Controlled Multiple Quantum Coherences of Nuclear Spins in a Nanoscale Device

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Quantum Computers using Coherence of Nuclear Spins

Quantum computation based on NMR

Experimental realization of D-J algorithm

Experimental realization of Shor's factoring algorithm

**PROBLEM**

Liquid-state NMR is not suitable for a scalable device

Quantum computers based on all-electrical solid-state NMR

Electronics + NMR
A self-contained semiconductor chip that can access nuclear spins in a nanoscale region

New NMR: Direct detection of multiple quantum coherences, which are invisible by conventional NMR

Nuclei often possess total spin angular momentum greater than a half and multiple spin levels are formed.

\[ |\frac{-3}{2}\rangle \quad |\frac{-1}{2}\rangle \quad |\frac{1}{2}\rangle \quad |\frac{3}{2}\rangle \]

multiple quantum coherences
Control and Detection of Coherence of Nuclear Spins

1. **Initialization (Polarization)**
   - Electron-nuclear spin coupling (flip-flop process).
   - Polarization only in the nanoscale region.

2. **Creation of quantum mechanical superpositions of states**
   - Nuclear magnetic resonance (NMR) on a self-contained semiconductor chip.

3. **Readout**
   - Electron-nuclear spin coupling.
   - Measurement of polarization by resistance.
Polarization of Nuclear Spins

Electron-nuclear spin coupling in 2D system in the fractional quantum Hall regime ($\nu=2/3$)

- **Long-time-scale resistance enhancement (~10 min)**
  - Due to long longitudinal (spin-lattice) relaxation time $T_1$

- **Current dependence**
  - Large current is required to polarize nuclear spins

- **Resistively detected CW-NMR**

  - Smet et al., PRL 86, 2412 (2001).
  - Hashimoto et al., PRL 88, 176601 (2002).
  - Kumada et al., PRL 89, 116802 (2002).
  - Kraus et al., PRL 89, 266801 (2002).
  - Hashimoto et al., PRL (2002).
Self-contained NMR Device

Three gate electrodes
1. **Back gate**: to control electron density.
2. **Split gate**: to define nanoscale region
3. **Antenna gate**: for r.f. irradiation

Channel

SEM Image

Number of Nuclei $<\sim10^8$
This is much smaller than the **detection limit** of standard NMR ($\sim10^{11}-10^{13}$).
Polarization of Nuclear spins in a Nanoscale Region

Temperature \( \sim 0.1 \) K

Current dependence of electron-nuclear spin coupling

By producing high current density region, nuclear spins can be polarized only in the nanoscale region.

r.f.-Pulse Irradiation
to create a quantum mechanical superposition of states

We interpret $\Delta R$ to have a direct relationship with the change in the $z$ component of the magnetization, $M_z$, induced by the altered population by the r.f. pulse.
Quadrupolar Interaction

Nuclear spin $I=3/2$ ($^{69}\text{Ga}$, $^{71}\text{Ga}$, $^{75}\text{As}$)

Energy Diagram of $I=3/2$ system

Zeeman Energy

Without Quadrupolar Interaction

With Quadrupolar Interaction

Zeeman Energy

$|3/2\rangle$

$|1/2\rangle$

$|-1/2\rangle$

$|-3/2\rangle$

$\hbar \omega_0$

$\hbar \omega_0$

$\hbar \omega_0$

$\hbar \omega_0 + 2 \Delta$

$\hbar \omega_0 - 2 \Delta$

$\hbar \omega_0 + 2 \Delta$

$\hbar \omega_0 - 2 \Delta$

$\hbar \omega_0$

NMR Spectrum of $^{75}\text{As}$

$\tau_p=0.12 \text{ ms}$
Time Evolutional Spectra

\[ \Delta R (\Omega) \]

\[ h\omega_0 - 2\Delta \quad h\omega_0 \quad h\omega_0 + 2\Delta \]

High \( B_1 = 1.4 \text{ mT} \)

Single-quantum coherences

Double-quantum coherences

Triple-quantum coherences

Multiple coherences (invisible)

Quantitative Discussion

**ASSUMPTION:**

The change in the resistance ($\Delta R$) is **proportional** to the change in the magnetization $M_z$ induced by altered population: $\Delta R \propto \Delta M_z$.

**Simulation of $M_z$ using rotating-frame approximation**

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = H |\Psi(t)\rangle$$

- Zeeman
- Quadrupolar
- r.f. field

$$H = -\gamma \hbar B_0 I_z + \Delta / 3 (3I_z^2 - I(I + 1)) + \gamma \hbar B_1 \cos(\omega t) I_x$$

- $\gamma$: gyromagnetic ratio
- $\Delta$: quadrupolar constant

The initial population is the same for all three panels.

$B_1$ is the only input parameter for each panel.

**Experiment**

[Images of experimental data for panels a, b, and c]
Numerical Calculations

We measure the change in $M_z$ by the resistance
Standard vs. Our NMR

**Standard NMR (induction detected)**

- **Magnetization** $M$ of nuclear spins
  - $xy$-component: $M_{xy}$
  - $z$-component: $M_z$

- Detection coil
- **Nuclear magnetic induction**
- **Fourier Spectrum**
  - **FFT**
  - Time
  - Frequency

**Our NMR**

- **Electron transport**
- Antenna
- **Electron transport scan**
- Spectrum
  - r.f. field
  - Frequency
Our NMR ($M_z$ detection)

- **Direct detection** of multiple quantum coherence
  - The oscillation amplitudes for higher order coherences are larger than those for single, reflecting greater change in spin.
  - Width is scaled down by the photon number.

- **High sensitivity** (<$10^8$)
  - Much less than the detection limit of standard NMR ($10^{11}$-$10^{13}$)

\[
\begin{align*}
\Delta R &= \frac{2}{3} - \frac{2}{1} - \frac{2}{1} \\
\Delta R &= 2/3 \\
\Delta m &= 1, 3
\end{align*}
\]
Conclusion

A self-contained semiconductor device with a novel paradigm of NMR, which accesses nuclear spins in a nanoscale region

Direct detection of multiple quantum coherences, which is invisible by conventional NMR

Three single, two double and one triple quantum coherences for one nuclide, 18 in total for three nuclides ($^{69}$Ga, $^{71}$Ga, $^{75}$As), are completely controlled by all-electrical means.