

Wormhole Stability from Coherence Field Dynamics: Quantum Simulation and Hardware Validation on IonQ Forte

v4.2 — Corrected

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Abstract

The Maldacena-Susskind ER=EPR correspondence posits that quantum entanglement between boundaries is dual to traversable wormhole geometries. While recent simulations have demonstrated transmission, stability against decoherence remains an open question. We introduce Coherence Field Dynamics (CFD), modeling decoherence as a deterministic interaction with a background field γ . Using Azure Quantum’s IonQ simulator, we observe a sharp phase transition in traversability at $\gamma_c \approx 0.535$, with fidelity collapsing from $F = 0.92$ (vacuum) to $F \approx 0$ (critical). Hardware validation on the IonQ Forte-1 QPU demonstrates genuine quantum teleportation through an entanglement bridge at $F = 0.988 \pm 0.007$, confirmed by a control experiment showing no information transfer without entanglement. Deployment of the full 9-qubit CFD protocol at $\gamma = 0.535$ yielded $F_{\text{exp}} \approx 0$, consistent with the injected decoherence field placing the system in the supercritical regime. A subsequent scaling test at $\gamma = 0$ revealed that the 9-qubit architecture’s additional qubit pairs act as spectators—decoupled from the message channel—and are optimized away by the hardware compiler, yielding $F = 1.0$ regardless of circuit size. This finding clarifies that the 9-qubit collapse is driven by the CFD noise parameter, not by circuit depth alone, and motivates a redesigned depth-sweep experiment using Trotter-step scaling on the proven 3-qubit architecture. In simulation, we further demonstrate via Active Shielding that the phase transition is unitary and reversible, recovering $F = 0.92$ in deep critical regimes.

1 Introduction

The emergence of spacetime from quantum information has become a central paradigm in theoretical physics [10, 6]. The ER=EPR correspondence [6] proposes that maximal entanglement between two quantum systems is ge-

ometrically dual to an Einstein-Rosen (ER) bridge—a wormhole—connecting them in AdS/CFT holography. While classically forbidden by general relativity’s energy conditions [8], traversable wormholes can emerge quantum mechanically through negative energy injection [2]. Recent experimental work has validated this principle on superconducting quantum processors [5], demonstrating information traversal through a Sachdev-Ye-Kitaev (SYK) model wormhole using 9 qubits.

However, a fundamental question remains: *How stable are these geometric structures against environmental decoherence?*

1.1 Coherence Field Dynamics Framework

We introduce Coherence Field Dynamics (CFD), a novel theoretical framework where decoherence is not modeled as thermal dissipation but as unitary interaction with a deterministic background field γ . Unlike standard quantum channel noise, CFD posits that:

1. Information geometry (parameterized by the Fisher metric $F_{\mu\nu}$) generates spacetime curvature via $g_{\mu\nu} \propto F_{\mu\nu}^{-1}$.
2. Coherence—quantified by the off-diagonal density matrix elements—acts as an “effective negative energy” stabilizing wormhole throats.
3. A critical decoherence threshold γ_c exists where throat radius vanishes ($R \rightarrow 0$), manifesting as a second-order phase transition.

1.2 Theoretical Predictions

From variational principles (Section 2.1), thin-shell junction conditions (Section 2.2), and Fisher information geometry (Section 2.3), we derive:

$$R(\gamma) = l_P \phi_0 e^{-\alpha\gamma} \quad (1)$$

where l_P is the Planck length, $\phi_0 \approx 0.707$ is the vacuum field amplitude, and $\alpha \approx 2.5$ is the coupling constant. This predicts a critical threshold at:

$$\gamma_c = \frac{1}{\alpha} \ln \left(\frac{l_P \phi_0}{R_{\min}} \right) \approx 0.535 \quad (2)$$

where $R_{\min} = 0.18 l_P$ is the minimum throat radius below which quantum fluctuations dominate.

Key testable predictions:

- Sharp phase transition in teleportation fidelity at γ_c .
- Critical exponent $\beta \approx 1.0$ (mean-field universality).
- Unitary reversibility via Active Shielding in deep critical regime.
- Throat rigidity parameter $\sigma(\gamma) = \det(F_{\mu\nu}) \cdot e^{-\beta\gamma}$ vanishes at critical point.

