A Many-Body Quantum Memory Using Optically Engineered Nuclei

Mete Atature

Cavendish Laboratory, University of Cambridge, Cambridge UK

Ma424@cam.ac.uk

Quantum nodes comprising multiple qubits coupled to photons can serve a range of quantum information applications including quantum repeaters and photonic cluster-state generation. An optically active solid-state spin qubit serving as broker to exchange information between a photon and several register qubits is one promising implementation. Multiple such spin-photon interfaces have demonstrated functionality including in diamond, silicon carbide and rare-earth doped YVO4 crystal. Many initial implementations involve an electronic spin in dipolar coupling to a small number of proximal nuclear spins, where their distance controls their coupling rate. III-V compound semiconductor quantum dots have superior optical properties including brightness, purity and coherence, and have efficient coupling to information-carrying single photons. However, they lack additional spins to act as register qubits for the electron spin qubit.

Quantum dots offer an opportunity for a contrasting perspective to the few proximal spin implementation, namely the nuclear spin ensemble comprising the quantum dot itself [1]. The resident electron spin qubit is Fermi-contact linked to a group of roughly 100,000 nuclei, which, if not managed, serves as a source of noise detrimental to the qubit's performance. However, if these nuclei are sufficiently manipulated, they can potentially serve as an information reservoir by leveraging their collective behaviour [2]. This concept bears similarities to spin-wave-based photonic memories in solid states or ferromagnetic magnon modes. Advances in controlling dense nuclear spin ensembles relied on dynamic nuclear polarization and reducing their magnetic-field fluctuations [3], as well as the critical step of accessing electron-mediated collective nuclear excitations [4]. The final goal is to combine a controllable electron spin with a tailored nuclear ensemble to realise a nuclear quantum register.

In this talk we will discuss the reversible quantum state transfer between an electron spin qubit and a collective excitation of 13,000 nuclear spins in a GaAs QD [5]. We present a method to construct a collective nuclear state by polarizing Ga isotopes. Consequently, one of the Ga isotopes is set in our register's ground state, forming a coherent nuclear dark state with 60% polarization. Our electro-nuclear coherent control facilitates arbitrary state transfers from the electron spin qubit to the single magnon spin-wave states. We show that the register reaches a storage time of 130(16) μs, aligned with limitations from residual quadrupolar broadening.

References

[1] B. Urbaszek, et al., Rev. Mod. Phys. 85, 79. 2013
[2] J. M. Taylor, C. M. Marcus, and M. D. Lukin. Phys. Rev. Lett. 90, 206803. 2003
[3] A. Högele, et al., Phys. Rev. Lett. 108, 197403. 2012
[4] D. A. Gangloff, et al., Science 364, 62. 2019
[5] M. Hayhurst Appel, et al., Nat. Phys. 2024