Collective effects enhanced quantum engines

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References

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Letter

Quadratic enhancement in the reliability of collective quantum engines

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Collective-effects-enhanced multiqubit information engines

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Motivation

- Scaling up of quantum machines can be crucial for the development of quantum technologies.
- How do we scale up quantum technologies?
- Do they provide any advantage over single body ones?
- Collective advantages in many-body quantum machines.

Overview

Many-body quantum machines

Interacting many-body quantum machines

- Quantum machines modelled with interacting spin systems:

$$H = -\sum_{r,r'} J_{r,r'}\sigma_r^x\sigma_{r'}^x + \sum_r \vec{h}_r.\vec{\sigma}_r$$

- Many-body effects, such as phase transitions, can play important roles.
- Hilbert space dimension $\sim\ 2^n \implies$ solutions can be highly non-trivial.

Collective effects in many-body quantum machines

- Multiple particles coupled collectively to a bath:

$$H = \sum_r \frac{(\sigma_r^z)^\theta}{n^{\theta-1}} + \lambda\mathcal{B}\otimes\sum_r \sigma_r^x$$

- Non-trivial correlations can develop between the particles, owing to the collective interaction.
- Superextentive scaling of work output in collective engines: $W \sim n^2$.

VM and U. Divakaran, J. Phys.: Condens. Matter **33** (2021) 454001.

Collective effects in many-body quantum machines

Question: How can we develop highly reliable quantum machines?

Reference: N. Jaseem, S. Vinjanampathy and VM, Phys. Rev. A **107**, L040202 (2023); N. Jaseem and V. Mukherjee, Phys. Rev. A **108**, 042219 (2023).

Collective effects in open quantum systems

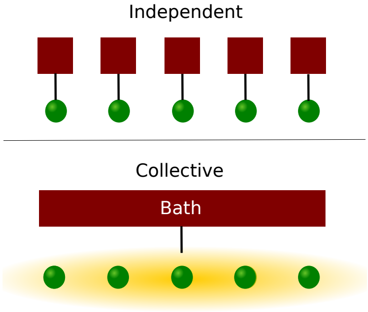

Figure: Independent and collective system-bath coupling

A photonic quantum engine driven by superradiance

Jinuk Kim, Seung-hoon Oh, Daeho Yang, Junki Kim, Moonjoo Lee & Kyungwon An

Nature Photonics **16**, 707–711 (2022) | Cite this article

Abstract

Performance of nano- and microscale heat engines can be improved with the help of quantum-mechanical phenomena. Recently, heat reservoirs with quantum coherence have been proposed to enhance engine performance beyond the Carnot limit even with a single reservoir. However, no physical realizations have been achieved so far. Here we report the first proof-of-principle experimental demonstration of a photonic quantum engine driven by superradiance employing a single heat reservoir composed of atoms and photonic vacuum. Reservoir atoms prepared in a quantum coherent superposition state underwent superradiance as they traversed the cavity. This led to about 40-fold increase in the effective engine temperature, resulting in near-unity engine efficiency. Moreover, the observed engine output power grew quadratically with respect to the atomic injection rate. Our work can be utilized in quantum-mechanical heat transfer as well as in boosting engine powers, opening a pathway to the development of photomechanical devices that run on quantum coherence embedded in heat baths.

Experimental realization $\rightarrow$ atoms in a cavity

J. M. Raimond, P. Goy, M. Gross, C. Fabre, and S. Haroche, Phys. Rev. Lett. **49**, 117 (1982).

The strokes of an Otto cycle

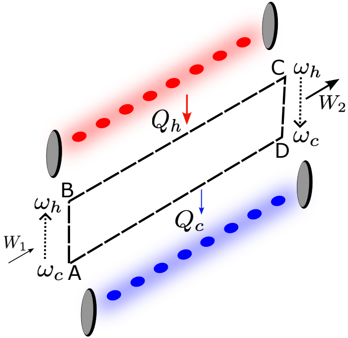

Figure: Independent and collective system-bath coupling

- **D $\rightarrow$ A:** Collective thermalization with cold bath
- **A $\rightarrow$ B:** Unitary quench
- **B $\rightarrow$ C:** Collective thermalization with hot bath
- **C $\rightarrow$ D:** Unitary quench

Work output $W = -(\mathcal{Q}_h - |\mathcal{Q}_c)$;
reliability $r = \langle W \rangle / \sqrt{Var(W)}$; TUR $= \langle \Sigma \rangle / r^2$

