

Letter ID

ToE Living Review Letters ID: The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

*A Complete Entropic Theory of Quantum Entanglement, the Attosecond
Formation-Time Evidence, and the Resolution of
Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture*

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May 3, 2026

Category: Research Letter — Theoretical Physics; Foundations of Physics; Information Theory;
Computational Theory ; Attosecond Physics; Entropic Dynamics; History and Philosophy of Physics

"I cannot seriously believe in [quantum mechanics] because the theory cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky action at a distance."

— *Albert Einstein*, Letter to Max Born, 3 March 1947

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"I would not call [entanglement] one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought."

— *Erwin Schrödinger*, Proceedings of the Cambridge Philosophical Society, 1935

"The physicist does not need to be told that the whole universe is connected. He knows that, but he knows that the connections are not at all like the EPR type; they are extremely complicated and indirect."

— *John Stewart Bell*, Speakable and Unspeakable in Quantum Mechanics, 1987

"No phenomenon is a real phenomenon until it is an observed phenomenon."

— *John Archibald Wheeler*, (1978)

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Keywords: Theory of Entropicity (ToE); Entropic Seesaw Model (ESSM); Quantum Entanglement; Entropic Field; Obidi Action; Entropic Manifold; Entropic Distance; Entropic Bridge; Coherence Strength Functional; Attosecond Entanglement Formation Time; Einstein-Podolsky-Rosen (EPR); ER=EPR; Maldacena-Susskind Conjecture; No-Rush Theorem; Entropic Time Limit; Entropic Decoherence; Measurement Threshold; Seesaw Collapse Criterion; Photoionization Entanglement; Attosecond Chronoscopy; Bell Inequality; Entropic Nonlocality; Formation-Persistence Distinction; Environmental Torque (EnvT); Entropic Torque (ET)

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Abstract

The present Letter — Letter ID in the *Theory of Entropicity (ToE) Living Review Letters Series* — introduces and fully formalizes the **Entropic Seesaw Model (ESSM)** as a self-contained, mathematically complete entropic theory of quantum entanglement. ESSM is developed within the broader framework of the Theory of Entropicity, an entropy-first program that posits the entropic field as the ontological ground of physical reality. The model is constructed in two conceptually distinct but mathematically unified stages. *First*, a **formation stage**, in which two previously independent entropic sectors — each described by a local entropic field configuration on its own manifold — undergo a local, finite-time, topological merger into a single shared entropic manifold. This merger is not an instantaneous kinematic fact but a genuine dynamical process requiring finite entropic resources and finite time, governed by a formation drive equation with a well-defined threshold-crossing time. *Second*, a **persistence stage**, in which the shared manifold is maintained under arbitrary spatial separation of the subsystems without the transport of any signal — the correlations survive not because information travels but because the two subsystems remain structurally identical to one entropic object, and the entropic distance between them remains near zero even as their spatial distance grows without bound.

ESSM resolves the Einstein-Podolsky-Rosen paradox at the ontological level by introducing a rigorous distinction between *spatial distance* and *entropic distance*. The core of the EPR argument is the assumption that spatial separation implies ontological separation. ESSM denies this premise: once the shared manifold M_{AB} has crystallized, the subsystems A and B remain entropically local ($d_E(A,B) \approx 0$) regardless of their spatial distance ($d_{space}(A,B) \gg 0$). Correlations measured at spacelike separation are therefore not "spooky action at a

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

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distance" but local facts in entropic geometry, apprehended from the standpoint of spatial geometry as nonlocal. This resolution preserves Bell's theorem, preserves the no-signaling principle, and requires no hidden variables — it simply relocates the locus of the relational fact from spacetime geometry to the entropic manifold.

The Letter further reinterprets the Maldacena-Susskind ER=EPR conjecture [23] as an **entropic bridge** rather than a literal spacetime wormhole. ESSM defines a bridge order parameter Ξ_{AB} whose nonzero expectation value signals the "turning on" of the entropic bridge, and derives a bridge length functional L_{AB} that shortens toward zero at maximal entanglement and diverges at decoherence. The relationship between ER bridges and entropic bridges is shown to be one of geometric shadow: in special gravitational regimes, the entropic bridge may admit a representation in Einstein-Rosen bridge language, but the ESSM bridge is the more general and more physically transparent object. ESSM thereby completes the ER=EPR conjecture by supplying the dynamical content — formation dynamics, coherence strength, threshold breakdown — that the original conjecture leaves unspecified.

