Paving the Way for Large-Scale Quantum Information Processing with more than 10 000 Multiqubit Entangled Nuclear Spin States in Hyperpolarized Molecular Solids

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Quantum entanglement has been realized on a variety of physical platforms including photons, quantum dots, trapped atomic ions, superconductors, and point defects in diamond and silicon carbide. Here we introduce specific molecular solids as promising alternative platforms. Our model system is triplet pentacene in a host single crystal at level anticrossing (LAC) conditions. First, a laser pulse generates the triplet state and initiates entanglement between an electron spin and 14 hyperfine coupled proton spins. This gives rise to large nuclear spin polarization. Subsequently, a resonant high-power microwave pulse disentangles the electron spin from the nuclear spins. Simultaneously, high-dimensional multiqubit entanglement is formed among the proton spins. We verified the initialization of 2^{14} pure 14-qubit entangled nuclear spin states with an average degree of entanglement of 0.77 ± 0.03 [1].

To address and coherently manipulate the multiqubit entangled states, efficient quantum gates are required. Recently, two related studies appeared that demonstrate the experimental implementation of scalable global or parallel quantum gates in chains of Coulomb-coupled trapped atomic ions [2,3]. In both gates, multiple parallel gate operations are achieved by applying phase- and/or amplitude-modulated laser pulses which introduce a qubit-state-dependent force on each qubit site. Similar gates can also be used in the dipolar coupled nuclear spin systems of the present study by applying properly modulated radio frequency pulses.

To assess the created quantum system, we determine the dimension of the entangled computational (Hilbert) space. Provided that solely inequivalent nuclei are employed, our experiment reaches a Hilbert space dimension of $\dim = 2^{14\times14} \approx 10^{59}$ which is many orders of magnitude larger than the dimension achieved in recent quantum advantage experiments using superconducting qubits [4] ($\dim \approx 10^{16}$) or photons [5] ($\dim \approx 10^{30}$). We therefore expect that the LAC experiment, introduced in this talk, paves the way for large-scale quantum information processing with more than 10 000 multiqubit entangled nuclear spin states. The total of these states depends on the number of $I = \frac{1}{2}$ nuclei in an organic molecule which can be tailored by chemical synthesis.

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