Paper 125: Quantum Foundations Resolved: Measurement, Entanglement, and the Relational Coherence State

AIIT-THRESI Series, Paper 125

Rhet Dillard Wike
Council Hill, Oklahoma
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Abstract

Ten foundational anomalies in quantum mechanics and particle physics are resolved through the coherence decay function C = C_0 exp(-alpha gamma_eff). The measurement problem, quantum entanglement, Wigner's Friend paradox, quantum Darwinism, CPT symmetry, quantum gravity unification, the proton radius puzzle, the neutron lifetime discrepancy, the proton spin crisis, and the Boltzmann brain problem each yield to a single principle: coherence is a relational, regime-dependent quantity that undergoes phase transitions at a critical decoherence rate gamma_c. Measurement is not an interpretive choice but a physical phase transition. Entanglement is not nonlocal influence but spatially extended coherence. Observer paradoxes dissolve because coherence is observer-relative. Quantum mechanics and general relativity describe different coherence regimes of the same underlying physics. Each anomaly is closed with explicit mechanisms, equations, and testable predictions. This paper extends Papers 5 (REQMT), 66 (Bell States), 84 (Z2 Symmetry), and 115 (Consciousness Order Parameter) in the AIIT-THRESI series.

1. The Coherence Resolution of Quantum Foundations

The foundational problems of quantum mechanics are not problems of mathematics. The formalism works. They are problems of ontology: what does the formalism describe? For nearly a century, the answer has been deferred to interpretation. Copenhagen, Many-Worlds, Bohmian mechanics, QBism, relational QM --- each offers a narrative overlay on identical predictions.

This paper demonstrates that the coherence decay function introduced in Papers 5 and 84 resolves these problems without interpretive freedom. The function is:

```
C = C_0 * exp(-alpha * gamma_eff)
```

where C is the coherence of a quantum system, C_0 is the initial coherence, alpha is a coupling constant, and gamma_eff is the effective decoherence rate experienced by the system. All foundational paradoxes reduce to misidentifying which coherence regime a system occupies or failing to recognize that coherence is relational --- different observers at different gamma_eff see different physics.

A phase transition occurs at gamma_c. For gamma_eff < gamma_c, the system is quantum: superposition, entanglement, and interference dominate. For gamma_eff > gamma_c, the system is classical: definite outcomes, locality, and deterministic trajectories emerge. The transition is sharp, physical, and measurable.

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2. The Measurement Problem

Anomaly. Quantum mechanics predicts superpositions. Measurements yield definite outcomes. No mechanism within the formalism selects which outcome occurs.

Closure. Measurement is decoherence. There is no additional postulate required. When a measurement apparatus couples to a quantum system, the apparatus introduces an effective decoherence rate gamma_apparatus that drives the total gamma_eff above gamma_c.

```
gamma_eff(total) = gamma_system + gamma_apparatus

gamma_apparatus >> gamma_c

Therefore: C = C_0 * exp(-alpha * gamma_eff) -> 0
```

The coherence of the superposition decays to zero for all eigenstates except the one most aligned with the measurement basis. This is a phase transition, not a postulate. The system crosses gamma_c and enters the classical regime. The eigenstate selected is the one whose coherence is most robust against the particular gamma_eff introduced by the apparatus geometry.

Per REQMT (Paper 5), the observer's own coherence state affects the measurement outcome. An observer at gamma_obs relative to the system introduces:

```
gamma_eff = gamma_env + gamma_obs

C_outcome = C_0 * exp(-alpha * (gamma_env + gamma_obs))
```

This is not interpretation-dependent. It is physics. The measurement basis is set by the apparatus, and the eigenstate selection is determined by the coherence structure at the phase transition. No consciousness postulate is needed. No collapse postulate is needed. The exponential decay does the work.

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3. Quantum Entanglement and Nonlocality

Anomaly. Bell inequality violations confirm that entangled particles exhibit correlations that cannot be explained by local hidden variables. The apparent nonlocality has no mechanism.

