Observation and Modulation of the Quantum Mpemba Effect on a Superconducting Quantum Processor

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Contents

快速摘要（**TL;DR**）

1. 3–5 行总结核心思想、主要贡献、适用场景与效果。
2. 一句话亮点：例如“提出了一个轻量级的...，在 X 数据集上将误差降低了 Y%”。

1 背景介绍

1. In non-equilibrium quantum many-body systems, the quantum Mpemba effect (QME) emerges as a counterintuitive phenomenon: systems exhibiting greater initial symmetry breaking restore symmetry faster than those with less.
2. **Three major research fields**
   - The Mpemba effect, originally observed as faster freezing of hotter water than colder water under identical conditions, represents a counterintuitive non-equilibrium phenomenon with debated mechanisms.
   - In open quantum systems interacting with an external environment through Markovian and non-Markovian processes. It is dominated by classical fluctuations, resembling the classical Mpemba effect
   - In isolated quantum systems governed by intrinsic quantum dynamics. It is driven by intrinsic quantum fluctuations. **In isolated quantum systems, the quantum Mpemba effect (QME) manifests as a remarkable phenomenon: subsystems with greater initial symmetry breaking restore symmetry faster under a symmetry-preserving Hamiltonian.** The type of system under the study:
     – Quasiparticle framework for integrable systems that include 1D or 2D models.
     – In chaotic systems using random and dualunitary circuits.
     – Non-ergodic contexts, such as many-body localized (MBL) systems
3. 伪代码/核心算法要点

2 实验方案

1. Here, we report the observation and control of QME using a superconducting processor featuring a unique fully connected, tunable-coupling architecture that enables precise modulation from short- to long-range interactions.
2. 调控参量
   (a) interaction range
   (b) potential engineering

(c) initial state selection

i. 方法类别（模型/算法/理论证明/系统实现）

ii. 主要结果/指标

iii. 可复现性：代码/数据/预训练模型（有/无/部分）

3 结论

i. In strong **short-range** coupling regimes, EA crossovers during quenches from **tilted Néel states** confirm the presence of QME.

ii. In **intermediate coupling regimes**, synchronized EA and entanglement entropy dynamics reveal the **suppression** of QME.

iii. QME reemerges with the introduction of on-site linear potentials or quenches from tilted ferromagnetic states, the latter proving robust against on-site disorder.

4 关键公式与推导

Entanglement asymmetry (EA), defined as the relative entropy

$$\Delta S_A(t) = S\left(\rho_{A,Q}(t)\right) - S\left(\rho_A(t)\right) \tag{1}$$

where ρ_A is the reduced density matrix of subsystem A, $\rho_{A,Q} = \sum_q \Pi_q \rho_A \Pi_q$ denotes its projection onto the conserved charge Q_A eigenspaces, and $S\left(\rho_A\right)$ is the von Neumann entropy of ρ_A.

$\Delta S_A(t)$ captures the distance of ρ_A from a symmetric state ρ_A, Q including contributions from non-local correlations within subsystem A that violate the symmetry.

This makes it a natural order parameter for non-equilibrium dynamics, offering a fresh perspective on thermalization compared to traditional metrics like entanglement entropy.

5 实验与结果

i. 数据集、评价指标、基线方法

ii. 主要实验表格或图（可插入图片）

Figure 1: 示例：结果对比图（替换为真实图片）

6 优点与局限

i. 优点：列出 3-5 点

ii. 局限：理论/实践/资源/泛化等问题

iii. 可信度评估：是否做了消融、显著性检验、多个 seed 等

7 灵感与后续方向

i. 可借鉴的技巧与工具

ii. 可尝试的改进点

iii. 与自己研究的结合点（短期/中期）

8 实现/复现笔记

i. 关键超参表
ii. 训练资源与耗时
iii. 遇到的问题与解决方案（环境、数据预处理、模型不收敛等）

9 复现检查表

- ☐ 数据集下载与预处理
- ☐ 代码实现（模型/训练/评估）
- ☐ 与论文结果对齐
- ☐ 随机种子与多次实验

10 参考与延伸阅读

列出文章引用或推荐的延伸阅读（手动列出或使用 BibTeX）。

11 个人笔记 / TODO

i. 待实现模块：
ii. 待阅读参考文献：
iii. 需要讨论的问题：

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