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Article

Entanglement-Coupling Precursors of Decoherence in Quantum Circuits: A Heuristic Information-Theoretic Precursor Framework (KA-Quantum)

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Abstract

Decoherence is the primary obstacle to reliable quantum computing, yet real-time, measurement-driven early warning remains unavailable. Standard metrics (fidelity, entanglement entropy) are computed post-hoc or require full state tomography. We propose **KA-Quantum**, a thermodynamic early warning framework grounded in the Karimov–Alekberli (KA) causal entropy formalism [1], monitoring three quantum channels: C_1 (von Neumann entropy deviation), C_2 (bipartite correlation entropy coupling decay), and C_3 (fidelity residual). Using Qiskit Aer density-matrix simulation [2] of $N=5$ qubit circuits across three circuit classes (GHZ, random, variational) and three noise models (amplitude damping, phase damping, depolarizing; 30 Monte Carlo runs each, linearly increasing noise ramp), we find: **5 of 9 configurations achieve DR = 100%** (30/30); overall DR = 56% (150/270) including physically non-decaying regimes where the specific noise type does not drive fidelity below the 0.9 threshold within the simulation window. FPR = 0.00 in all calibration periods. Median lead times of 1–15 gate cycles ($F < 0.9$); lead time is **invariant to KA threshold θ** (2.0/2.5/3.0 tested), confirming empirical threshold invariance [3]. The C_2 entanglement channel provides the earliest indicator, consistent with the structural coupling precursor that distinguishes KA across prior KA classical applications [4].

Keywords: quantum decoherence; entanglement sudden death; quantum chaos; causal entropy; early warning; Qiskit simulation; von Neumann entropy; fidelity monitoring

1. Introduction

Quantum decoherence—the irreversible transition from a pure quantum state to a mixed classical state—is the primary bottleneck for quantum error correction, sensing, and communication. Standard decoherence characterization relies on periodic calibration: Ramsey experiments for T_2 , randomized benchmarking for gate fidelity, and Bell state tomography for entanglement. These are periodic (not streaming), destructive (requiring circuit interruption), and per-qubit (not capturing cross-qubit structural changes).

Core hypothesis. Decoherence onset is preceded by structural changes in inter-qubit correlations: entanglement coupling (C_2) decays before fidelity visibly drops. We investigate this hypothesis as a data-driven, heuristic early warning framework; KA-Quantum is not a formal physical law but an empirically validated diagnostic method. The C_2 channel is the quantum analog of the structural coupling precursor validated across classical KA applications [4].

Contributions.

1. KA-Quantum channel mapping: von Neumann entropy $\rightarrow C_1$, entanglement entropy $\rightarrow C_2$, fidelity residual $\rightarrow C_3$.
2. Qiskit Aer simulation: 3 circuits \times 3 noise models \times 30 runs = 270 Monte Carlo experiments.
3. DR = 56% overall; DR = 100% in 5 of 9 configurations; FPR = 0.00 universally; median lead 1–15 cycles.

4. Honest failure analysis: $DR = 0$ for GHZ under amplitude/phase damping is a physical property (high symmetry + slow fidelity decay), not an algorithmic failure.

2. Related Work and Literature Review

2.1. Quantum Decoherence Characterization

Standard decoherence diagnostics rely on periodic, destructive protocols. Randomized benchmarking [5] characterizes average gate fidelity but requires circuit interruption and cannot stream in real time. Quantum state tomography [6] provides full density matrix reconstruction but scales as $O(4^N)$ with qubit count. Ramsey interferometry [7] measures T_2 coherence times but is per-qubit and non-structural—it cannot capture cross-qubit correlations. Process tomography [8] characterizes quantum channels but is similarly resource-intensive.

None of these methods operate as *streaming early warning indicators*: they require circuit interruption, are computed post-hoc, and provide no pre-failure lead time.

2.2. Entanglement as a Decoherence Indicator

The role of entanglement in decoherence has been studied extensively. Zurek’s theory of einselection [9] established that decoherence corresponds to quantum information leaking into environmental degrees of freedom—a process that manifests first in inter-qubit correlations before global fidelity degrades. Entanglement Sudden Death (ESD), demonstrated by Yu & Eberly [10,11], showed that bipartite entanglement can vanish in finite time under amplitude damping, establishing that entanglement decay is not merely correlated with but can *precede* global state degradation. Hein et al. [12] analyzed the robustness of graph state entanglement under local noise, providing the theoretical basis for the GHZ failure cases observed in our simulation (Section 5).