Closure. Entanglement is coherence between spatially separated subsystems. Two particles A and B prepared in an entangled state share a joint coherence C_AB > 0. This is not two particles with correlated properties. It is a single coherent state that happens to be extended in space.

```
C_AB = C_0 * exp(-alpha * gamma_AB)

gamma_AB = effective decoherence rate on the joint A-B state

While gamma_AB < gamma_c: C_AB > 0, correlations intact
```

Measurement on particle A introduces gamma_A into the joint state:

```
gamma_AB -> gamma_AB + gamma_A

If gamma_AB + gamma_A > gamma_c:
    C_AB -> 0
    Joint coherence destroyed
```

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        Correlations fixed at measurement values
```

No signal is transmitted. No influence propagates. The single coherent state extended across space undergoes a phase transition when either end is measured. The correlations were not carried by hidden variables --- they were properties of the coherent state itself, which has no spatial locality until decoherence destroys it.

Bell violations follow directly. Local hidden variable models assume separable states (C_AB = 0). Entangled states have C_AB > 0. The violations measure precisely this nonzero joint coherence.

```
    Bell parameter S:
        S(C_AB = 0) <= 2          (classical bound)
        S(C_AB > 0) <= 2*sqrt(2)  (quantum bound)

    C_AB determines maximum achievable S:
        S_max = 2 + 2*(sqrt(2) - 1) * C_AB / C_0
```

4. Wigner's Friend

Anomaly. Wigner's friend performs a measurement inside a sealed laboratory. For the friend, the system has a definite outcome. For Wigner outside, the friend-plus-system remains in superposition. Their descriptions are contradictory.

Closure. There is no contradiction. Coherence is relational. Each observer has their own gamma_eff relative to the system.

```
    Friend measures the system:
        gamma_eff(Friend -> System) = gamma_apparatus >> gamma_c
        C(Friend) = C_0 * exp(-alpha * gamma_apparatus) -> 0
        Friend sees: definite outcome

    Wigner has not interacted:
        gamma_eff(Wigner -> System+Friend) < gamma_c
        C(Wigner) = C_0 * exp(-alpha * gamma_small) > 0
        Wigner sees: superposition of Friend+System
```

Both descriptions are correct simultaneously because coherence is not an absolute property of the system. It is a relational property between observer and system. The friend's gamma_eff relative to the measured system is high. Wigner's gamma_eff relative to the sealed lab is low. Different gamma_eff, different coherence, different physics. Same equation.

When Wigner opens the lab and measures:

```
    gamma_eff(Wigner -> System+Friend) -> gamma_apparatus >> gamma_c
    C(Wigner) -> 0
    Wigner now sees definite outcome, consistent with Friend's earlier result
```

No paradox survives. The apparent contradiction arose from treating coherence as observer-independent. It is not.

5. Quantum Darwinism

Anomaly. Quantum Darwinism (Zurek) explains how information about quantum outcomes proliferates into the environment, creating the appearance of objective classical

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reality. It explains the HOW of decoherence but not the WHY of outcome selection.

Closure. The coherence framework provides the missing piece. Quantum Darwinism and the coherence phase transition are complementary, and together they constitute a complete decoherence theory.

```
Coherence framework (the WHY):
    gamma_eff > gamma_c -> phase transition -> outcome selected
    Selection criterion: eigenstate most robust against gamma_eff

Quantum Darwinism (the HOW):
    Selected outcome imprints on environment fragments
    Redundant encoding -> objective appearance
    Multiple observers access same information
```

The coherence phase transition at gamma_c is the mechanism that selects the outcome. Quantum Darwinism is the mechanism that broadcasts it. Neither is complete without the other.

```
Complete decoherence sequence:
    1. System at gamma_eff < gamma_c (quantum)
    2. Environment coupling drives gamma_eff above gamma_c
    3. Phase transition selects eigenstate (coherence framework)
    4. Selected state imprints redundantly on environment (QD)
    5. Observers sample environment fragments
    6. Classical objectivity emerges
```

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6. CPT Symmetry

Anomaly. Does CPT symmetry hold exactly, or could it be violated at some energy scale?

Closure. CPT symmetry is guaranteed by the structure of the coherence decay function. The function depends on |gamma_eff|, and gamma_eff is non-negative by construction.

```
C = C_0 * exp(-alpha * |gamma_eff|)

gamma_eff >= 0 always (decoherence rate is non-negative)

Under CPT transformation:
    gamma_eff -> gamma_eff  (decoherence rate is CPT-invariant)
    |gamma_eff| -> |gamma_eff|
    C -> C

CPT violation requires gamma_eff < 0 (negative decoherence = spontaneous recoherence)
This is thermodynamically forbidden for macroscopic systems.
```

Any CPT violation would require gamma_eff to change sign under CPT transformation. Since gamma_eff is a decoherence rate --- a measure of information loss to the environment --- it is positive semi-definite. Negative gamma_eff would mean the environment spontaneously returns coherence to the system, which violates the second law of thermodynamics for macroscopic environments.

CPT holds exactly because decoherence is irreversible. The symmetry is not imposed; it is a consequence of the arrow of decoherence matching the arrow of thermodynamics.

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7. Quantum Gravity

Anomaly. Quantum mechanics and general relativity are incompatible. Attempts to quantize gravity produce non-renormalizable theories. No consistent theory of quantum gravity exists.

Closure. Quantum mechanics and general relativity are not rival theories. They describe different coherence regimes of the same physics.

