Thermodynamics of a minimal algorithmic cooling refrigerator

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Setup: Heat-Bath Algorithmic Cooling in an *NV* Center

— Heat-Bath Algorithmic Cooling (HBAC)

What is it?

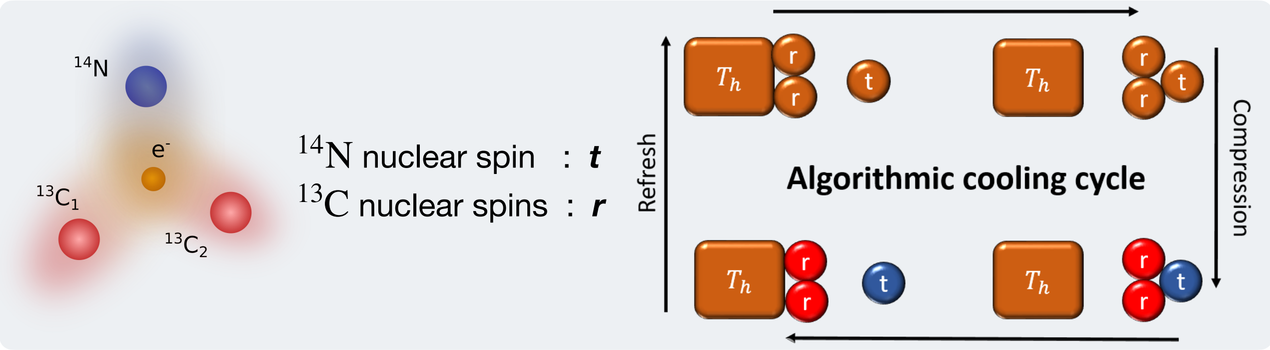
1. Protocol for initializing pure qubits for computation.
2. A thermodynamic device: a refrigerator

— Our Work

Goals:

1. **Improve & Explain** the model behind an experiment that achieves the HBAC cooling limits.[1]
2. **Thermodynamic analysis** of HBAC.

[1] Zaiser, S., Cheung, C.T., Yang, S., Dasari, D.B.R., Raeisi, S. and Wrachtrup, J., 2021. Cyclic cooling of quantum systems at the saturation limit. *npj Quantum Information*, 7(1), pp.1-7.



— Processes

Central electron spin e^-:

1. Interaction mediator in Compression step,
$$U\colon |\overbrace{100}^{trr}\rangle \rightleftarrows |011\rangle\,.$$
2. Thermal bath in the Refresh step,
$$\rho_{trr} \mapsto \mathrm{tr}_{rr}\{\rho_{trr}\} \otimes \rho_{rr}(T_h)\,.$$

$$W = \sum_{i=t,r_1,r_2} \mathrm{tr}\{H_i\, \delta\rho_i\}\,.$$

$$Q = \mathrm{tr}\{H_t\, \Delta\rho_t\}\,.$$

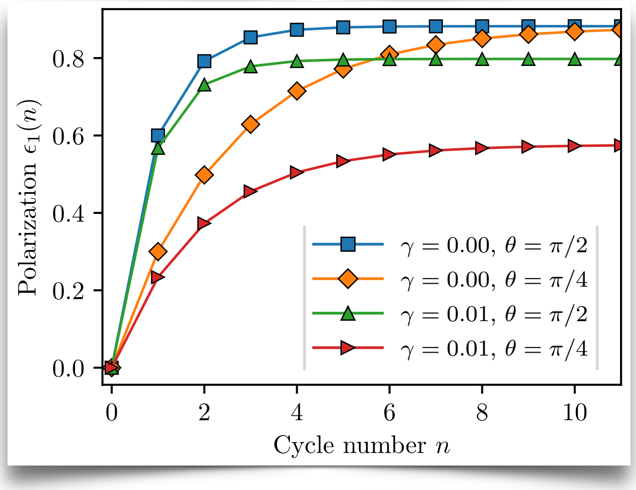
Refrigerator

— The Improved Model

Consider

1. Amplitude-damping towards target excited state ($\{K(\gamma)\}$).
2. "Stochastic activation" of compression ($K(\theta)$).

— Full analytic solution by solving the linear dynamics in Liouville space for any initial polarization $(\epsilon_1, \epsilon_2, \epsilon_3)$ and any (γ, θ).