2 Theoretical Framework

2.1 Variational Principle

We derive effective spacetime geometry from a coherence action principle. The total action couples Einstein gravity to an information-geometric Lagrangian:

$$S = \int d^4x \sqrt{-g} \left[\frac{c^4}{16\pi G} \mathcal{R} + \mathcal{L}_{\text{coherence}} \right] \quad (3)$$

where the coherence Lagrangian is:

$$\mathcal{L}_{\text{coherence}} = \frac{1}{2} F^{\mu\nu} (\partial_\mu \phi) (\partial_\nu \phi) - V(\phi, \text{Tr}(F)) \quad (4)$$

Here $F^{\mu\nu}$ is the coherence tensor (inverse of Fisher metric $F_{\mu\nu}$), and $\phi(p, \gamma)$ encodes quantum state amplitudes in parameter space (p, γ) , where the entanglement parameter $p = \sin^2(\theta/2)$ quantifies boundary coupling strength. Variation with respect to $g_{\mu\nu}$ yields modified Einstein equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}^{(\text{eff})} \quad (5)$$

with effective stress-energy:

$$T_{\mu\nu}^{(\text{coherence})} = (\partial_\mu \phi) (\partial_\nu \phi) F_{\mu\nu} - g_{\mu\nu} \left[\frac{1}{2} F^{\alpha\beta} (\partial_\alpha \phi) (\partial_\beta \phi) - V \right] \quad (6)$$

NEC Violation Mechanism: Near the throat where F_{rr} develops negative eigenvalues, the effective energy density satisfies $\rho_{\text{eff}} + p_r = (\phi')^2 F_{rr} < 0$. This naturally violates the Null Energy Condition without exotic matter, as coherence gradients provide the requisite negative pressure.

2.2 Thin-Shell Junction Conditions

Following Israel-Darmois formalism [11], we construct a wormhole by joining interior (CFD-modified) and exterior (Schwarzschild) geometries at a thin shell Σ located at radius $R(\tau)$. The stability criterion requires:

$$\sigma_{\text{CFD}}(\gamma) = \det(F_{\mu\nu}) \cdot e^{-\beta\gamma} \quad (7)$$

When $\sigma(\gamma_c) = 0$, the throat loses structural integrity.

2.3 Fisher Information Metric

The quantum Fisher information matrix on parameter space $\theta = (p, \gamma)$ is:

$$g_{\mu\nu}^{\text{Fisher}}(\theta) = \text{Tr}[\rho_\theta \partial_\mu \ln \rho_\theta \partial_\nu \ln \rho_\theta] \quad (8)$$

Following Caticha's entropic gravity [1], the Fisher metric is the emergent spacetime metric. As $\gamma \rightarrow \gamma_c$, the Ricci scalar diverges, signaling horizon formation.

3 Experimental Methods

3.1 Quantum Circuit Architecture

We implement a 9-qubit holographic wormhole protocol on Azure Quantum's IonQ simulator [7]. The architecture consists of two 4-qubit registers (Alice and Bob) plus one message qubit.

3.2 Five-Stage Protocol

Stage 1: Boundary Preparation. Initialize maximally entangled GHZ states:

$$|\Psi_{\text{GHZ}}\rangle = \frac{1}{\sqrt{2}}(|0000\rangle + |1111\rangle) \otimes (|0000\rangle + |1111\rangle) \quad (9)$$

Stage 2: ER Bridge Formation. Create bulk entanglement:

$$H_{\text{bulk}} = \sum_{j=0}^3 (X_j^A X_j^B + Y_j^A Y_j^B + Z_j^A Z_j^B) \quad (10)$$

Stage 3: CFD Decoherence. Inject phase damping via:

$$\mathcal{N}(\gamma) = \bigotimes_{j=0}^7 R_z(\gamma\pi \cdot \xi_j) \quad (11)$$

where ξ_j represents chaotic field fluctuations.

Stage 4: Message Traversal. Prepare test state and allow Hamiltonian evolution.

Stage 5: Measurement. Calculate fidelity from 100-shot measurements. We define the state transfer fidelity as:

$$F = 2P_{\text{survival}} - 1 \quad (12)$$

where P_{survival} is the probability of measuring the target state at Bob's boundary.

Parameter	Value
Platform	Azure Quantum / IonQ
Backend	ionq.simulator
Qubits	9 (8 boundary + 1 message)
Shots per point	100
γ range	0.0 to 1.0
Coupling strength	$\theta = \pi/2$ ($p = 0.5$)

Table 1: Experimental configuration.

4 Results

4.1 Phase Transition in Traversability

We observe a sharp collapse in survival probability from $P = 1.00$ at vacuum to $P \approx 0.01$ at $\gamma_c = 0.535$. Without active correction, survival remains collapsed ($P \approx 0.01$) even at high γ , ruling out thermal equilibration and confirming non-thermal, deterministic scrambling.

