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Purification at the ultimate limit using quantum superpositions of causal order

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***Abstract*—**Pure states are essential to quantum technologies. We show how generate an unlimited number of pure states by applying a pair of operations in a superposition of their causal order.

Keywords*—purification, refrigeration, HBAC, ICO*

I. Introduction

Many intriguing and useful protocols require pure quantum states – the more, the better. Unfortunately, nature seldom supplies pure states, so we must resort to clever schemes to create them. The "proven" best algorithm for creating arbitrary numbers of pure states is heat-bath algorithmic cooling (HBAC), which produces a probabilistic mixture of n qubits with a generous probability of being completely pure [1]. Protocols employing indefinite causal order (ICO) [2], which circumvent the assumptions [3] used to prove HBAC's optimality, can do significantly better: ICO allows us to herald the creation of arbitrary numbers of pure states without any residual mixedness [4], which can then be used in a variety of quantum technologies.

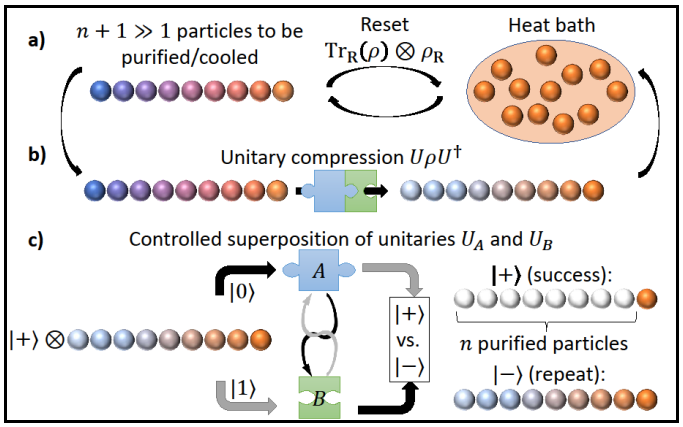

Fig. 1: Schematic of HBAC augmented with ICO. The original protocols repeatedly apply **a)** and **b)**; here, we add the ICO step **c)**. **a)** One particle is replaced by a particle that has thermalized with an external bath. **b)** A unitary operation shuttles entropy from the particles on the left to those on the right, thereby cooling the particles on the left. **c)** A control qubit in a superposition state causes two unitaries to be applied in a superposition of two orders. Measuring the control to be $|+\rangle$ completely purifies all but one particle; measuring the control to be $|-\rangle$ requires a repetition of the protocol. The maximum number of allowed particles is unlimited and we define $|\pm\rangle \propto |0\rangle \pm |1\rangle$ throughout.

II. Heat Bath Algorithmic Cooling

The essential components of HBAC are schematized in Fig. 1**a)** and **b)**. A set of particles to be cooled and thereby purified has one particle exchanged with one that has thermalized with a large heat bath at some fixed, possibly large temperature T. Next, a unitary is applied that rearranges the heat distribution among the particles to be cooled. By serially repeating this process, the overall system approaches a unique ground state, with the following probability distribution in the $\{|g\rangle^{\otimes n}, |g\rangle^{\otimes n-1} \otimes |e\rangle, \cdots, |e\rangle^{\otimes n}\}$ -basis, where all of the particles are considered to be qubits:

$$\boldsymbol{p} = \frac{1-e^{-2\varepsilon}}{1-e^{-(2\hat{}n)2\varepsilon}}\left(1, e^{-2\varepsilon}, e^{-4\varepsilon}, \cdots, e^{-(2^n-1)2\varepsilon}\right).$$

Here, $\varepsilon = (E_e - E_g)/k_B T$ characterizes the energy gap of the qubits and is seldom small enough for $\boldsymbol{p}$ to approximate a pure state.

III. Indefinite Causal Order Enhances Heat-Bath Algorithmic Cooling

We split the unitary transformation U from Fig. 1**b)** into two unitaries U_A and U_B such that both of the products $U_A U_B$ and $U_B U_A$ each reproduce the same transformation on $\boldsymbol{p}$ as does U alone. Using a quantum switch [5], the order in which the unitaries are applied can be controlled by the state of an auxiliary system that can itself be put into a quantum superposition, per Fig. 1**c)**. The state of the control system is then measured to herald the production of n pure ground-state qubits [4]

$$\boldsymbol{p} = (1,0,0,\cdots,0).$$

This process can be repeated until success and, because it can be used to produce an unlimited number of pure states with a success probability largely independent from that number n, the required overhead of a pure control qubit is negligible.

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