Increase $\epsilon_1(n)$ means lowering the temperature of the target.

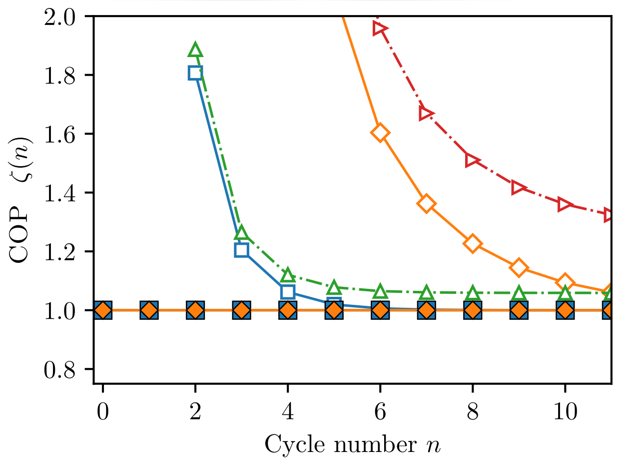
1a) Cooling above reset temperatures $\epsilon_2 = \epsilon_3 = \epsilon_r = 0.6$ towards

$$\epsilon_1(\infty) = \frac{2\epsilon_r}{1+\epsilon_r^2}$$

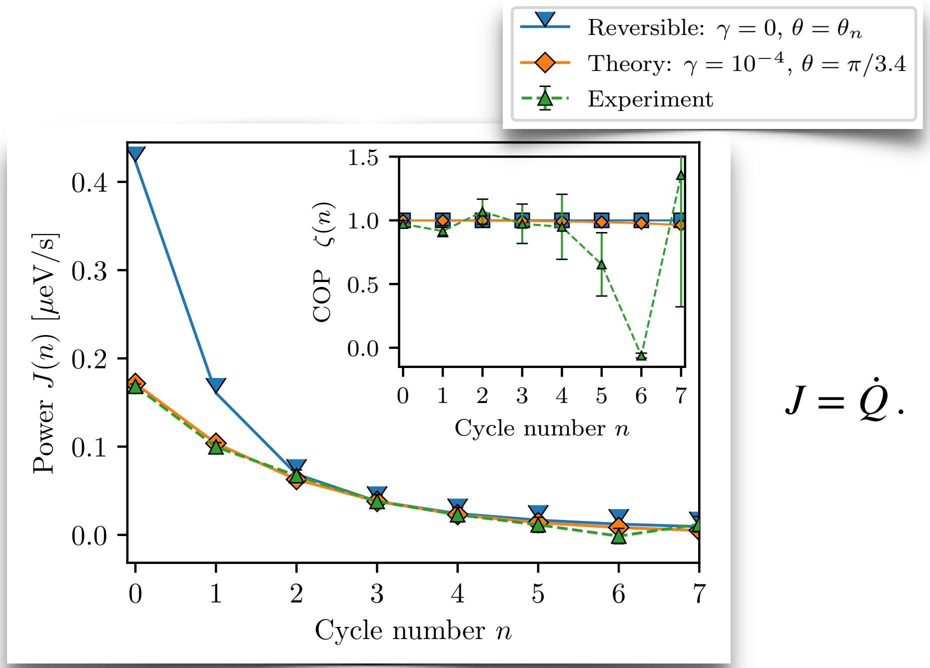
1b) HBAC achieves fundamental thermodynamic bounds

$$\zeta = -\frac{Q}{W},$$

$$\zeta(n) \xrightarrow{\gamma\to 0} 1 = \zeta_C\,.$$



Theory vs Experiment



$$J = \dot{Q}\,.$$

2a)

1. Thermodynamic performance matches the experiment (see Power and COP).
2. Maximal coefficient of performance maintained near cooling limits (compare with *Fig. 1b*).
3. Spin-off: maximal power achieved under protocol $\theta = \theta_n$.

Key results

1. **Generalized cooling limits**
$$\epsilon_1(\infty) = \frac{\epsilon_2+\epsilon_3}{1+\epsilon_2\epsilon_3},$$
2. **Model better fits experimental data.**
3. **Demonstration that HBAC can achieve the Carnot fundamental COP bounds of cooling.**

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