The empirical grounding of ESSM is provided by the rapidly advancing attosecond photoionization literature [33]. Jiang et al. (2024, *Physical Review Letters* 133, 163201) [27] demonstrated, through numerical solution of the full-dimensional time-dependent Schrödinger equation for helium, that photoionization time delays can serve as an attosecond probe of interelectronic coherence and entanglement. The widely cited figure of roughly 232 attoseconds is reported in institutional summaries — notably the TU Wien news release of October 2024 [34] — as the timescale for entanglement development in the helium system; however, the present Letter emphasizes that the primary 2024 *PRL* paper by Jiang et al. is a numerical and theoretical attosecond chronoscopy study, and the “232

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

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May 3, 2026

attoseconds” figure appears in news summaries rather than as a directly measured coincidence result in the primary paper. Subsequent experimental works provide increasingly direct attosecond-scale evidence: Shobeiry et al. (2024, *Scientific Reports* 14, 19630) [28] demonstrated direct control of emission direction of entangled photoelectrons in dissociative H₂ ionization; Stenquist and Dahlström (2025, *Physical Review Research* 7, 013270) [29] showed how time-symmetry can be harnessed to alter entanglement in photoionization; Makos et al. (2025, *Nature Communications* 16, 8554) [30] revealed ionic coupling effects on attosecond time delays through entanglement in CO₂ photoionization; and Koll et al. (2026, *Nature* 652, 82–88) [31] provided the most direct experimental demonstration to date that ion–photoelectron entanglement influences electronic coherence in attosecond molecular photoionization of H₂. These experiments collectively demonstrate that entanglement formation is a finite-time, channel-dependent, dynamically rich process — precisely as ESSM predicts.

The mathematical architecture developed in this Letter includes: the ESSM two-sector effective action in symmetric and antisymmetric entropic mode variables; the bridge order parameter and its symmetry-breaking potential; the coherence strength functional Γ_{AB} ; the equation of motion for the antisymmetric mode S_- ; the formation drive equation and its analytic solution; the seesaw collapse criterion and decoherence rate decomposition; the entropic bridge length functional; and the entropic formation functional connecting ESSM formation to the Obidi Action's variational philosophy.

This Letter — Letter ID in the ToE Living Review Letters Series — builds upon the foundational materials established in Letter I [1] (ontological primacy of entropy), Letter IA [2] (the Haller correspondence), Letter IB [3] (the Haller-Obidi Action and Lagrangian), and Letter IC [4] (the Alemoh-Obidi Correspondence). The present Letter gives the reader

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A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

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May 3, 2026

a veritable expose on the synthesis of the ToE formal proposals on the Entropic Seesaw Model (ESSM).

Letter ID thus establishes the Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE) as a rigorously formulated, experimentally falsifiable, and physically motivated entropic framework for quantum entanglement — one that takes the entanglement problem seriously as a question about the physical world and provides, for the first time within any entropic program, the mathematical apparatus to answer it.

* * *

General Introduction

Quantum entanglement is, by broad consensus, the most profoundly non-classical feature of modern physics. Since its identification by Einstein, Podolsky, and Rosen in 1935 [20] and its christening by Schrödinger [43] in the same year, entanglement has migrated from the margins of interpretive debate to the center of theoretical and experimental physics. It underwrites quantum computation, quantum cryptography, quantum teleportation, and the emerging consensus that spacetime itself may be stitched together by entanglement [24]. And yet, despite nearly a century of investigation, the foundational theory of entanglement remains strangely incomplete. Standard quantum mechanics treats entanglement as a *kinematic* feature of Hilbert space — a non-factorizability of the state vector — but offers no *dynamical* account of how entanglement forms, why it persists under arbitrary spatial separation, or what physical process governs its breakdown under measurement or decoherence. The present Letter addresses this deficit head-on.

The Einstein-Podolsky-Rosen paradox remains, at its philosophical core, unresolved. Bell's theorem [22] demonstrated that no local hidden-variable theory can reproduce the quantum predictions, and decades of experimental confirmation — from Aspect's [38] pioneering tests through the loophole-free demonstrations of the 2010s — have established that quantum correlations violate Bell inequalities. But establishing that entanglement is real and nonlocal is not the same as explaining what it *is*. The EPR argument relies on the premise that spatial separation guarantees ontological independence; this premise is denied by entanglement but never *replaced* by a positive account of what structure underwrites the correlations. The Copenhagen tradition declares the question meaningless; the many-worlds interpretation distributes the correlations across branching

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

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May 3, 2026

worlds; Bohmian mechanics [44] introduces a pilot wave that is explicitly nonlocal. None of these provides a dynamical ontology for the relational structure of entanglement itself.

A striking development from the high-energy and quantum-gravity community is the ER=EPR conjecture of Maldacena and Susskind [23], which proposes that entangled systems are connected by Einstein-Rosen bridges [21] — spacetime wormholes. This conjecture, elaborated by Van Raamsdonk's spacetime-from-entanglement program [24] and more recently by the "ER for typical EPR" analysis of Magán, Sasieta, and Swingle [25], has the great merit of treating entanglement as a structural, geometric fact rather than a mere correlation. But ER=EPR, in its original form, is a conjecture framed within AdS/CFT duality and black-hole thermodynamics; it does not specify the dynamical mechanism by which the bridge forms, nor does it apply straightforwardly to the laboratory Bell pairs and photoionization entanglements of atomic physics. The conjecture names the connection but does not build it.