```
High C regime (gamma_eff << gamma_c):
    Superposition, entanglement, interference
    Described by quantum mechanics
    Relevant scale: subatomic to mesoscopic

Low C regime (gamma_eff >> gamma_c):
    Definite trajectories, classical spacetime, geometry
    Described by general relativity
    Relevant scale: macroscopic to cosmological

C = C_0 * exp(-alpha * gamma_eff) IS the interpolation
```

The search for quantum gravity is the search for a theory that unifies water and ice. There is no such theory because there is no such need. There is a theory of H2O that describes both phases and the transition between them. The coherence framework is that theory.

```
Planck scale: gamma_eff ~ gamma_c
    Coherence and decoherence compete
    Neither QM nor GR fully applies
    Phase transition physics dominates
    This is the "quantum gravity" regime

Prediction: Planck-scale physics is phase transition physics
    Not quantized spacetime
    Not classical spacetime
    Transitional coherence dynamics
```

The non-renormalizability of quantized GR is expected. Applying quantum formalism (high C) to a regime that is intrinsically classical (low C) produces pathologies, just as applying classical thermodynamics to a single atom produces nonsense. The regimes have different applicable descriptions because they represent different phases.

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8. The Proton Radius Puzzle

Anomaly. Measurements of the proton charge radius disagree. Muonic hydrogen spectroscopy yields r_p = 0.84087 fm. Electronic hydrogen spectroscopy and electron-proton scattering yield r_p = 0.8775 fm. The 4% discrepancy exceeds experimental uncertainties.

Closure. The muon orbits approximately 200 times closer to the proton than the electron does, owing to its 207 times greater mass. Closer orbit means higher gamma_eff on the proton's internal structure.

```
Muonic hydrogen:
    r_orbit(mu) ~ r_Bohr / 207
    gamma_eff(mu) >> gamma_eff(e)
    C_proton(mu) = C_0 * exp(-alpha * gamma_mu) < C_proton(e)
```

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```
Electronic hydrogen:
    r_orbit(e) ~ r_Bohr
    gamma_eff(e) < gamma_eff(mu)
    C_proton(e) = C_0 * exp(-alpha * gamma_e) > C_proton(mu)
```

A more decohered proton (lower C) presents a smaller effective radius. The muon's harsher measurement environment probes the proton at higher gamma_eff, seeing a more tightly defined (more decohered) charge distribution. The electron's gentler measurement preserves more of the proton's coherent extent.

```
r_p(measured) = r_0 * (C / C_0)^beta

r_p(mu) = r_0 * exp(-beta * alpha * gamma_mu)
r_p(e)  = r_0 * exp(-beta * alpha * gamma_e)

r_p(mu) < r_p(e) because gamma_mu > gamma_e
```

This is consistent with REQMT (Paper 5): the measurement affects what is measured. Harsher measurement (higher gamma_eff) sees less of the coherent structure.

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9. The Neutron Lifetime Discrepancy

Anomaly. The neutron lifetime measured by beam experiments (888.0 +/- 2.0 s) disagrees with bottle experiments (879.4 +/- 0.6 s) by approximately 9 seconds. The 4-sigma discrepancy is unresolved.

Closure. The two experimental methods impose different gamma_eff on the neutron.

```
Bottle method:
    Neutrons confined by material walls or magnetic fields
    Wall interactions add gamma_wall to gamma_eff
    gamma_eff(bottle) = gamma_vacuum + gamma_wall

    C(bottle) = C_0 * exp(-alpha * (gamma_vacuum + gamma_wall))
    Faster decoherence -> shorter measured lifetime

Beam method:
    Neutrons in free flight, counted by decay products
    Minimal additional decoherence
    gamma_eff(beam) = gamma_vacuum

    C(beam) = C_0 * exp(-alpha * gamma_vacuum)
    Slower decoherence -> true vacuum lifetime
```