R. Kosloff and Y. Rezek, Entropy **19**, 136 (2017).

Collective effects in open quantum systems

Independent Coupling

$$
\begin{aligned}
H_{\text{ind}} &= \sum_r H_r \\
H_r &= \omega \sigma_r^z + \sigma_r^x \otimes B_r + H_{\text{B},r}
\end{aligned}
$$

Collective Coupling

$$
\begin{aligned}
H_{\text{col}} &= \omega \sum_r \sigma_r^z + \left(\sum_r \sigma_r^x \right) \otimes B + H_{\text{B}}. \\
\Longrightarrow H_{\text{col}} &= \omega \mathcal{J}_z + \mathcal{J}_x \otimes B + H_{\text{B}}, \\
\mathcal{J}_\alpha &= \sum_r \sigma_r^\alpha; \quad \alpha = x, y, z
\end{aligned}
$$

Steady states

- Steady states for independent and collective coupling are different.

- Independent coupling $\rightarrow$ uncorrelated states of individual qubits: $\rho^{\rm ss}_{n,{\rm ind}} = \otimes^n_r \rho^{\rm th}_{{\rm ind},r}(\beta)$; eg. $T \rightarrow \infty \implies \langle \sigma^z_r \rangle = 0 \ \forall \ r$.

- Collective coupling $\rightarrow$ correlated states of individual qubits: $\rho^{\rm ss}_{n,{\rm col}} = \sum_{m=-n/2}^{n/2} \frac{e^{-\beta\omega m}}{Z} |\frac{n}{2}, m\rangle\langle\frac{n}{2}, m| \neq \rho^{\rm ss}_{n,{\rm ind}}$;
eg. $T \rightarrow \infty \implies \langle \sum_{r=1}^{n} \sigma^z_r \rangle = 0$.

- Equivalent results for interacting spin s systems with collective system-bath coupling as well: $H_S = \omega(t)\mathcal{J}_z^{\theta}$; $\theta = 1, 2, 3, \ldots$; LMG model.

C. L. Latune, I. Sinayskiy and F. Petruccione, Phys. Rev. Research **1**, 033192 (2019)

Variance and mean

Independent engines

- $C_v \sim n$
- $\langle W \rangle \sim n$
- $\Delta W = \sqrt{\mathrm{Var}\,(W)} \sim \sqrt{n}$
- $r_{ind} = \langle W \rangle / \Delta W \sim \sqrt{n}$

Collective engines

$$\eta \;\to\; \eta_{\mathrm{C}} = 1 - T_c/T_h$$

- $C_v \sim n^2$
- $\langle W \rangle \sim n^2$
- $\Delta W = \sqrt{\mathrm{Var}\,(W)} \sim n$
- $r_{col} = \langle W \rangle / \Delta W \sim n$

Conclusion

Collective effects make engines more reliable! $\lambda_r = \frac{r_{col}^2}{r_{ind}^2} \sim n$

W. Niedenzu and G. Kurizki, New J. Phys. **20** (2018) 113038; N. Jaseem, S. Vinjanampathy and VM, Phys. Rev. A **107**, L040202 (2023)

Collective effects with interaction

The working medium consists of multiple interacting or non-interacting identical spin s particles, such as the Lipkin-Meshkov- Glick model (Nuclear Physics, **62**, 188 (1965)).

$$H = \omega(t)\left[\frac{1}{n}(\mathcal{J}_x^2 + \mathcal{J}_y^2) + \gamma\mathcal{J}_z\right],$$

or x-body inter-particle interactions,

$$H = n\omega(t)(\mathcal{J}_z/n)^x \quad \text{for } x = 1, 2, 3....$$

Required state state:

$$\rho_{ss} = \sum_{m=-ns}^{ns} \frac{\exp\left[-\beta\epsilon_m\right]}{Z} |ns, m\rangle\langle ns, m|.$$

Collective effects in open quantum systems

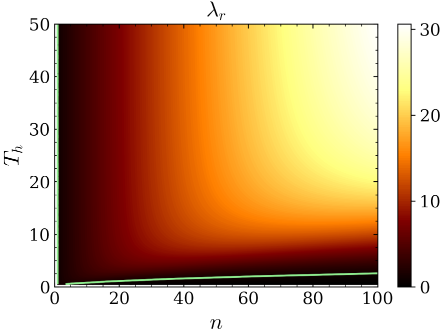

Figure: Quadratic enhancement in reliability $\lambda_r = r_{col}^2 / r_{ind}^2$ for collective engines