Meanwhile, the experimental landscape has been transformed by the attosecond revolution. For the first time in the history of physics, experiments can probe entanglement formation in real time. The 2024 numerical/theoretical attosecond chronoscopy study by Jiang et al. [27] demonstrated that photoionization time delays in helium, computed from the full-dimensional time-dependent Schrödinger equation, can monitor the ultrafast variations of interelectronic coherence and entanglement. Institutional summaries, notably from TU Wien [34], reported a timescale of roughly 232 attoseconds for entanglement development. The 2026 experimental work by Koll et al. [31], published in *Nature*, provided direct evidence that ion-photoelectron entanglement affects electronic coherence in the attosecond molecular photoionization of H₂, demonstrating experimental control over the degree of entanglement. These results confirm that entanglement is not

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

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May 3, 2026

an instantaneous kinematic fact but a process that unfolds on a definite, finite, physically meaningful timescale — a timescale that any complete theory of entanglement must predict and explain.

The Theory of Entropicity (ToE) enters this landscape with a foundational claim: *entropy is not a statistical summary of underlying mechanical degrees of freedom but a dynamical field — the primary ontological entity from which all physical structure emerges*. The entropic field $S(x)$, defined on an entropic manifold M_S , generates gravitational geometry, quantum behavior, and thermodynamic law as emergent consequences of its dynamics, governed by the Obidi Action [1, 3, 6]. The ToE program has been developed across a series of Letters and papers: Letter I [1] establishes the ontological primacy of entropy; Letter IA [2] identifies the deep correspondence between the ToE framework and John Haller's action-as-entropy formulation [19]; Letter IB [3] formalizes the Haller-Obidi Action and Lagrangian; and Letter IC [4] presents the Alemoh-Obidi Correspondence, a monograph-scale examination of the mathematical and conceptual foundations. The present Letter — Letter ID — is the entanglement-specific sector of the ToE program.

The Entropic Seesaw Model (ESSM) is the theory developed here. Its name is not merely pedagogical. A physical seesaw is a single rigid object whose two ends appear spatially distinct but are dynamically constrained: if one end rises, the other falls, not because a signal travels along the plank but because the plank is one object. ESSM asserts that entangled systems stand in exactly this relation in the entropic manifold. The "seesaw" is the shared manifold M_{AB} , and the spatial separation of the two subsystems is geometrically real but entropically irrelevant: the entropic distance between them is zero, and correlations are structural facts of the shared object, not signals transmitted between separate objects.

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

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May 3, 2026

What this Letter accomplishes is as follows. Section 1 analyses the entanglement problem in contemporary physics. Section 2 presents the ontological core of the ESSM. Section 3 develops the complete mathematical architecture — the ESSM effective action, the bridge order parameter, the coherence strength functional, and the equations of motion. Section 4 treats formation dynamics and the entropic genesis of entanglement. Section 5 addresses persistence, propagation, and the seesaw equilibrium. Section 6 formalizes decoherence, measurement, and the seesaw collapse threshold. Section 7 provides the attosecond empirical anchors. Section 8 dissolves the EPR paradox. Section 9 reinterprets and completes ER=EPR. Section 10 presents testable predictions and experimental protocols. Section 11 surveys open mathematical frontiers and offers a concluding assessment. Throughout, original ToE/ESSM proposals are explicitly identified.

* * *

Table of Contents

Abstract	4
General Introduction	8
1. The Entanglement Problem in Contemporary Physics	15
1.1 The Standard Quantum-Mechanical Account	15
1.2 The Dynamical Deficit	16
1.3 The Need for an Ontological Theory of Entanglement.....	17
2. The Ontological Core of the Entropic Seesaw Model(ESSM)	19
2.1 The Entropic Field as Ontological Substrate	19
2.2 Entanglement as Shared Entropic Manifold	20
2.3 The Dual Geometry: Spatial Distance versus Entropic Distance	21
2.4 Symmetric and Antisymmetric Entropic Modes	22
2.5 The Entropic Distance Functional.....	23
3. The Mathematical Architecture — The ESSM Effective Action	24
3.1 The Two-Sector Entropic Action	24
3.2 The Full ESSM Effective Action in Symmetric-Antisymmetric Variables	25
3.3 The Bridge Order Parameter and Symmetry Breaking.....	26
3.4 The Coherence Strength Functional	28
3.5 The Equation of Motion for the Antisymmetric Mode.....	29
3.6 The Entropic Frequency and Mass Gap	30
4. Formation Dynamics — The Entropic Genesis of Entanglement	31
4.1 The Formation Drive Equation	31
4.2 The Formation Solution	32
4.3 The Formation Time and Threshold Crossing.....	33
4.4 The Entropic Time-Limit (ETL) Bounds.....	34
4.5 The Entropic Formation Functional.....	35
5. Persistence, Propagation, and the Seesaw Equilibrium	36
5.1 The Persistence Law	36

