Ultrafast Control of Nuclear Spins Using Only Microwave Pulses: Towards Switchable Solid State Gates for Quantum Information Processing

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Since the idea of quantum information processing (QIP) fascinated the scientific community [1-3], electron and nuclear spins have been regarded as promising candidates for quantum bits (qubits) [4] because they are natural two-state systems and decoherence times for the spin degree of freedom are usually larger than for charge degrees of freedom. Indeed, nuclear magnetic resonance (NMR) in liquid state was the first spectroscopic technique used to demonstrate quantum computation algorithms such as Deutsch, Grover and Shor algorithms [5]. However, when a large number of qubits is required, the bulk NMR method suffers from sensitivity problems because of the small nuclear Zeeman energy compared to the thermal energy kT even at extremely low temperatures (T << 1 K) [6]. These scalability limitations can be overcome by using electron paramagnetic resonance (EPR) spectroscopy because in this case pure states are experimentally accessible with current technology. In addition, due to their larger relaxation rates, electron spins can result in higher clock rates (GHz) compared to the low nuclear spin transition frequencies (MHz).

A fundamental challenge in the realization of a solid state quantum computer is the construction of fast and reliable two-qubit quantum gates. Of particular interest in this direction are hybrid systems of electron and nuclear spins, where the two qubits are coupled through the hyperfine interaction. However, the significantly different gyromagnetic ratios γ_i of electron and nuclear spins do not allow for their coherent manipulation at the same time scale. Here we demonstrate the control of the α-proton nuclear spin, I=1/2, coupled to the stable radical ·CH(COOH)$_2$, S=1/2, in a γ-irradiated malonic acid single crystal, using only microwave (mw) pulses. We show that, depending on the state of the electron spin (m_S=±1/2), the nuclear spin can be locked in a desired state or oscillate between m_I=+1/2 and m_I=-1/2 on the nanosecond time scale. We believe that this procedure is important for QIP technologies because it provides a fast and efficient way of controlling nuclear spin qubits, and also enables the design of spin-based quantum gates by addressing only the electron spin.

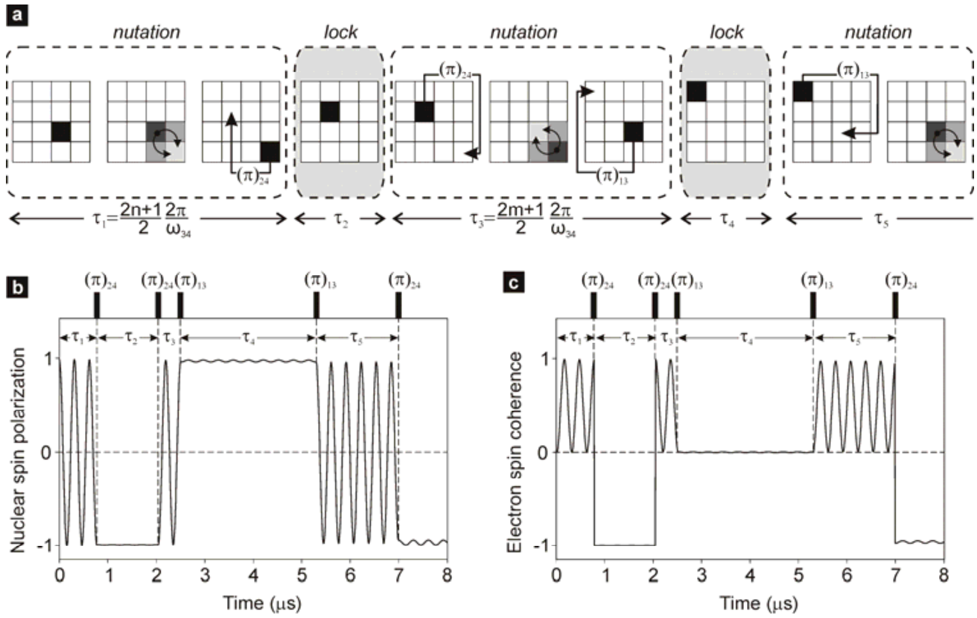

Figure 1: Manipulation of the proton nuclear spin solely by using mw pulses for the case of exact cancellation. (a) Representation of the density matrix in the product basis $|\alpha\alpha\rangle, |\alpha\beta\rangle, |\beta\alpha\rangle, |\beta\beta\rangle$ during nutation or locking time periods. (b) Numerical simulation of the nuclear spin polarization $\langle I_z \rangle$ during the applied pulse sequence that uses semi-selective mw π-pulses (shown at the top). (c) Corresponding numerical simulation of the electron spin coherence $\langle S_x \rangle$ after the detection pulse sequence $(\pi/2)_{2324} - \tau - (\pi)_{2324} - \tau$ with $\tau = 2\pi/\omega_{34} = 310\,\text{ns}$.

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