Experimental Proposal for Testing the Structured Energy Return (SER) Model in Quantum Systems

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Abstract

The Structured Energy Return (SER) model has been proposed as a feedback-based mechanism for mitigating quantum decoherence. This document outlines three feasible experimental approaches to validate the SER model in real-world quantum systems: (1) superconducting qubits in circuit QED, (2) trapped ion qubits in a Paul trap, and (3) neutral atom arrays with Rydberg excitations. We describe the required setup, methodology, observables, and expected outcomes for each experiment.

1 Introduction

Quantum decoherence remains a fundamental challenge in quantum information science. The SER model proposes a structured feedback mechanism to reshape decoherence dynamics, potentially preserving coherence and delaying entropy increase in open quantum systems.

This proposal details three experimental platforms to test SER:

1. Superconducting qubits coupled to a high-Q microwave cavity (circuit QED).
2. Trapped ion qubits in a Paul trap with motional phonon modes.
3. Neutral atom arrays using Rydberg-mediated feedback.

Each approach is designed to measure SER's ability to mitigate decoherence and sustain quantum coherence.

2 Superconducting Qubits in Circuit QED

2.1 Experimental Setup

- **Superconducting qubit:** Transmon or flux qubit.
- **Microwave cavity:** High-Q resonator coupled to the qubit.
- **Feedback control:** Tunable microwave fields controlled via FPGA.
- **Observables:** Coherence, purity, and entropy evolution.

2.2 System Hamiltonian

The system follows the Jaynes–Cummings Hamiltonian:

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

where ω_q and ω_c are the qubit and cavity frequencies, g is the coupling strength, and Ω represents external driving.

The SER-modified Lindblad equation includes a feedback term:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H,\rho] + \gamma L\rho L^\dagger - \frac{1}{2}\{L^\dagger L, \rho\} + \beta F(\rho)(I-\rho)L\rho L^\dagger(I-\rho) \tag{2}$$

2.3 Expected Results

- Without SER: Coherence decays exponentially.
- With SER: Coherence stabilizes or is partially restored.
- Entropy reshaping is observed, differing from monotonic increase.

3 Trapped Ion Qubits in a Paul Trap

3.1 Experimental Setup

- **Qubit:** Hyperfine states of $^{171}Yb^+$ or $^{40}Ca^+$.
- **Phonon mode:** Acts as an analog of the cavity field.
- **Feedback control:** Laser-driven interactions.
- **Observables:** Quantum state tomography, coherence decay.

3.2 System Hamiltonian

Trapped-ion dynamics are described by:

$$H = \frac{\omega_q}{2}\sigma_z + \omega_m b^\dagger b + g(\sigma^+ b + \sigma^- b^\dagger) + \Omega_L\sigma_x \tag{3}$$

where ω_m is the phonon mode frequency and b represents motional excitations.

3.3 Expected Results

- SER feedback maintains coherence longer than in normal Lindblad evolution.
- Measurable entropy suppression effects.
- Slower decoherence compared to superconducting qubits.

4 Neutral Atom Arrays with Rydberg Excitations

4.1 Experimental Setup

- **Qubit:** Alkali atoms (^{87}Rb, ^{133}Cs).
- **Rydberg states:** Serve as cavity-like interaction modes.
- **Feedback control:** Optical tweezers and coherent laser fields.
- **Observables:** Rabi oscillations, coherence stabilization.

4.2 System Hamiltonian

Rydberg-mediated interactions modify the qubit Hamiltonian:

$$H = \frac{\omega_q}{2}\sigma_z + \omega_r n_r + g_r(\sigma^+ n_r + \sigma^- n_r^\dagger) + \Omega\sigma_x \tag{4}$$

where n_r represents the Rydberg-excited state.

4.3 Expected Results

- SER feedback sustains coherence in multi-atom arrays.
- Enables scalability to entangled qubit systems.

5 Comparison of Platforms

Platform	Control Method	Coherence Time	Feasibility
Superconducting Qubits	Microwave feedback	10–100 μs	Very High
Trapped Ions	Laser feedback	Seconds–minutes	High
Neutral Atom Arrays	Rydberg-mediated	Milliseconds	Moderate

Table 1: Comparison of experimental platforms for SER testing.

6 Conclusion

This proposal outlines three experimentally feasible approaches for testing the SER model. The circuit QED platform provides the most immediate testbed, while trapped ions and neutral atom arrays offer advantages in coherence time and scalability. A successful implementation of SER feedback could provide significant advances in quantum error mitigation.

References

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