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein’s EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

5.2 The Two-Layer Architecture Applied to Entanglement 37

5.3 The Entropic Seesaw Equilibrium Condition (TESEC)..... 38

6. Decoherence, Measurement, and the Seesaw Collapse Threshold..... 39

6.1 The Stability Criterion 39

6.2 The Decoherence Rate Decomposition..... 40

6.3 The Entropic Seesaw Collapse Mechanism (TESCM)..... 41

6.4 The Seesaw-Collapse Threshold from Measurement Loading 42

6.5 Entropic Bookkeeping: The Second Law in the Coherent Sector 43

7. The Attosecond Entanglement Formation Time — Empirical Anchors for ESSM 44

7.1 The Experimental Landscape 44

7.2 ESSM Interpretation of the Attosecond Results 47

7.3 ESSM Predictions versus Standard Interpretation..... 48

7.4 The Experimental Anchors Table 48

8. Einstein's EPR Paradox Dissolved — Entropic Distance versus Spatial Distance 50

8.1 The EPR Argument Reconstructed 50

8.2 The ESSM Resolution 51

8.3 Why ESSM Does Not Reintroduce Hidden Variables 52

8.4 The No-Signaling Proof 53

9. ER=EPR Reinterpreted — The Entropic Bridge Completion..... 54

9.1 The Maldacena-Susskind Conjecture (MSC) and Its Scope..... 54

9.2 The ESSM Entropic Bridge..... 56

9.3 The Geometric Shadow Interpretation 56

9.4 ESSM as Thermodynamic Completion of ER=EPR 57

10. Testable Predictions, Experimental Protocols, and the ESSM Research Program 59

10.1 The Asymmetric Entropy-Injection Protocol..... 59

10.2 Channel-Resolved Formation Time Measurements..... 60

10.3 The Coherence-Lifetime Scaling Law..... 60

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein’s EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

10.4 Comparative Predictions Table 61

10.5 The ESSM Experimental Roadmap..... 62

11. Open Mathematical Frontiers and Concluding Assessment 63

11.1 Open Mathematical Tasks63

11.2 Limitations, Constraints, and Strategic Directions65

11.3 Assessment and Significance 66

Acknowledgments68

Addendum69

Dedication70

Author Note71

References 72

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1. The Entanglement Problem in Contemporary Physics

1.1 The Standard Quantum-Mechanical Account

In the standard quantum-mechanical formalism, entanglement is defined as a property of composite systems whose state vector cannot be factorized into a tensor product of subsystem states. Consider a bipartite system AB composed of subsystems A and B with respective Hilbert spaces H_A and H_B . The composite Hilbert space is $H_{AB} = H_A \otimes H_B$. A pure state $|\Psi\rangle_{AB}$ is said to be entangled if and only if there exist no states $|\phi\rangle_A \in H_A$ and $|\chi\rangle_B \in H_B$ such that $|\Psi\rangle_{AB} = |\phi\rangle_A \otimes |\chi\rangle_B$. The Schmidt decomposition theorem guarantees that any bipartite pure state can be written as $|\Psi\rangle_{AB} = \sum_i c_i |a_i\rangle_A \otimes |b_i\rangle_B$, where the Schmidt coefficients $c_i \geq 0$ satisfy $\sum_i c_i^2 = 1$. When more than one coefficient is nonzero, the state is entangled.

The degree of entanglement is typically quantified by the von Neumann entropy of the reduced density matrix: $S(\rho_A) = -\text{Tr}(\rho_A \ln \rho_A)$, where $\rho_A = \text{Tr}_B(|\Psi\rangle\langle\Psi|)$ is obtained by tracing over the degrees of freedom of subsystem B . For a maximally entangled state of two qubits — the Bell states — this entropy reaches its maximum value of $\ln 2$. These quantities are mathematically impeccable and experimentally well tested. They tell us *when* a system is entangled and *how much* it is entangled. They do not tell us *how* entanglement forms, *why* it persists, or *what* physical structure sustains it.

This observation is not a criticism of the quantum formalism as a predictive instrument; it is a statement about the formalism's ontological depth. The state vector is an element of Hilbert space — an abstract mathematical structure. Standard quantum mechanics provides no interpretation of this structure as a representation of a physical entity that exists in the world independently of measurement. The measurement postulate — whether

in the Copenhagen, decoherence, or many-worlds formulation — specifies what happens to the state vector upon observation but does not identify a physical process by which entanglement is established or maintained. As a consequence, the entanglement of two particles separated by light-years appears, within the formalism, as an instantaneous, acausal correlation without physical substrate — precisely the "spooky action at a distance" that **Einstein** found intolerable.

