin-flip from up to down induces a net nuclear “down” polarization ($\langle I_z \rangle < 0$) which in turn results in a positive B_{Ov} (due to the negative sign of g^*) [6,9]. Accordingly, a positive I_{pump} will lead to an increased energy splitting $\Delta E_z + \Delta E_{Ov}$ between the spin-polarized edge states, as illustrated in Fig. 3. Thus, the output voltage, measured between the two edge channels, will be *negative*, $V_{\text{out}} = -\Delta E_{Ov}/|e|$.

Our experiment therefore gives us direct access to the Overhauser shift in the region of local nuclear spin polarization. Figure 4 shows in more detail the measured output voltage as a function of I_{pump} . It can be seen that maximum $|V_{\text{out}}|$ is observed around $I_{\text{pump}} = +50$ nA and that the Overhauser field does not saturate but rather *decreases* for higher pumping currents. This decrease in the nuclear polarization with increasing positive bias ($I_{\text{pump}} > 100$ nA) is in good agreement with previous results on a

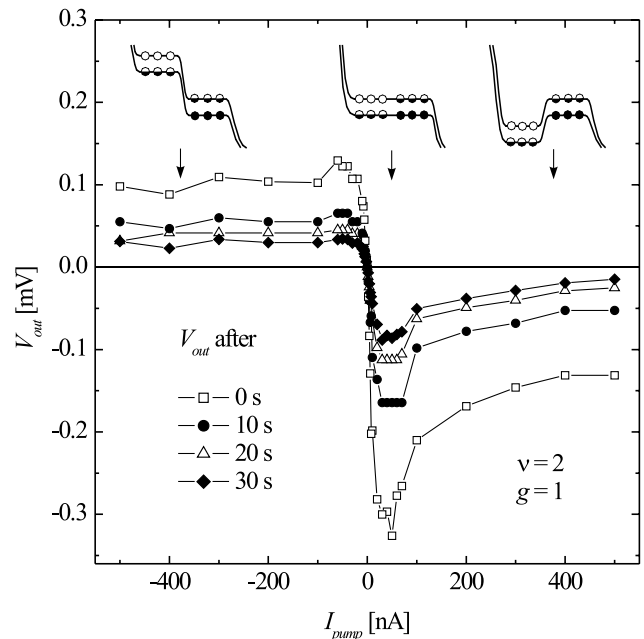


FIG. 4. Output voltage V_{out} as a function of the pumping current, for different times after switching off I_{pump} . Pumping is most effective around $I_{\text{pump}} = +50$ nA. At this current the resulting bias allows for resonant electron transfer between the different spin systems, as schematically shown in the middle inset.

similar sample, obtained using a different experimental approach [9].

A possible explanation for the sharp maximum in $|V_{\text{out}}|$ is sketched in the insets to Fig. 4. Here, the energetic structure of the edge states [13] is shown for a negative (left), small positive (middle), and large positive (right) bias voltage which corresponds to the current I_{pump} between the edge states [11]. For both negative and large positive voltage, the electrons have to undergo tunneling processes and/or inelastic scattering to transfer from one channel to the other. When the applied voltage is equal to the energy gap between the spin-resolved states, electrons can resonantly transfer between the inner and outer edge channels, which is accompanied by a dramatic decrease in the resistance [11]. In the present sample, the differential resistance reaches its minimum value around +40 nA (see inset in Fig. 2), when the edge states first fully equilibrate their electrical potentials in the gate gap region. As this value is in rough agreement with the value which leads to optimum nuclear polarization, we infer that under resonant pumping conditions (middle inset in Fig. 4) the nuclear polarization is induced most efficiently. At higher biases (right inset in Fig. 4) the inelastic processes necessary for equilibration may be so slow that the relaxation (and thus the flip-flop process) takes place outside the gate gap region. This does not effect the I - V characteristic, which is insensitive to the location of electronic spin-flip, but strongly reduces the local nuclear spin polarization in the gate gap and thus the output voltage V_{out} .

The results shown in Fig. 4 can be used to estimate the maximum value of the Overhauser field in the gate gap: $B_{\text{Ov}} = B|eV_{\text{out}}|/\Delta E_z$ [16], where $B = 9.1$ T is the external field and ΔE_z is the exchange-enhanced electronic spin splitting. The latter can be determined to be $\Delta E_z \approx 0.56$ meV by evaluating the nonlinear I - V curve [11], shown as an inset to Fig. 2. To ensure that ΔE_z is free of contributions from the hyperfine field, the nuclear spins are allowed to relax for 600 s at $I_{\text{pump}} = 0$ before each measurement $V(I)$ is taken. With $|eV_{\text{out,max}}| \approx 0.32$ meV and $\Delta E_z \approx 0.56$ meV we find $B_{\text{Ov,max}} = 5.2$ T. This is among the highest values determined experimentally so far and close to the maximum Overhauser field of 5.3 T, predicted for 100% nuclear polarization in GaAs [17]. We attribute this high degree of nuclear polarization to the optimum choice of the pumping current which corresponds to a resonant electron transfer between the spin split states (see Fig. 4).

Finally, we would like to mention that the polarized nuclear spin system in the present device not only serves—via the hyperfine interaction—as an ordinary, battery-type voltage source. Because of the 100% spin-polarization of the edge channels, a *spin current* will be concomitant with any charge current drawn from our device. In this respect, the present experimental realization resembles the various schemes for “spin batteries” (with

and without electric potentials) that have been envisioned recently [18].

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