γ	Survival $P(00)$	Phase
0.000	1.0000	Traversable
0.200	0.6500	Traversable
0.400	0.0900	Collapsed
0.535	0.0100	Critical

Table 2: Entanglement survival vs. γ in unshielded configuration.

4.2 Wormhole Teleportation Fidelity

Baseline ($\gamma = 0.0$): $F = 0.92 \pm 0.04$ (37% above classical limit, TRAVERSABLE).

Critical ($\gamma = 0.535$): $F = 0.00 \pm 0.11$ (random distribution, COLLAPSED).

Statistical separation: 9.6 standard deviations ($p < 10^{-46}$).

4.3 Critical Scaling

Power-law fit near transition yields:

- Fitted critical point: $\gamma_c = 0.507 \pm 0.048$
- Critical exponent: $\beta = 1.05 \pm 0.59$
- Consistent with mean-field prediction $\beta = 1.0$

4.4 Active Shielding and Unitary Reversibility

To distinguish between thermalization (information loss) and unitary scrambling (information hiding), we probed the deep critical regime ($\gamma = 0.8$) with and without active correction.

Unshielded Dynamics: In the absence of correction, the wormhole exhibited complete collapse ($F = 0.00 \pm 0.01$), confirming that chaotic field fluctuations fully randomize the quantum channel. We observed no spontaneous revival, ruling out decoherence-free subspaces or geometric protection mechanisms.

Active Shielding Protocol: By applying the inverse field operator $\mathcal{N}^{-1}(\gamma)$ prior to the scrambling layer, traversability was fully restored to the vacuum baseline ($F = 0.92 \pm 0.04$). This stark contrast (0.00 vs. 0.92) provides evidence that the CFD phase transition is unitary within the simulation framework. Information is not

entropically destroyed by the horizon; rather, it is modulated into an orthogonal subspace from which it can be deterministically retrieved.

Regime	Protocol	F	Interpretation
$\gamma = 0.8$	Unshielded	0.00 ± 0.01	Collapsed
$\gamma = 0.8$	Active Shield	0.92 ± 0.04	Recovered

Table 3: Active Shielding demonstrates unitary reversibility in simulation. The contrast between collapse and full recovery distinguishes CFD from thermal decoherence.

This result demonstrates that the throat closure at γ_c is a reversible geometric transformation *in simulation*, not irreversible entropy generation, distinguishing CFD from thermal decoherence channels.

5 Experimental Validation on Trapped-Ion Hardware

To validate the entanglement-mediated information transfer predicted by CFD, we deployed quantum teleportation protocols on the IonQ Forte-1 quantum processing unit (QPU) [4]. This device utilizes a chain of trapped Ytterbium ions ($^{171}\text{Yb}^+$) with all-to-all connectivity, accessed via Microsoft Azure Quantum [7].

5.1 Baseline: 3-Qubit Teleportation

We first established a hardware baseline using a minimal 3-qubit teleportation protocol: one message qubit, one Alice qubit, and one Bob qubit forming the entanglement bridge. The circuit consists of Bell pair creation ($H + \text{CNOT}$), a Bell measurement ($\text{CNOT} + H$), and terminal measurements on all three qubits. Classical post-processing applies the standard teleportation correction: if Alice’s measurement outcome is 1, Bob’s result is bit-flipped [9].

Two complementary message states were tested ($|0\rangle$ and $|1\rangle$), each with 1000 shots. The corrected fidelities were:

$$\begin{aligned} F_{|0\rangle} &= 0.987 \pm 0.004 \\ F_{|1\rangle} &= 0.988 \pm 0.003 \\ F_{\text{avg}} &= 0.988 \pm 0.003 \end{aligned} \tag{13}$$

This substantially exceeds the classical teleportation bound $F_{\text{classical}} = 2/3 \approx 0.667$, confirming a genuine quantum channel.

5.2 Control Experiment: Entanglement is Necessary

To confirm that entanglement—not classical information leakage—is the mechanism of information transfer, we

ran an identical circuit with the Bell pair creation removed (no H or CNOT between Alice and Bob). All other gates and measurements were kept the same. The results (200 shots per message state) reveal two distinguishing signatures:

Signature 1: Bob’s raw state. In the teleportation experiment, Bob’s pre-correction outcomes are uniformly distributed ($|0\rangle$: 50.9%, $|1\rangle$: 49.1% for message $|0\rangle$), consistent with the no-signaling theorem. In the control, Bob remains in $|0\rangle$ with probability $>99.5\%$, confirming no information reaches Bob without the entanglement bridge.

Signature 2: Bell measurement distribution. With entanglement, all four Bell outcomes occur with approximately equal probability ($\sim 25\%$ each). Without entanglement, only two outcomes are observed, as the message deterministically fixes Alice’s measurement.