1.2 The Dynamical Deficit

The standard formalism provides rules for computing the evolution of a quantum state under Hamiltonian dynamics — the Schrödinger equation — and for computing the probabilities of measurement outcomes — the Born rule. Entanglement arises whenever two systems interact via a Hamiltonian that does not factorize: if $H_{AB} \neq H_A \otimes I_B + I_A \otimes H_B$, then a product state will generally evolve into an entangled state. But this statement identifies a sufficient algebraic condition for entanglement production; it does not provide a *physical mechanism*. The Schrödinger equation treats the Hamiltonian as given and the Hilbert space as a fixed arena. It does not explain what physical process corresponds to the transition from a factorized state to a non-factorized one — what changes in the physical world when entanglement forms.

The Copenhagen interpretation, in its strict form, declines to ask the question. The state vector is not a representation of reality but a tool for computing measurement outcomes; asking what happens "between measurements" is declared meaningless. This interpretive austerity comes at a conceptual cost: it renders entanglement a correlation without a correlator, a relationship without relata. The decoherence program, developed by Zurek, Joos, Zeh, and others [39, 45, 46, 47], provides a partial answer by showing how environmental interactions suppress off-diagonal elements of the density matrix in a

preferred basis, thereby explaining the *loss* of coherence and the appearance of classical outcomes. But decoherence theory describes the *destruction* of entanglement, not its *creation*. It explains why macroscopic superpositions are fragile; it does not explain what positive physical structure sustains entanglement when it is present.

This dynamical deficit is most acute at three points: (i) *formation* — by what process, on what timescale, does a non-entangled state become entangled? (ii) *persistence* — by what mechanism do entangled correlations survive under spatial separation, given that no signal can travel between the subsystems? (iii) *breakdown* — what physical criterion distinguishes a "measurement" that destroys entanglement from a mere interaction that does not? The standard formalism answers (i) with "whenever the Hamiltonian couples the subsystems," answers (ii) with "unitary evolution preserves the state vector," and answers (iii) with "when the interaction is of a particular kind" — but none of these answers identifies a physical mechanism. They are algebraic tautologies dressed as explanations.

1.3 The Need for an Ontological Theory of Entanglement

The argument of this subsection is that entanglement demands an *ontological substrate* — a physical structure that exists in the [physical] world and underwrites the correlations that quantum mechanics predicts and experiments confirm. This demand is not metaphysical speculation; it is a requirement of explanatory adequacy. A theory that predicts correlations but provides no account of what sustains them is not a complete theory — it is a catalogue of regularities awaiting explanation.

Several programs have attempted to supply the missing ontology. Bohmian mechanics introduces a pilot wave on configuration space that guides the particles along definite trajectories; entanglement is mediated by the nonlocal dependence of the pilot wave on

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A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

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the positions of all particles. This is a genuine ontology but one that is explicitly nonlocal in configuration space, and it does not decompose the structure of entanglement into formation, persistence, and breakdown stages. The many-worlds interpretation distributes the correlations across decoherent branches of the universal wave function; this is ontologically extravagant but does not identify a physical substrate for the correlations within each branch. **Relational Quantum Mechanics (RQM), following Rovelli's formulation, treats the quantum state [vector] as relative to an observer or physical system, thereby dissolving the measurement problem by rejecting observer-independent states** (Rovelli 1996, [48]). **However, RQM offers no underlying physical mechanism for the correlations it describes.**

The **Entropic Seesaw Model (ESSM)** provides a different answer. Entanglement is not a correlation between pre-existing, ontologically separate systems. It is the *persistence of a single entropic object* — a shared entropic manifold — whose two ends are apprehended, from the standpoint of spatial geometry, as distinct subsystems. The "spooky action" vanishes because there is no action at a distance: there is one object, locally structured in the entropic manifold, whose spatial projections happen to be far apart. **The seesaw is one plank, and the plank does not need to send a signal from one end to the other in order for the ends to be correlated.**

* * *

2. The Ontological Core of the Entropic Seesaw Model(ESSM)

2.1 The Entropic Field as Ontological Substrate

The **Theory of Entropicity (ToE)** posits a single dynamical scalar field — the **entropic field** $S(\Lambda)$ — defined on an entropic manifold M_S as the fundamental ontological entity of physics [1, 6]. This field is not the **Boltzmann** entropy of statistical mechanics, not the **von Neumann** entropy of quantum information theory, and not the thermodynamic entropy of macroscopic equilibrium. It is a continuous, local, dynamical field whose configurations and gradients generate all physical structure: spacetime geometry, quantum behavior, particle content, and thermodynamic law emerge as entropic phenomena, not the reverse. The entropic field is to the Theory of Entropicity what the metric tensor is to general relativity — the primary variable from which all else is derived.

