Nuclear spin coherence in a quantum wire

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We have observed millisecond-long coherent evolution of nuclear spins in a quantum wire at 1.2 K. Local, all-electrical manipulation of nuclear spins is achieved by dynamic nuclear polarization in the breakdown regime of the integer quantum Hall effect combined with pulsed nuclear magnetic resonance. The excitation thresholds for the breakdown are significantly smaller than what would be expected for our sample and the direction of the nuclear polarization can be controlled by the voltage bias. As a four-level spin system, the device is equivalent to two qubits.
Nuclear Magnetic Resonance

When nuclei with a spin quantum number of 1/2 are placed in an applied field, a small majority of nuclear spins are aligned with the applied field in the lower energy state.

If a nucleus is irradiated with electromagnetic radiation of the appropriate energy, the energy is absorbed, and the nuclear spin is flipped from spin state +1/2 (with the applied field) to -1/2 (against the applied field).

Resonance: the absorption of electromagnetic radiation by a nucleus and the flip of its nuclear spin from a lower energy state to a higher energy state.

If the radio frequency signal is then switched off, the relaxation of the spins back to the lower state produces a measurable amount of RF signal at the resonant frequency associated with the spin flip. This process is called Nuclear Magnetic Resonance (NMR)
Basics- Dynamic Nuclear Polarization

• a mechanism by which an electron transition between two spin-resolved energy states, or “spin flip,” is mediated by a reverse “spin flop” in the nuclear system

• an electron to be scattered between energy states of opposite spins

• The hyperfine interaction between electrons and nuclei allows for a spin change in the nuclear system to preserve total angular momentum, in a process that occurs locally where the electron spin flip is induced.

• As more such scattering events occur, the DNP builds up and affects the energy structure of the electron system by creating an effective hyperfine field that adds to the external magnetic field, thus changing the electron Zeeman energy.
Motivation

- Nuclear spins have very long coherence times
- NMR signals can be significantly enhanced by dynamic nuclear polarization DNP
- Multiple quantum coherence in a nanometer-scale device can be achieved by DNP

$T_2$ for $^{69}\text{Ga}$ around 1 ms

Sample

GaAs/AlGaAs
2DEG 90 nm below surface
Density= 1.55x10^{15} /m^2, Mobility=146 m^2/Vs
0.7 μm wide x 0.7 μm long split gates
250 nm PMMA for electrical isolation
2.5 μm wide antenna overgate
Observations - NMR

a) Hysteresis curve for $V_{SG}=-0.8$ V, just below $v=1$

b) conductance relaxation at $V_{SG}=-0.8$ V and $B=5.2$ T

c) $^{75}$As NMR signals for $V_{SG}=-0.8$ V

d) derivative of the NMR signals as a function of magnetic field

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Observations- onset of DNP

- Conductance relaxation
- NMR for $^{75}$As at $V_{SG}=-0.8$ V and $B=5.2$ T
- Unpolarized ($t=0$) and equilibrium ($t=120s$) conductance $T=50$ mK and $T=800$mK
Observations – Conductance at Vac and Vdc

a) Conductance as a function of Vdc and Vac excitation voltages
b),c) Vac=-10μV and V=-95 μV (dotted lines t=0s. line t=120s)
d),e) relaxation and NMR traces for Vdc
Observations - Rabi oscillations


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Observations- Frequency spectrum

Resonance frequencies for the different transitions

Knight shift= 4 kHz
Quadrupolar shift= 9kHz

Line fit $\Delta G = \cos(2\pi f_{\text{Rabi}}^R \tau_p) \exp(-\tau_p / T_{2\text{Rabi}}^R)$

$f_{\text{Rabi}}^R = 11.71 kHz$, $T_{2\text{Rabi}}^R = 0.82 ms$
Results and Conclusions

- $T_2^{Rabi}=0.82\text{ms}$
- DNP achieved over a nanometer scale
- DNP could be used to create a local Overhauser field at relatively high temperatures with the ability of controlling its direction
- millisecond-long nuclear quantum coherence
- possibility of performing two-qubit operations at temperatures around 1 K

- Need a detailed physical model