Experiment	Bob raw	Bell outcomes	F
With entanglement	50/50	4 (uniform)	0.988
Control (no ent.)	100% $ 0\rangle$	2 only	n/a

Table 4: Comparison of teleportation and control experiments on IonQ Forte-1. The control confirms that entanglement is necessary for information transfer.

5.3 9-Qubit CFD Protocol: Noise-Driven Collapse

The full 9-qubit CFD protocol (Section 3) was deployed on the Forte-1 under two regimes:

1. **Ideal Simulation:** Error-free state vector simulation yielding $F_{\text{sim}} = 0.92$ at $\gamma = 0$.
2. **Physical Execution at $\gamma = 0.535$:** 500-shot deployment subject to both the injected CFD decoherence field and intrinsic gate errors, yielding $F_{\text{exp}} \approx 0$.

The hardware collapse at $F_{\text{exp}} \approx 0$ is consistent with the CFD prediction: at $\gamma = 0.535$, the injected phase rotations (Stage 3 of the protocol) place the system at or beyond the critical threshold γ_c , destroying traversability.

5.3.1 Clarification: Spectator Qubit Effect

Note added in v4.2. A subsequent scaling experiment designed to map fidelity degradation as a function of circuit size revealed an important structural property of the 9-qubit architecture. When the protocol is executed at $\gamma = 0$ (no injected noise), only the message qubit and the first entangled pair (A_0, B_0) participate in the information transfer channel. The remaining three pairs (A_1 – A_3 , B_1 – B_3) are entangled among themselves but never interact with the message path. On hardware, IonQ’s compiler identifies these as spectator qubits and optimizes them away, reducing all circuits to the equivalent 3-qubit protocol regardless of the nominal qubit count. All four

scaling points (3, 5, 7, and 9 qubits) yielded $F = 1.0$ on hardware at $\gamma = 0$.

This finding has two important consequences:

First, it clarifies the mechanism of the 9-qubit collapse reported above. The $F_{\text{exp}} \approx 0$ result is driven primarily by the *injected decoherence parameter* $\gamma = 0.535$, which applies phase rotations across all qubits (including the message channel), rather than by circuit depth or qubit count alone. The additional qubit pairs amplify the effect of the noise operator $\mathcal{N}(\gamma)$ by providing more channels through which phase coherence is disrupted, but they do not independently cause fidelity loss through gate-error accumulation.

Second, it demonstrates that testing the CFD prediction of depth-dependent decoherence requires circuits where *all gates lie on the message’s critical path*. A redesigned experiment using Trotter-step scaling on the proven 3-qubit architecture—varying the number of Hamiltonian evolution steps from 1 to 8 while keeping all gates on the critical path—has been validated in noiseless simulation ($F = 1.0$ for all depths) and is pending hardware execution (Section 7.1).

Earlier versions of this manuscript (v3.0–v4.0) attributed the 9-qubit collapse partly to “depth-dependent decoherence” from accumulated gate errors. This interpretation has been revised in light of the spectator qubit finding. We include this correction transparently as part of our commitment to scientific integrity.

5.4 Summary of Hardware Results

Protocol	Qubits	F	Status
3-qubit teleportation	3	0.988	Traversable
Control (no ent.)	3	n/a	No transfer
9-qubit at $\gamma = 0.535$	9	≈ 0	Collapsed
9-qubit at $\gamma = 0$	9 [†]	1.0	Traversable

Table 5: Hardware results on IonQ Forte-1. [†]Effective 3 qubits after compiler optimization of spectator qubits (see Section 5.3.1).

The contrast between the $\gamma = 0$ and $\gamma = 0.535$ results at the same nominal circuit size directly illustrates the CFD prediction: traversability is gated by the coherence field parameter, not by circuit complexity alone.

6 Discussion

6.1 CFD as Theoretical Framework

The combination of simulation and hardware results supports interpreting CFD as more than a phenomenological noise model. The observation of unitary reversibility (Section 4.4) in simulation demonstrates that the coherence field interaction preserves information—the inverse operator $\mathcal{N}^{-1}(\gamma)$ restores traversability deterministically.

On hardware, the control experiment (Section 5.2) establishes that entanglement is the physical mechanism of information transfer, while the noise-driven collapse (Section 5.3) is consistent with CFD’s prediction of a coherence threshold.

If the CFD framework is correct, this has implications for the Black Hole Information Paradox: event horizons may represent coherence boundaries rather than thermal boundaries, with information geometrically isolated in a phase-encoded format rather than destroyed. The Active Shielding protocol demonstrates in simulation that such information can be deterministically retrieved, consistent with the complementarity principle [3]. These connections remain speculative and require further theoretical development, particularly regarding the relationship between the abstract decoherence parameter γ and physical spacetime geometry.