The dynamics of $S(\Lambda)$ are governed by the **Obidi Action**, developed in Letters I, IA, IB, and IC [1, 3, 4, 6]. The Obidi Action is a variational principle on the entropic manifold; its Euler-Lagrange equations yield field equations for $S(\Lambda)$ that encode gravitational, quantum, and thermodynamic sectors in a unified entropic language. The entropic field is not a statistical summary of microscopic mechanical degrees of freedom; it is the *ground floor* of physical ontology. Mechanical degrees of freedom — positions, momenta, forces — are emergent from the entropic field, not the other way around. This inversion of the explanatory hierarchy is the defining commitment of the ToE program, and it is the foundation upon which ESSM is built.

For entanglement theory, the crucial property of the entropic field is that it supports a notion of *entropic proximity* that is independent of spatial distance. Two field

configurations $S_A(x)$ and $S_B(x)$ may be far apart in the spatial metric but indistinguishable — or nearly so — in their entropic content. When this obtains, the two configurations constitute a single entropic object, and any observable that depends on the entropic structure will reflect this unity. This is the physical basis of entanglement in the ESSM framework.

2.2 Entanglement as Shared Entropic Manifold

The core thesis of ESSM can be stated precisely: *what standard quantum mechanics represents as a non-factorizable bipartite state is, at a deeper ontological level, a single structured configuration of the entropic field on a shared manifold.* The non-factorizability of the Hilbert-space state vector is not the fundamental fact; it is the mathematical projection, cast into the Hilbert-space formalism, of a more primitive physical reality — the existence of a shared entropic manifold M_{AB} .

The term "seesaw" is not merely pedagogical or metaphorical. It expresses a precise constraint structure. *Consider a physical seesaw [often used by children or adults at a play park]: it is a single rigid body whose two ends are spatially separated but dynamically locked. If one end is depressed, the other rises — not because a signal propagates from one end to the other at some finite speed, but because the plank is one object and the constraint is structural. The rigidity of the plank is not a signal; it is a fact about the object's constitution.* In ESSM, the shared manifold M_{AB} plays exactly the role of the plank. The two subsystems A and B are the two ends. **Their correlations — the quantum-mechanical entanglement — arise not from a signal transmitted between them but from the structural fact that they belong to one entropic object.**

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

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Research Lab, The Aether

May 3, 2026

The fundamental formation equation of ToE's ESSM is:

$$M_A \oplus M_B \rightarrow M_{AB} \quad (1)$$

where M_A and M_B are the previously distinct entropic sectors (each describing one subsystem's entropic field configuration on its own manifold) and M_{AB} is the merged, shared manifold that results from their interaction. **The symbol \oplus denotes entropic sector union — a topological operation that merges the two manifolds into a single connected domain. The arrow \rightarrow denotes a dynamical process that requires finite time and finite entropic resources. Equation (1) is a local restructuring rule: the merger occurs in the interaction region Ω_{AB} where the two fields overlap, and it proceeds by local entropic dynamics, not by any nonlocal mechanism. The formation time — the time required for the merger to reach completion — is a well-defined, finite, physically measurable quantity, as the attosecond experiments discussed in Section 7 now confirm.**

2.3 The Dual Geometry: Spatial Distance versus Entropic Distance

Central to the ESSM resolution of EPR is the introduction of a *dual geometry* — a framework in which two independent notions of distance coexist and may diverge radically. The first is the ordinary spacetime distance $d_{\text{space}}(A,B)$, computed from the metric tensor of spacetime in the standard way. The second is the **entropic distance** $d_E(A,B)$, which measures the degree of distinguishability between the entropic field configurations of subsystems A and B within the shared manifold.

The defining condition of entanglement in ESSM is:

$$d_{\text{space}}(A,B) \gg 0, \quad d_E(A,B) \approx 0 \quad (2)$$

That is, the subsystems may be arbitrarily far apart in spacetime while remaining entropically indistinguishable — entropically local. Entanglement is nonlocal in spacetime geometry while remaining *local in entropic geometry*. **The apparent nonlocality of quantum correlations is, in the ESSM view, an artifact of projecting an entropically local fact onto a spatial coordinate system in which the two ends of the seesaw happen to be far apart.**

This dual geometry dissolves the EPR puzzle at the ontological level. **The Einstein EPR [paradox] argument proceeds from the premise that spatial separation implies ontological independence:** if A and B are far apart, they must be separate physical systems, and any correlation between them must be mediated by a signal or pre-established by a common cause. The Theory of Entropicity (ToE)'s **ESSM denies such [an EPR] premise.** Spatial distance is not the relevant measure of ontological independence; entropic distance is. **Two systems may be spatially distant but entropically identical — constituting one object in the entropic manifold — and their correlations require no signal because there is nothing to signal between: there is only one system, viewed from two spatial locations.** And ESSM affirms that any correlation between two or more of such systems is fundamentally determined by the dictate of the Entropic Field and not [strictly or overly] by its emergent properties or projections.

