Entanglement distillation between solid-state quantum network nodes

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A future quantum network will rely on the distribution of high-quality entanglement between the network nodes. Unavoidable imperfections during the state generation require methods to boost remote entangled state fidelities via local operations. Entanglement distillation [1,2] (Fig. 1) promises to overcome these obstacles by generating a high-quality entangled state from several raw states that are shared between the network nodes. It has therefore become one of the central building blocks for quantum communication protocols [3,4,5].

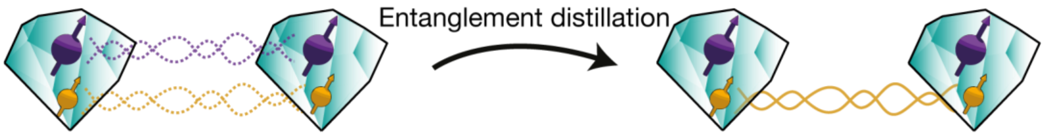

Figure 1. A state of higher quality (right) is distilled from two lower-quality resource states that are shared between spins in remote diamonds.

Here we experimentally demonstrate entanglement distillation on a universal quantum network primitive consisting of two nodes separated by two meters [6]. Our nodes comprise a nitrogen-vacancy (NV) electron spin and an adjacent ^{13}C nuclear spin which is used for state storage. NV centres at cryogenic temperatures are ideally suited for this task due to their spin-selective optical interface and due to recently developed techniques for robust state storage in weakly coupled nuclear spins [7]. The protocol uses the NVs to generate a raw entangled state by overlapping their emission on a beamsplitter. The state is then swapped onto the nuclei and coherently stored during a second round of state generation. Local operations and classical communication distil a higher-quality state once two raw states were successfully generated.

Any demonstration of distillation has to improve on the quality of the raw input states. We generate raw states of the form (for details see [6])

$$(1-\sin^2\theta)\left|\Psi_\phi^\pm\right\rangle\left\langle\Psi_\phi^\pm\right| + \sin^2\theta\,|0,0\rangle\langle 0,0|$$

and pertain full control over θ during state initialization. Here $|\Psi_\phi^\pm\rangle$ are maximally entangled Bell states with an unreferenced internal phase ϕ and an additional phase $(\pm)$ that depends on the detection signature. Figure 2 shows the measured state fidelities of the raw and distilled states for varying degrees of separability in the raw state; i.e. for different θ. Because of the unreferenced internal phase of the raw state, all coherences are washed out. The distilled state (which turns out to be agnostic to ϕ [6]) therefore clearly surpasses the measured raw state in fidelity.

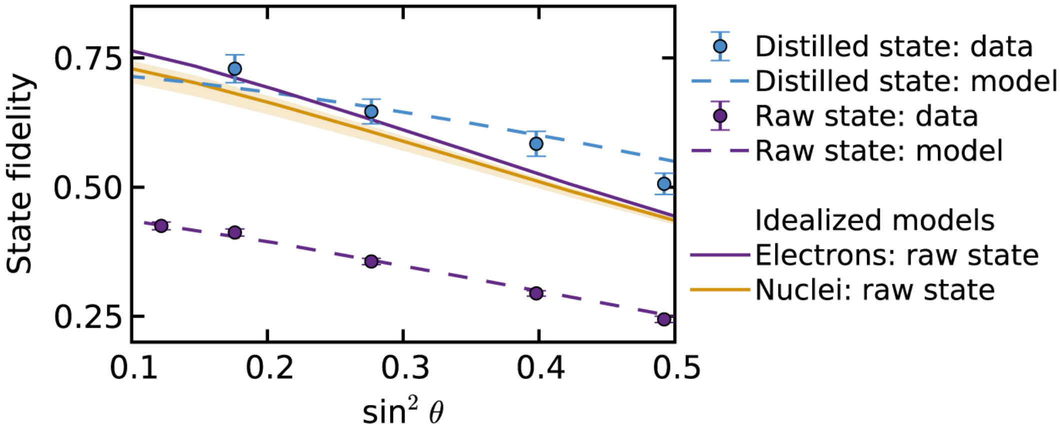

Figure 2. Experimental demonstration of entanglement distillation. The state fidelities of the distilled state (blue) and the raw state (purple) are compared as function of the raw admixture $sin^2\theta$. Additionally idealized models for the raw state are derived (solid lines).

We extend our analysis by modelling the raw state assuming that ϕ was accessible (solid purple and orange lines in Fig. 2). For small separable admixtures (low θ) the gain in fidelity via distillation is offset by local control errors. However, for larger admixtures the distilled state fidelity surpasses the raw state significantly. This demonstrates entanglement distillation on our elementary quantum network.

The shown combination of key capabilities, i.e. generation, storage and processing of remote entangled qubits provides a universal primitive for extended quantum networks. The intra-node functionality can be readily extended as the shown techniques are compatible with recent demonstrations of multi-qubit control in diamond [7,8]. The developed methods therefore prompt the system to the exploration of many-particle entanglement on a multi-node quantum network.

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