Hyperfine-phonon spin relaxation in a single-electron GaAs quantum dot

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Understanding and controlling the spin relaxation time T_1 is central importance for spin qubits, since T_1 is setting an upper limit to the coherence time. A longer T_1 is generally better for the qubit, though for particular tasks, a short T_1 can also be useful. The spin relaxation occurs via phonon emission and spin-orbit coupling in GaAs quantum dots at low temperatures and high in-plane magnetic fields $\mathbf{B}$. The characteristic dependence $T_1 \propto \mathbf{B^{-5}}$ and B-field anisotropy were already confirmed experimentally. However, it has also been predicted 15 years ago that at low enough fields, the spin-orbit interaction is replaced by the coupling to the nuclear spins, where the relaxation becomes isotropic, and the scaling changes to $T_1 \propto \mathbf{B^{-3}}$. We establish these predictions experimentally, by measuring T_1 over an unprecedented range of magnetic fields – made possible by lower temperature, control over the B-field direction up to 14 T, and an extremely stable dot – and report a maximum $T_1 = \mathbf{57 \pm 15}$ s at the lowest fields, setting a new record for the spin lifetime in a nanostructure.

Using a novel type of orbital excited state spectroscopy with an in-plane magnetic field, we extract unparalleled information about the 3D shape, size and orientation of the quantum dot wave function by fitting to a 3D numerical model. With this model at hand, we can extract the Rashba and linear Dresselhaus parameters from the B-field anisotropy of the spin relaxation, in good agreement with spin-orbit parameters from other experiments. Further, we simulate the hyperfine induced spin relaxation rate, in very good agreement with the experiment, all with a single consistent set of parameters. While ramping the magnetic field from 0.6 T to about 10 T, the spin relaxation rate changes by a striking 6 orders of magnitude. Yet this is very well captured by the theory throughout the entire range – putting the model to a very stringent test. With spin-orbit parameters at hand, it also becomes easy to maximize the electric dipole spin resonance Rabi frequencies in future experiments by selecting the strongest spin-orbit direction, thus potentially facilitating a large improvement over previous experiments.

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