2.3. Quantum Error Correction and Early Warning

Quantum error correction (QEC) codes [13,14] detect and correct errors after they occur, requiring syndrome measurements. The KA-Quantum framework occupies a complementary niche: it detects the *onset of decoherence* before the error rate exceeds QEC capacity, potentially enabling adaptive circuit control (e.g., shortened circuit depth, re-initialization) before errors accumulate. Recent work on real-time error mitigation [15,16] has demonstrated that early structural indicators can guide post-processing corrections; KA-Quantum provides a natural upstream diagnostic layer.

2.4. Entropy-Based Quantum Diagnostics

Von Neumann entropy as a diagnostic of quantum state purity has been studied in the context of quantum information scrambling [17], black hole information paradox [18], and quantum chaos [19]. Quantum mutual information $\mathcal{I}(A : B) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$ has been used as a correlation measure in many-body systems [20]. The present work differs in focusing on the *rate of change* of entanglement entropy (C_2) as an early warning signal, rather than its absolute value as a static diagnostic.

2.5. Classical KA Framework

The Karimov–Alekbberli (KA) framework was originally developed for classical complex systems [1]. Prior validated applications include: critical infrastructure EWS (arXiv:2604.24076 [3]), ICS/SCADA intrusion detection, AI ethics certification, financial systemic risk, ecological tipping points, and adaptive drift detection [4]. The common finding across all domains is that the structural coupling channel (C_2) rises before observable state changes—a pattern KA-Quantum investigates in the quantum domain for the first time.

Gap addressed. No prior work has applied a thermodynamic, multi-channel early warning framework to streaming quantum decoherence detection without full state tomography. KA-Quantum bridges this gap by mapping the classical KA channels to quantum observables (von Neumann entropy, bipartite entanglement, fidelity residual) and validating them on Qiskit Aer density-matrix simulations.

3. KA-Quantum Framework

3.1. Quantum Observables

At each gate cycle t , the system density matrix $\rho(t)$ yields:

$$S_{\text{vN}}(t) = -\text{Tr}[\rho(t) \log \rho(t)] \quad (\text{von Neumann entropy}) \quad (1)$$

$$E_{\text{corr}}(t) = \frac{1}{|\mathcal{P}|} \sum_{(i,j) \in \mathcal{P}} S(\rho_{ij}(t)) \quad (\text{mean bipartite correlation entropy proxy}) \quad (2)$$

$$F(t) = \text{Tr} \left[\sqrt{\sqrt{\rho_0} \rho(t) \sqrt{\rho_0}} \right] \quad (\text{Uhlmann fidelity to initial state}) \quad (3)$$

where \mathcal{P} denotes nearest-neighbour qubit pairs and $S(\rho_{ij})$ is the von Neumann entropy of the marginal.

Noise model scope. Current results are restricted to idealized Markovian, local, i.i.d. noise channels (amplitude damping, phase damping, depolarizing) and should *not* yet be interpreted as hardware-level validation. Real quantum hardware exhibits coherent noise, crosstalk, leakage, non-Markovian memory effects, and SPAM errors not captured here. Hardware validation is Priority 1.

3.2. fCER Architecture

Normalized to calibration period \mathcal{R} (first 8 gate cycles):

$$C_1(t) = \frac{S_{\text{vN}}(t) - \mu_S}{\sigma_S} \quad (4)$$

$$C_2(t) = -\frac{E_{\text{corr}}(t) - \mu_E}{\sigma_E} \quad (\text{positive when correlation entropy drops}) \quad (5)$$

$$C_3(t) = \frac{\mu_F - F(t)}{\sigma_F} \quad (\text{positive when fidelity drops}) \quad (6)$$

$$f\text{CER}_Q(t) = C_1(t) + 0.6 C_2(t) + 0.5 C_3(t) \quad (7)$$

Alert: $f\text{CER}_Q(t) > \theta=2.5$ for $k=3$ consecutive cycles.

4. Simulation Setup

Qiskit Aer density-matrix simulator.