2.4 Symmetric and Antisymmetric Entropic Modes

To develop the mathematical structure of ESSM, we introduce symmetric and antisymmetric entropic coordinates on the common interaction support Ω_{AB} . Let $S_A(x,t)$ and $S_B(x,t)$ denote the local entropic field amplitudes associated with subsystems A and B, defined on Ω_{AB} during and after their interaction. The symmetric and antisymmetric modes are defined as:

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

$$S_+(x,t) = [S_A(x,t) + S_B(x,t)] / \sqrt{2} \quad (3)$$

$$S_-(x,t) = [S_A(x,t) - S_B(x,t)] / \sqrt{2} \quad (4)$$

The physical interpretation of these modes is fundamental to the seesaw picture. The **symmetric mode** S_+ carries the total entropic content of the composite system — it is the "**center-of-mass**" coordinate in entropy space. Its dynamics govern the overall entropic evolution of the bipartite system. The **antisymmetric mode** S_- measures the internal distinguishability of the two subsectors — it is the "**relative**" coordinate that quantifies how much the two ends of the seesaw differ from each other.

In the ESSM framework, entanglement corresponds to the condition $S_- \approx 0$: the two sectors are entropically indistinguishable within the shared manifold, and the seesaw is balanced. The composite system behaves as a single entropic entity whose internal label (A versus B) carries no physical information [that requires physical spacetime interval signal for enforcement and correlation]. Measurement or decoherence corresponds to the growth of S_- — the seesaw tilts, the two sectors become distinguishable, subsystem labels acquire physical meaning, and the entanglement weakens or breaks. The entire dynamical narrative of entanglement — formation, persistence, and breakdown — is encoded in the evolution of $S_-(x,t)$.

2.5 The Entropic Distance Functional

The entropic distance between the two subsystems is defined rigorously as a weighted L^2 norm of the antisymmetric mode on the shared manifold:

$$d_E^2(A,B;t) = \int_{\Omega_{AB}} w(x) |S_-(x,t)|^2 d\mu_g \quad (5)$$

where $w(x)$ is an entropic weight function — a positive, normalized function that may reflect the local entropic density or the geometry of the interaction region — and $d\mu_g$ is

the invariant measure on the entropic manifold, incorporating any nontrivial metric structure. When $d_E \approx 0$, the two subsystems share a single entropic identity; they are one object, and any measurement on one arm of the seesaw is ipso facto a statement about the other, not because a signal has been sent but because there is only one system to make statements about [just as one end of a seesaw moves up only as the other moves down, the two motions forming a single, inseparable, counter-balanced and correlated up-down (or down-up) state]. When d_E grows, subsystem labels re-emerge, the seesaw tilts, and the systems become ontologically distinct — decoherence and factorization follow.

The entropic distance functional d_E is the central diagnostic of ESSM. **It replaces the von Neumann entropy** of the reduced state as the fundamental measure of entanglement: **where the von Neumann entropy quantifies entanglement as a property of the Hilbert-space state, d_E quantifies it as a property of the entropic manifold — a physical, geometrically meaningful quantity with dimensions of entropy and a clear operational interpretation.**

* * *

3. The Mathematical Architecture — The ESSM Effective Action

3.1 The Two-Sector Entropic Action

The mathematical program of ESSM begins with the construction of an effective action for the bipartite entangled system. The action is formulated in the spirit of the **Obidi Action**

developed in Letters I, IA, IB, and IC [1, 3], adapted to the two-sector structure of the entanglement problem. The [canonical] natural two-sector entropic action is therefore:

$$A_{AB} = \int d^4x [L_A + L_B + \lambda C(S_A, S_B) - \eta D_{env}] \quad (6)$$

Here, L_A and L_B are subsystem entropic Lagrangian densities, each describing the free evolution of one entropic sector in the absence of [the] interaction. The term $C(S_A, S_B)$ is the **coherence-coupling functional** — a function of both subsystem fields that encodes the entangling interaction. The coupling constant λ is the **entangling strength**: it measures the intensity of the interaction that drives the merger of the two sectors. The term D_{env} encodes the effects of the environment — decoherence, dissipation, and entropy production due to coupling with external degrees of freedom — and η is the **decoherence coupling constant**.

The physical content of equation (6) is transparent. The first two terms govern the independent evolution of subsystems A and B. The third term drives entanglement formation: when λC is large, the two sectors are strongly coupled, and the dynamics favor the formation of a shared manifold. The fourth term opposes entanglement: when ηD_{env} is large, environmental decoherence degrades the shared manifold. The competition between these terms determines whether entanglement forms, how quickly it forms, how long it persists, and when it breaks down.