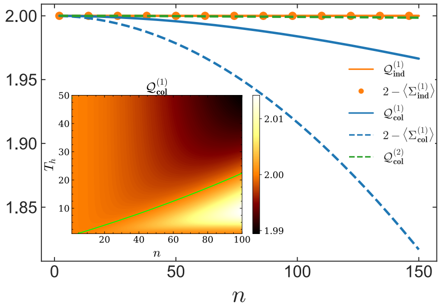

Figure: $\mathcal{Q}_{col} < \mathcal{Q}_{ind}$

Thermodynamic uncertainty ratio: $\mathcal{Q} = \langle \Sigma \rangle / r^2; \quad \langle \Sigma \rangle = -\left(\frac{\langle Q_h \rangle}{T_h} + \frac{\langle Q_c \rangle}{T_c} \right)$

Quantum Information Engines

Quantum information engines

$$H = \frac{\hbar\omega}{2}\sum_{j=1}^{N}\sigma_j^z = \frac{\hbar\omega}{2}\mathcal{J}_z$$

Steps of a multi-quibit quantum information engine

- Initialize the qubits in a thermal state in the collective / independent basis.
- Measure the total magnetization m; $m \lesseqqgtr 0$.
- $m > 0 \implies$ useful state; a majority of the spins are up.
- Apply unitary to flip all the spins to extract work.
- $m \leq 0 \implies$ not a useful state; go back to step 1, i.e., initialize the system in the thermal state in the collective / independent basis.

Collective quantum information engines

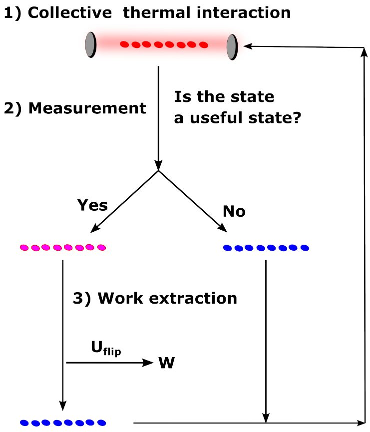

Figure: Steps of a collective quantum information engine

Collective quantum information engines

Collective quantum heat and information engines

- In contrast to heat engines, here only the populations in the $m > 0$ states are relevant for work extraction.
- Here collective advantages at high temperatures stem from higher occupation probabilities of the higher energy states.

Collective advantage in work output

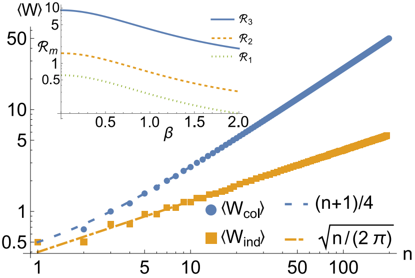

Figure: Quadratic advantage in work output due to collective effects; $\mathcal{R}_m = p_m^{(col)}/p_m^{(ind)}$.

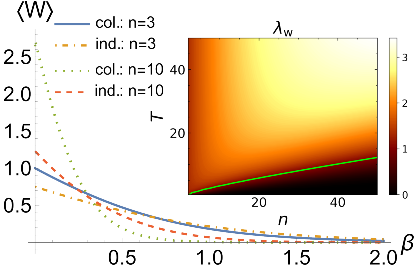

Figure: Quadratic advantage in work output due to collective effects; $\lambda_W = \langle W_{\rm col}\rangle / \langle W_{\rm ind}\rangle$.

Collective quantum information engines at finite temperatures

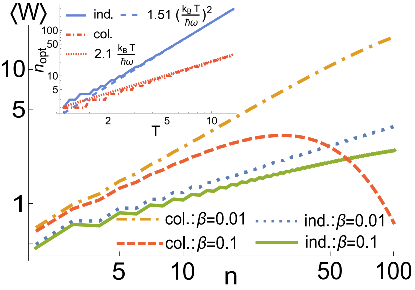

Figure: Optimal system size for maximal work output: $n_{\rm opt}^{\rm (ind)} \sim (k_{\rm B}T/\hbar\omega)^2$; $n_{\rm opt}^{\rm (col)} \sim k_{\rm B}T/\hbar\omega$.

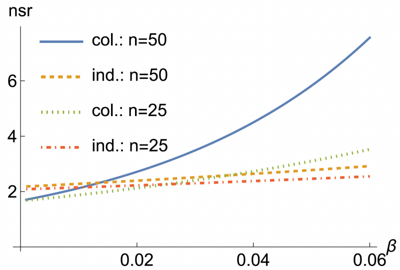

Figure: Collective effects reduce fluctuations.

Conclusions

- Collective effects can enhance the work output and reliability in quantum heat and information engines.
- Collective advantages in quantum heat engines stem from enhancement in specific heat.
- Collective advantages in quantum information engines stem from higher occupation probabilities of the $m > 0$ states.
- Collective advantages are most pronounced for high temperatures and large n.

Thank You