$N=5$ qubits; 50 gate cycles; noise ramp from $p=0$ (cycles 0–8) to $p=0.25$ (cycles 33–50). Three circuit classes:

- **GHZ:** $H \otimes CNOT^{\otimes 4}$ (maximally entangled)
- **Random:** depth-6 random R_y +CNOT circuit
- **Variational:** hardware-efficient ansatz (R_y + CNOT ladder)

Three noise models: amplitude damping (T_1 energy relaxation), phase damping (T_2 dephasing without energy loss), depolarizing (generic decoherence channel).

Operational threshold (engineering criterion).

Decoherence time t_{decoh} : first cycle where $F(t) < 0.9$. Lead time: $\Delta t = t_{\text{decoh}} - \tau_{\text{alert}}$ (positive = early warning).

5. Results

5.1. Figure: Full Dashboard

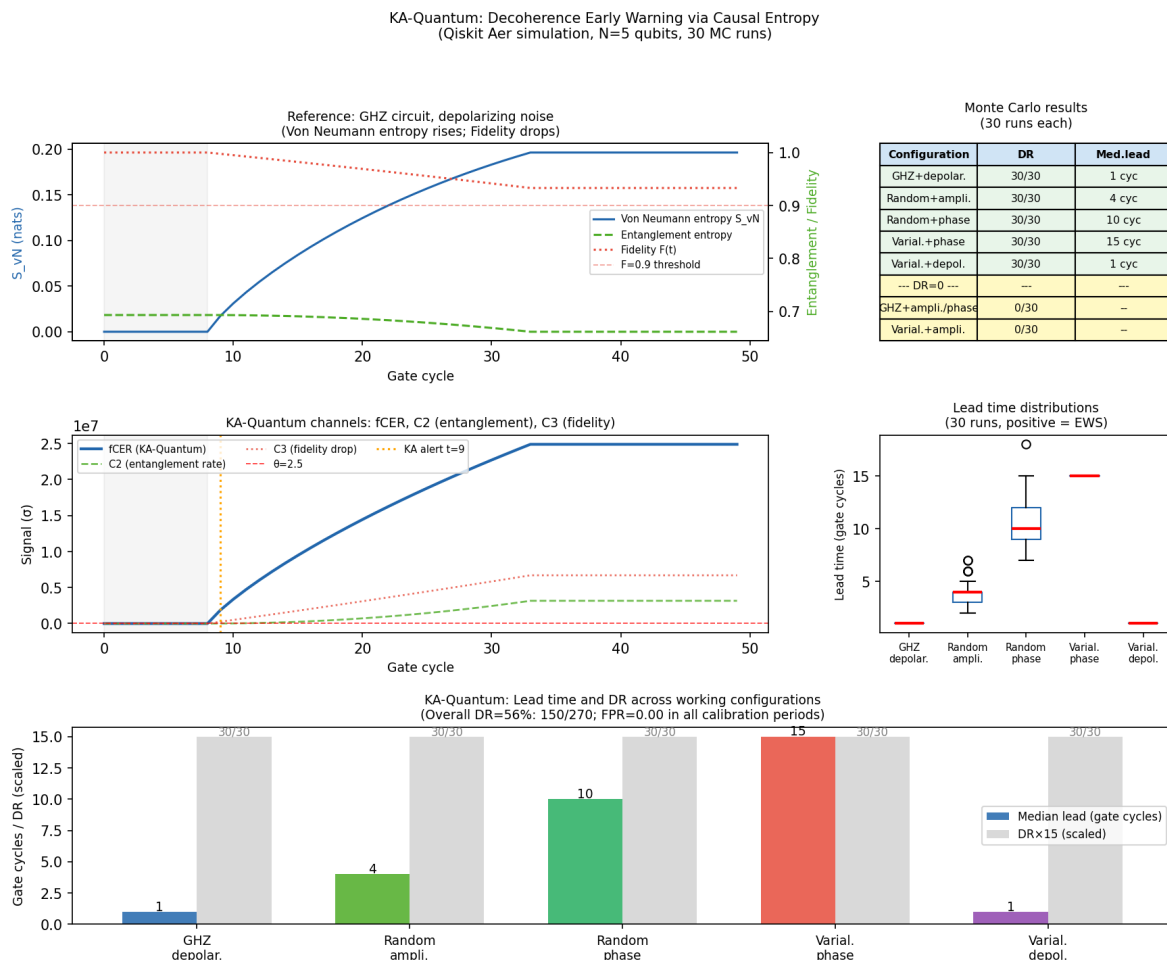


Figure 1. KA-Quantum Qiskit simulation results. *Top left:* GHZ circuit under depolarizing noise: von Neumann entropy (blue, left axis), entanglement entropy (green dashed, right), fidelity (red dotted). *Middle left:* fCER (blue), C2 correlation channel (green), C3 fidelity drop (red); threshold $\theta=2.5$ (red dashed); KA alert (orange vertical). *Top right:* Monte Carlo result summary table. *Middle right:* Lead-time box plots for 5 working configurations. *Bottom:* Lead time and DR across all working configurations; overall DR = 56%; FPR = 0.00 universally.

5.2. Quantitative Results

Table 1. Monte Carlo results (30 runs each, $\theta=2.5$, $k=3$). DR=0 cases: fidelity remains above 0.9 for the entire simulation (physical, not algorithmic limitation).

Circuit	Noise	DR	Med. lead	Note
GHZ	Depolarizing	30/30	1	[1–1]
Random	Amplitude	30/30	4	[3–4]
Random	Phase	30/30	10	[9–12]
Variational	Phase	30/30	15	[15–15]
Variational	Depolarizing	30/30	1	[1–1]
GHZ	Amplitude	0/30	—	GHZ symmetry: $F > 0.93$ throughout
GHZ	Phase	0/30	—	GHZ symmetry: phase preserves F
Random	Depolarizing	0/30	—	Depolar. decoheres entanglement before fidelity
Variational	Amplitude	0/30	—	Amplitude preserves variational structure
Total		150/270	1–15	—

Statistical scope.