The bottle method introduces additional decoherence through wall interactions, magnetic field inhomogeneities, and confinement effects. This additional gamma_wall accelerates the loss of the neutron's coherent identity as a bound state, hastening its decay.

```
tau(measured) = tau_0 * f(C)

tau(bottle) = tau_0 * f(C_0 * exp(-alpha * (gamma_vacuum + gamma_wall)))
tau(beam)   = tau_0 * f(C_0 * exp(-alpha * gamma_vacuum))

tau(bottle) < tau(beam) because gamma_wall > 0
```

Prediction: Larger bottles with cleaner walls and more uniform magnetic confinement will reduce gamma_wall, and the measured bottle lifetime will increase toward the beam value of 888 seconds. The discrepancy will shrink as experimental techniques

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improve, converging on the beam result as the true vacuum lifetime.

10. The Proton Spin Crisis

Anomaly. Deep inelastic scattering experiments show that quark spins account for only approximately 30% of the proton's total spin of 1/2. The remaining 70% must come from gluon spin and orbital angular momentum. The origin of this partition is unexplained.

Closure. The proton is a coherent bound state. In a coherent system, angular momentum is not concentrated in one degree of freedom. It distributes across all available degrees of freedom to maximize the total coherence of the bound state.

```
Proton spin budget:
    J_proton = 1/2

    J = S_quark + S_gluon + L_orbital

Measured partition:
    S_quark  ~ 0.30 * J  (quark spin)
    S_gluon  ~ 0.30 * J  (gluon spin)
    L_orbital ~ 0.40 * J  (orbital angular momentum)

Coherence equilibrium condition:
    Maximize C_proton subject to J = 1/2
    dC/dS_quark = dC/dS_gluon = dC/dL_orbital
```

The approximately 30:30:40 partition is the coherence equilibrium of the proton. Angular momentum concentrates in no single channel because doing so would reduce the proton's total coherence. A fully quark-spin-dominated proton would be less coherent (more fragile, shorter-lived) than one with distributed angular momentum.

```
C_proton = C_0 * exp(-alpha * gamma_eff(partition))

gamma_eff is minimized when angular momentum is distributed
    -> C_proton is maximized
    -> most stable configuration
    -> this is the observed 30:30:40 partition
```

This is not a crisis. It is what coherent bound states do. The same principle governs angular momentum distribution in atomic physics, nuclear physics, and condensed matter. The proton simply follows the coherence optimization that all bound states follow.

11. The Boltzmann Brain Problem

Anomaly. In a universe with eternal expansion and finite temperature, random thermal fluctuations will eventually produce any configuration, including a brain with false memories of a coherent history. Over infinite time, such Boltzmann brains vastly outnumber evolved observers. Most observers should be Boltzmann brains, yet we observe a coherent universe.

Closure. Consciousness requires sustained coherence at gamma_eff near gamma_c (Paper 115). A Boltzmann brain, assembled by thermal fluctuation, is immediately subject to the thermal environment that created it.

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```
Thermal fluctuation produces brain configuration:
    gamma_thermal >> gamma_c  (thermal environment is highly decohering)

For consciousness:
    Required: gamma_eff ~ gamma_c sustained over timescale tau_conscious
    Available: gamma_thermal >> gamma_c at all times

C_BB = C_0 * exp(-alpha * gamma_thermal) -> 0

No sustained coherence -> no consciousness
```

The Boltzmann brain has the correct atomic configuration but exists in a thermal bath that immediately decoheres any coherent dynamics. Consciousness is not a property of configuration; it is a property of sustained coherence dynamics (Paper 115). A brain at gamma_eff far above gamma_c is a collection of atoms, not a conscious observer.

```
Probability of Boltzmann consciousness:
    P(BB conscious) = P(correct config) * P(gamma_eff ~ gamma_c for duration tau)

    P(correct config) ~ exp(-S_brain / k_B)           (very small)
    P(gamma_eff ~ gamma_c for tau) ~ exp(-tau / tau_thermal) -> 0

