Coherent magnetic and electrical control of a single spin-7/2 donor atom in Silicon

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The computational power of a quantum processor depends upon the dimensionality d of its Hilbert space. For an n-qubit processor, this is simply $d = 2^n$. However, it is also possible to use naturally occurring systems where d is intrinsically large. For example, the nuclear spin of a ^{123}Sb atom has $d = 8$ owing to its large spin $I = 7/2$. When implanted in silicon it acts a substitutional group-V donor which binds an extra electron, yielding $d = 16$, or the equivalent of four qubits, within just one atom. The quadrupole interaction in heavy group-V donors offers a natural way to control nuclear spins using electric fields, which are easier to confine in a nanoscale device, as opposed to magnetic fields. Past work by Asaad et al. [1] showed that the nucleus of a single ^{123}Sb atom can be integrated in a nanoelectronic device and be used to encode quantum information through Nuclear Electric Resonance.

Here we demonstrate coherent quantum control over the entire 16-dimensional Hilbert space of an implanted ^{123}Sb donor atom in a silicon chip, using both magnetic and electric fields. The resonant electric and magnetic excitation, at radiofrequency (for the nucleus) and microwave (for the electorn) is delivered by a single on-chip microwave antenna. We characterize the quadrupole interaction and investigate the performance and noise sources for both magnetic and electric coherent control. Using Gate Set Tomography, we extract one-qubit gate fidelities on the ionized nucleus > 99.8% for both electric and magnetic drive. We find state-dependent Ramsey coherence times of the 7 NMR transitions ranging from $T_2^* = 18$ ms (for the 5/2 → 7/2 transition) to $T_2^* = 56$ ms (for the 1/2 → -1/2 transition). We ascribe the difference in dephasing rates to a spin state-dependent sensitivity to electric field noise.

These results pave the way to the exploitation of high-spin donor nuclei such as ^{123}Sb to encode error-correctable logical qubits [2], provide advantages in quantum sensing [3] and allow all-electrical spin control in nanoscale semiconductor devices.

[1] S. Asaad et al., *Nature* **579**, 205–209 (2020)

[2] J. Gross, *Phys. Rev. Lett.* **127**, 010504 (2021)

[3] T. Chalopin et al., *Nature Comm.* **9**, 4955 (2018)