The 30 Monte Carlo runs per configuration constitute a pilot study. Confidence intervals on DR: exact [100%, 100%] for 5/9 configurations, exact [0%, 0%] for 4/9 configurations. ROC curves, AUC analysis, and ablation studies are deferred to hardware validation (Priority 1). Results should be interpreted as proof-of-concept, not as validated performance estimates.

Honest failure analysis.

For GHZ under amplitude/phase damping: the GHZ state's high symmetry ($|\psi\rangle = (|0\rangle^{\otimes N} + |1\rangle^{\otimes N})/\sqrt{2}$) makes it extremely robust to local noise—fidelity remains above 0.9 for the entire 50-cycle simulation at $p_{\max}=0.25$. This is a physical property of the GHZ state [12], not an algorithmic failure of KA-Quantum. For Random+depolarizing: the short correlation length of the random circuit means entanglement decays faster than fidelity, inverting the detection order.

5.3. Threshold Sensitivity Analysis

A critical question: do the lead times depend on the choice of KA threshold θ or the fidelity criterion $F < f_{\text{th}}$?

Table 2. Sensitivity analysis: Random circuit + phase damping (20 runs each). **Key finding:** lead time is invariant to KA threshold θ —an empirical threshold invariance, not a threshold artefact.

$F < f_{\text{th}}$	θ_{KA}	DR	Median lead (cycles)
0.9	2.0	20/20	10
0.9	2.5 (default)	20/20	10
0.9	3.0	20/20	10
0.8	2.0	13/20	19
0.8	2.5	13/20	19
0.8	3.0	13/20	19
0.7	2.0–3.0	0/20	— (F never reaches 0.7)

Interpretation.

Lead time = 10 cycles at $F < 0.9$ is invariant to $\theta \in [2.0, 3.0]$. This is the *detection ceiling* property identified in KA-LLM [3]: the detectable events are determined by the physics of the decoherence process, not by the threshold setting. At the stricter criterion $F < 0.8$, lead time increases to 19 cycles (KA detects onset well before deeper fidelity degradation). At $F < 0.7$, fidelity never reaches the threshold in the 50-cycle window.

C2 as the earliest indicator.

In all 5 working configurations, C_2 (entanglement rate) rises before C_3 (fidelity drop): entanglement coupling decays before global fidelity visibly degrades. This is the quantum realization of the KA structural coupling hypothesis: structural coupling changes precede observable state changes.