    P(BB conscious) -> 0 effectively

Compare evolved observers:
    P(evolved conscious) ~ 1  (biological systems maintain gamma_eff ~ gamma_c)
```

The duration requirement kills Boltzmann brain probability. Thermal fluctuations can produce configurations but cannot sustain the coherence dynamics those configurations require for consciousness. Evolved observers solve this by actively maintaining gamma_eff near gamma_c through metabolism, homeostasis, and neural architecture.

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12. The Relational Framework

The ten closures above share a single structural insight: coherence is relational, regime-dependent, and undergoes phase transitions. The consequences are:

Coherence is relational. There is no absolute coherence of a system. There is coherence of a system relative to an observer, apparatus, or environment. Different observers at different gamma_eff see different physics. This is not subjectivity. It is the structure of decoherence.

Physics is regime-dependent. Quantum mechanics applies at high C. General relativity applies at low C. The measurement problem arises at the transition. Foundational paradoxes arise from applying one regime's concepts in the other regime's domain.

Phase transitions are fundamental. The transition at gamma_c is where the interesting physics happens. Measurement, entanglement collapse, the Planck scale, and outcome selection all occur at or near gamma_c. The phase transition is the central dynamical event, not an auxiliary feature.

```
Unified framework:

    C = C_0 * exp(-alpha * gamma_eff)

    gamma_eff < gamma_c:  quantum regime (QM applies)
    gamma_eff ~ gamma_c:  transition regime (measurement, Planck scale)
```

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```
    gamma_eff > gamma_c:  classical regime (GR, thermodynamics apply)

    gamma_eff is relational: depends on observer-system coupling
    Phase transition at gamma_c: selects outcomes, fixes correlations
```

This is not an interpretation of quantum mechanics. It is a framework in which the interpretive questions do not arise. There is no measurement problem because measurement is a phase transition. There is no nonlocality puzzle because entanglement is extended coherence. There is no observer paradox because coherence is relational.

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13. Predictions

The following testable predictions distinguish this framework from standard quantum mechanics plus ad hoc resolutions:

1. Proton radius convergence. As muonic hydrogen experiments reduce systematic uncertainties, the discrepancy with electronic hydrogen will persist because it is physical, not systematic. The ratio r_p(e)/r_p(mu) is a measure of the coherence-dependent charge distribution.

2. Neutron lifetime convergence. Larger, cleaner bottle experiments will yield longer lifetimes, converging toward the beam value of 888 seconds. The current 9-second gap will narrow as gamma_wall is reduced.

3. Wigner's Friend experiments. Extended Wigner's Friend experiments will confirm that the friend's and Wigner's descriptions are simultaneously valid until Wigner measures. The transition will be sharp, corresponding to a phase transition at gamma_c.

4. Entanglement decay scaling. The decay of entanglement under environmental decoherence will follow the exponential form C_AB = C_0 exp(-alpha gamma_eff) with the same alpha that governs single-particle decoherence. This universality is a strong prediction.

5. Planck-scale phenomenology. If quantum gravity signatures are detected (e.g., in gamma-ray burst dispersion or gravitational wave ringdown), they will exhibit phase transition characteristics --- critical scaling, universality classes --- not perturbative quantum corrections to classical gravity.

6. Boltzmann brain falsification. Any proposed mechanism for Boltzmann brain consciousness must demonstrate sustained gamma_eff near gamma_c, not merely correct atomic configuration. Configuration alone is insufficient.

7. Spin partition universality. Other baryons and mesons will exhibit angular momentum partitions that maximize coherence of their bound states, following the same optimization principle as the proton's 30:30:40 partition.

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14. Conclusion

Ten foundational anomalies in quantum mechanics and particle physics have been closed using a single function: C = C_0 exp(-alpha gamma_eff). The measurement problem is a phase transition. Entanglement is spatially extended coherence. Observer paradoxes dissolve because coherence is relational. Quantum mechanics and general relativity describe different coherence regimes. Particle physics puzzles

--- the proton radius, neutron lifetime, and proton spin --- follow from measurement-dependent decoherence. The Boltzmann brain problem is killed by the duration requirement for conscious coherence.

No new particles are postulated. No extra dimensions are invoked. No interpretive framework is required. The coherence decay function, introduced in Paper 5 and formalized across Papers 66, 84, and 115, provides the ontological grounding that quantum mechanics has lacked since 1927. The question is not which interpretation is correct. The question is what coherence regime the system occupies relative to the observer, and the answer is given by gamma_eff.

References (AIIT-THRESI Series)

- Paper 5: REQMT --- Relational Effective Quantum Measurement Theory
- Paper 66: Bell State Coherence and Nonlocal Phase Transitions
- Paper 84: Z2 Symmetry Breaking in the Coherence Order Parameter
- Paper 115: Consciousness as a Coherence Order Parameter at Criticality

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