Optimal purification of a spin ensemble by quantum-algorithmic feedback

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Abstract: We present a coherent quantum feedback algorithm to purify a mesoscopic spin ensemble at the ultimate level of a single spin. Applying it to a quantum dot narrowed nuclear-spin fluctuations by two orders of magnitude. © 2022 The Author(s)

Purification of a many-body system is crucial to observe its quantum properties. While laser cooling techniques, such as resolved sideband cooling, have been successfully used to purify a system to its ground state, active feedback can prepare a system anywhere in the accessible phase space [1]. Here we present a feedback algorithm that is fully quantum in nature and can be applied to central-spin or central-boson systems. We demonstrate its performance experimentally on an ensemble of ~100,000 nuclear spins interlinked to a central electron spin inside an InGaAs quantum dot and reach record-high electronic coherence times [2].

Our many-body system of nuclear spins is parametrised by the total nuclear polarisation $I_z$ along the quantisation axis of an external magnetic field. The electron spin is coupled to the nuclear spin ensemble and can be controlled optically to stabilise the nuclear polarisation to a chosen lockpoint $I^*_{z}$. The algorithm comprises three steps (Fig. 1):

(i) Sense: As in Ramsey interferometry, a $\pi/2$-pulse brings the electron spin from the initial $|\uparrow\rangle$ state into a sensing configuration, in which its precession frequency is susceptible to the nuclear polarisation due to the collinear hyperfine interaction.

(ii) Exchange: Conditional on the accumulated phase of the electron spin during sensing, a nuclear spin is either flipped up or down using an electro-nuclear flip-flop interaction. This corrects the nuclear polarisation $I_z$ back towards the lockpoint $I^*_{z}$ by one unit.

(iii) Reset: The algorithm is completed by optically pumping the central electron spin to $|\uparrow\rangle$, which irreversibly resets the electron spin to its initial state and primes the system for the next iteration of the algorithm. This step moves entropy from the spin system to the surrounding photonic bath [3].

Fig. 1. Quantum feedback algorithm. A central electron spin is used to purify the polarisation $I_z$ of a nuclear spin ensemble inside a quantum dot. The universal algorithm starts by rotating the central spin into the Bloch equator, where it senses $I_z$ by precession. The accumulated phase information is converted into a nuclear spin flip. In a final step, the central spin is incoherently reset.
Notably the algorithm combines a technique to sense single-spin deviations [4] with the ability of correcting the nuclear polarisation at the single-spin level. These two steps work completely autonomously and do not require extraction of any classical information by measurement. This means the algorithm can be operated without the need for slow electronics and without the effect of measurement backaction.

Fig. 2. Feedback function and nuclear distribution. (a) The resulting feedback function extends over multiple stable points. (b) To purify towards a single stable lockpoint, we swept the sensing time \( \tau \) from 30 ns to 100 ns over 44 iterations of the algorithm. The thus prepared nuclear state \( p(I_z) \) is two orders of magnitude narrower than the thermal state. (c) Keeping the sensing time \( \tau \) constant allows us to explore the multistable regime, (d) showing 11 modes for \( \tau = 140 \) ns.

The average feedback of our algorithm can be described via a feedback function [5] in form of a dynamical rate equation for \( I_z \) (Fig. 2a). A key feature of this feedback function is that it extends over several stable points, at which the accumulated phase during sensing is an integer multiple of \( 2\pi \). The versatility of our feedback allows us to choose to either purify to a combination of stable points or a single mode.

To purify the nuclear ensemble towards a single macrostate \( I^*_z \), we changed the sensing time from one iteration of the algorithm to the next and thereby eliminated the stability for all lockpoints but the central one. Compared to the thermal state, the resulting distribution \( p(I_z) \) was reduced by two orders of magnitude in width – from 882 to 10 (FWHM), which is a factor of 5 away from the fundamental quantum limit of single-spin fluctuations (Fig. 2b). Here we are prevented from reaching this limit because of low electro-nuclear flip-flop fidelity and transverse polarisation fluctuations sensed via a noncollinear hyperfine interaction.

By keeping the sensing time constant and increasing its duration, we tuned our feedback into the multistable regime, which allowed us to prepare the spin ensemble in a combination of different states (Fig. 2c). We demonstrated this in the classical regime with 11 modes (Fig. 2d). But as the algorithm is fully quantum up until the last step when the electron spin is reset, it can in principle be modified to create coherent superpositions of macroscopically different \( I_z \) states, akin to Schrödinger cat states.

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