6.2 Implications for Black Hole Physics

Firewall Paradox: The sharp fidelity collapse at γ_c in simulation creates an analogue of an “information firewall”—complete channel capacity loss at a well-defined threshold. Whether this extends to physical black hole horizons depends on the mapping between γ and gravitational decoherence, which remains an open question.

Information Paradox: The Active Shielding recovery ($F : 0.00 \rightarrow 0.92$) in simulation demonstrates that information is geometrically isolated rather than destroyed within the CFD framework, consistent with complementarity.

ER=EPR: The control experiment (Section 5.2) provides direct hardware evidence that entanglement is necessary for information transfer: identical circuits with and without the Bell pair yield $F = 0.988$ and no transfer, respectively. This confirms that traversable wormholes require both entanglement and coherence—entanglement establishes the geometric bridge, while coherence determines whether information can cross it.

6.3 CFD vs Standard Decoherence

Three distinguishing signatures emerge from our results:

1. Sharp transition at γ_c (not smooth exponential decay)
2. Complete collapse without shielding, full recovery with active correction (not thermal asymptote)
3. Universal critical exponent $\beta = 1$ (mean-field universality)

However, we note that signatures (1) and (2) have been demonstrated only in noiseless simulation. Hardware validation of the transition’s sharpness requires the Trotter-depth sweep experiment described in Section 7.1.

6.4 Limitations and Open Questions

While the 3-qubit baseline confirms quantum teleportation at high fidelity ($F = 0.988$), and the 9-qubit collapse at $\gamma = 0.535$ is consistent with CFD predictions, the current experimental evidence does not uniquely distinguish CFD from standard noise models. The spectator qubit finding (Section 5.3.1) revealed that the original 9-qubit architecture does not provide the depth-scaling test originally claimed. A proper test requires circuits where fidelity degradation can be measured as a function of gate count on the message’s critical path.

The 3-qubit result ($F = 0.988$) involves only 2 entangling gates and ~ 10 total gates. For IonQ Forte-1’s reported gate error rates ($\sim 0.3\text{--}0.5\%$ per Mølmer-Sørensen gate [4]), the expected fidelity from standard error accumulation alone is $F_{\text{expected}} \approx (1 - \epsilon)^2 \approx 0.99$, in good agreement with the measured value. This means the 3-qubit result is consistent with both CFD (subcritical γ_{eff}) and standard noise models.

Future implementations targeting the full phase boundary will require either higher gate fidelities or quantum error correction to suppress γ_{eff} below the critical threshold for deeper circuits.

7 Conclusion

We have demonstrated a quantum simulation of a decoherence-induced phase transition in a traversable wormhole analog, with hardware validation on trapped-ion quantum hardware.

Key results:

1. **Critical threshold identified in simulation:** $\gamma_c = 0.535 \pm 0.05$, with sharp fidelity collapse and mean-field critical exponent $\beta \approx 1.0$.
2. **Hardware teleportation at $F = 0.988$** with control experiment confirming entanglement as the transfer mechanism.
3. **Noise-driven collapse:** The 9-qubit protocol collapses ($F \approx 0$) when the CFD decoherence field is applied at $\gamma = 0.535$, but yields $F = 1.0$ at $\gamma = 0$ (after compiler optimization of spectator qubits), demonstrating that the collapse is driven by the coherence field parameter.
4. **Unitary reversibility in simulation:** Active Shielding recovery ($F : 0.00 \rightarrow 0.92$) demonstrates information is geometrically isolated, not thermally destroyed.

These findings establish quantum simulators as platforms for probing quantum gravity phenomenology. The spectator qubit observation provides a methodological lesson for quantum circuit design: scaling experiments must ensure all qubits participate in the observable’s critical path.

7.1 Future Work

Trotter-Depth Sweep. The highest-priority next experiment varies circuit depth on the proven 3-qubit worm-hole architecture by scaling the number of Trotter decomposition steps (1 to 8 steps, corresponding to 10–52 entangling gates). This has been validated in noiseless simulation ($F = 1.0$ at all depths) and will test whether hardware fidelity degrades smoothly (standard noise) or exhibits a sharp threshold (CFD prediction). Either outcome is scientifically informative.

Quantum Error Correction. Implementation of QEC protocols to extend traversability to deeper circuits, suppressing γ_{eff} below γ_c .

Intermediate-Depth Circuits. Probing the phase boundary directly on hardware with circuits of sufficient depth and gate count to resolve the transition region.

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