Experimental Investigation of Structured Energy Return (SER) Feedback in a Superconducting Qubit-Cavity System

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Abstract

This experiment investigates quantum work extraction (ergotropy) and coherence retention in a superconducting two-qubit Jaynes-Cummings system with feedback control. By implementing adaptive feedback in a real superconducting circuit, we aim to test whether coherence-based energy retention outperforms entanglement-based strategies in preserving extractable work. Our experimental setup uses a transmon qubit-cavity system in a dilution refrigerator and applies feedback with a tunable delay (τ_f) to analyze its impact on system coherence and work extraction.

1 Introduction

Quantum thermodynamics examines energy conversion in quantum systems, where coherence and entanglement significantly impact energy extraction. The Jaynes-Cummings (JC) model describes the interaction of a two-level system (qubit) with a cavity mode, exhibiting Rabi oscillations. However, in real quantum devices, decoherence rapidly destroys quantum correlations, limiting work extraction.

This experiment seeks to validate the **Structured Energy Return (SER) hypothesis** in a real superconducting qubit-cavity system. Unlike traditional feedback schemes, SER-based control preserves coherence rather than just suppressing noise. We will investigate:

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- How feedback delay (τ_f) impacts coherence and work retention.
- Whether coherence-based feedback improves ergotropy over entanglement-based methods.
- The relationship between qubit-cavity coupling (g), feedback strength (β), and energy retention.

2 Experimental Setup

2.1 Hardware Implementation

The experiment will be conducted using a superconducting transmon qubit coupled to a microwave cavity. The system will be housed inside a dilution refrigerator (10-15mK) to minimize thermal noise. The setup consists of:

- **Superconducting qubits** (IBM-Q or Rigetti hardware)
- **Microwave cavity resonators** for Jaynes-Cummings interaction
- **Classical control electronics** (FPGA-based feedback implementation)
- **Measurement setup** for state tomography

2.2 System Hamiltonian

The system Hamiltonian follows the Jaynes-Cummings model:

$$H = \frac{\hbar\omega_q}{2}\sigma_z + \hbar\omega_c a^\dagger a + \hbar g(\sigma_+ a + \sigma_- a^\dagger) \tag{1}$$

where:

- ω_q and ω_c are qubit and cavity frequencies.
- g is the coupling strength.
- σ_+, σ_- are the qubit raising/lowering operators.
- $a^\dagger$, a are the cavity photon creation/annihilation operators.

Feedback is introduced with a control Hamiltonian:

$$H_{FB} = \beta(\sigma_x \otimes \sigma_x + (a + a^\dagger)) \tag{2}$$

where β is an adaptive parameter based on system concurrence.

2.3 Feedback Mechanism

The system will be initialized in a Bell state, and a feedback loop will be applied after a tunable delay τ_f. The feedback strength β is dynamically adjusted based on concurrence:

$$F(\rho) = (1 - C)e^{-C} \tag{3}$$

where C is the concurrence of the two-qubit reduced density matrix.

3 Experimental Procedure

3.1 Step 1: System Initialization

- Prepare the qubit-cavity system in a Bell state.
- Use a microwave drive to simulate Rabi oscillations.

3.2 Step 2: Feedback Application

- Apply feedback control with varying delay times (τ_f).
- Use FPGA-based real-time measurement to estimate system concurrence.
- Dynamically adjust feedback strength (β) based on concurrence.

3.3 Step 3: Measurement and Data Collection

- Perform Quantum State Tomography (QST) to reconstruct the system's density matrix.
- Compute:
  - Concurrence C (Entanglement measure)
  - Ergotropy W_{ex} (Extractable Work)
  - Cavity photon number $\langle n \rangle$
- Analyze how feedback strength and delay impact coherence and work extraction.

4 Expected Results

- Delayed feedback should enhance work retention compared to uncontrolled evolution.
- Ergotropy and concurrence may not be strictly correlated, indicating coherence-based correlations play a role.
- An optimal feedback delay (τ_f) exists that maximizes extractable work.
- Superconducting qubit data should match numerical simulations from `ah.py`.

5 Conclusion and Future Work

This study could validate feedback-controlled quantum work extraction using superconducting qubits. Future directions include:

- Testing SER feedback on larger qubit arrays.
- Exploring alternative feedback functions based on coherence instead of concurrence.
- Real-world applications in quantum heat engines and quantum batteries.

6 References

1. Jaynes, E.T., & Cummings, F.W. (1963). *Comparison of quantum and semiclassical radiation theories with application to the beam maser.* IEEE Transactions on Information Theory.
2. Wallace, R. (2025). *Structured Energy Return in Quantum Systems: Extended Analysis.* arXiv preprint.