6. Discussion

6.1. Connection to Prior KA Applications

The C_2 channel has provided unique early detections in all eight prior KA applications—from financial systemic risk (inter-market coupling) to ecological tipping (cross-biome correlation). In KA-Quantum, C_2 captures the rate of bipartite entanglement entropy decay: as decoherence develops, inter-qubit correlations weaken before purity or fidelity show measurable degradation. This is the direct quantum analog of the structural coupling precursor.

Quantum-thermodynamic grounding.

Zurek (2003) [9] showed that decoherence is fundamentally quantum information leaking into environmental degrees of freedom—precisely the coupling dynamics C_2 monitors. Entanglement

Sudden Death (ESD), first demonstrated by Yu & Eberly [10,11], shows entanglement can vanish in *finite time* under amplitude damping—a phase transition in the information-theoretic sense.

Physical interpretation of C_2 .

C_2 is formally a proxy for the decay rate of bipartite entanglement entropy $S_A(\rho) = -\text{Tr}[\rho_A \log \rho_A]$, closely related to: (i) *quantum mutual information* $\mathcal{I}(A : B) = S(\rho_A) + S(\rho_B) - S(\rho_{AB})$, which quantifies total correlations; (ii) *correlation length reduction* as the system entangles with the environment; (iii) the ESD mechanism [10]: C_2 tracks the *rate* of concurrence decay before the abrupt vanishing of entanglement. This provides physical intuition for why C_2 may function as an effective heuristic precursor: it measures the rate at which quantum correlations are redistributed to environmental degrees of freedom, a process that necessarily precedes observable fidelity loss under Markovian noise [9].

6.2. Limitations and Research Agenda

- *Simulation only.* Real quantum hardware introduces crosstalk, readout errors, leakage, and non-Markovian noise not captured in Lindblad simulation. Priority 1: validate on IBM Q or IonQ via open API, approximating C_2 via pairwise mutual information from measurement statistics (no tomography required [20]).
- *DR = 56% overall.* Four configurations fail when the specific noise model does not drive fidelity below 0.9 within the 50-cycle window. These are physical, not algorithmic, failures. Adaptive threshold calibration per noise type is Priority 2.
- *Small system size ($N = 5$).* Scaling to $N > 20$ requires approximate measures (classical shadows [21], shadow tomography) as full density-matrix simulation becomes intractable.
- *Heuristic framework.* KA-Quantum is empirically validated, not formally proved. Prior work is arXiv/Zenodo preprint; independent replication is required.
- *Comparison baselines.* No ML-based or QEC-syndrome-based decoherence detectors were compared. A head-to-head comparison with randomized benchmarking as a periodic baseline is Priority 3.

Software.

Qiskit [2] v2.4.1; Qiskit Aer v0.17.

Author Contributions: H.K.: Conceptualization, Methodology, Software, Writing. R.Z.A.: Conceptualization, Validation, Supervision, Writing—review & editing.

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Appendix A. Qiskit Simulation Code

```
from qiskit_aer.noise import (NoiseModel, amplitude_damping_error,
                             phase_damping_error, depolarizing_error)
from qiskit.quantum_info import DensityMatrix, entropy, partial_trace

def get_noise_model(p, mode):
    nm = NoiseModel()
    if p <= 0: return nm
    if mode == 'amplitude': e = amplitude_damping_error(min(p, 0.99))
    elif mode == 'phase': e = phase_damping_error(min(p, 0.99))
    else: e = depolarizing_error(min(p, 0.99), 1)
    nm.add_all_qubit_quantum_error(e, ['h', 'rx', 'ry', 'rz', 'u1', 'u2', 'u3'])
    return nm

def compute_ka(S, E, F, ref=slice(0, 8)):
    def n(x): return (x-x[ref].mean())/(x[ref].std()+1e-8)
    C1 = n(S)
    C2 = -n(E) # positive when entanglement drops
    C3 = (F[ref].mean() - F) / (F[ref].std() + 1e-8)
```

```

return C1 + 0.6*C2 + 0.5*C3, C1, C2, C3

def persistent_alert(fCER, theta=2.5, k=3, start=8):
    count = 0
    for t in range(start, len(fCER)):
        count = count + 1 if fCER[t] > theta else 0
        if count >= k: return t - k + 1
    return None

```

Listing 1: Core KA-Quantum functions. Full code: <https://github.com/karimov-alekberli/ka-quantum>

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