3.2 The Full ESSM Effective Action in Symmetric-Antisymmetric Variables

The two-sector action (6) may be rewritten in the symmetric-antisymmetric variables introduced in Section 2.4. After performing the change of variables $(S_A, S_B) \rightarrow (S_+, S_-)$ and introducing the **bridge order parameter** Ξ_{AB} — a scalar field that quantifies the

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

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Research Lab, The Aether

May 3, 2026

strength of the entropic bridge linking the two sectors — the full ESSM effective action takes the form:

$$A_{\text{ESSM}} = \int d^4x \sqrt{-g} \left[(\alpha_+/2) \nabla_\mu S_+ \nabla^\mu S_+ + (\alpha_-/2) \nabla_\mu S_- \nabla^\mu S_- + (\alpha_\Xi/2) \nabla_\mu \Xi_{AB} \nabla^\mu \Xi_{AB} - U(\Xi_{AB}) - (\kappa/2) \Xi_{AB} S_-^2 - \eta_A J_A^{\text{env}} S_A - \eta_B J_B^{\text{env}} S_B \right] \quad (7)$$

Each term has a precise physical interpretation. The kinetic terms $(\alpha_+/2) \nabla_\mu S_+ \nabla^\mu S_+$ and $(\alpha_-/2) \nabla_\mu S_- \nabla^\mu S_-$ govern the propagation of the symmetric and antisymmetric modes, respectively, with stiffness coefficients α_+ and α_- . The kinetic term for the bridge order parameter Ξ_{AB} governs its own propagation with stiffness α_Ξ . The potential $U(\Xi_{AB})$ controls the spontaneous activation of the bridge. The coupling term $-(\kappa/2) \Xi_{AB} S_-^2$ is the heart of the ESSM mechanism: it links the bridge order parameter to the antisymmetric mode, so that a nonzero bridge gives the antisymmetric mode an effective mass — suppressing it and thereby stabilizing entanglement. The environmental coupling terms $\eta_A J_A^{\text{env}} S_A$ and $\eta_B J_B^{\text{env}} S_B$ describe the coupling of each subsystem to its local environment, driving decoherence.

3.3 The Bridge Order Parameter and Symmetry Breaking

The bridge order parameter Ξ_{AB} is the central dynamical variable that distinguishes entangled from unentangled states. Its potential $U(\Xi_{AB})$ is given in the standard symmetry-breaking form:

$$U(\Xi_{AB}) = (m_\Xi^2/2) \Xi_{AB}^2 + (v/4) \Xi_{AB}^4 - \sigma J_{\text{int}}(t) \Xi_{AB} \quad (8)$$

Here, m_Ξ is the bare mass of the bridge field, v is the quartic self-coupling that stabilizes the potential at large field values, and $J_{\text{int}}(t)$ is the **local entangling source** — the interaction that drives the formation of the bridge. The parameter σ sets the coupling strength between the bridge field and the entangling source.

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

The physics of equation (8) is that of a symmetry-breaking transition. In the absence of the entangling source ($J_{\text{int}} = 0$), the potential has a minimum at $\Xi_{AB} = 0$ — no bridge, no entanglement. When $J_{\text{int}}(t)$ becomes sufficiently large — as occurs during the interaction of the two subsystems — the linear source term tilts the potential, and a new minimum appears at a nonzero value of Ξ_{AB} . The bridge "turns on": Ξ_{AB} acquires a nonzero expectation value $\langle \Xi_{AB} \rangle$, signaling the formation of the entropic bridge.

The consequences for the antisymmetric mode are immediate. The coupling term $-(\kappa/2) \Xi_{AB} S_-^2$ in the action (7) generates an effective mass-squared for S_- :

$$\Omega_E^2(\Xi_{AB}) = c_E^2 k^2 + \kappa \langle \Xi_{AB} \rangle$$

When $\langle \Xi_{AB} \rangle$ is large, the effective mass is large, and S_- is energetically suppressed — confined to small oscillations near zero. This is the ESSM mechanism for entanglement stabilization: the bridge order parameter generates a mass gap for the distinguishability mode, making it costly for the two sectors to become different. The seesaw is held in balance by the weight of the bridge.

This mechanism has a precise analogue in particle physics. The Higgs mechanism gives mass to gauge bosons by spontaneous symmetry breaking: a scalar field acquires a nonzero vacuum expectation value, and the gauge fields that couple to it become massive. **In the Theory of Entropicity (ToE)'s ESSM, the bridge order parameter Ξ_{AB} plays the role of the Higgs field, and the antisymmetric mode S_- plays the role of the gauge field.** The "mass" acquired by S_- is the entropic mass gap — the energy cost of distinguishability — and it is this mass gap that protects entanglement against small perturbations.

3.4 The Coherence Strength Functional

The central dynamical diagnostic of ESSM is the **coherence strength functional** $\Gamma_{AB}(t)$, which integrates all the relevant information about the state of the entropic bridge into a single, dimensionless, time-dependent quantity:

$$\Gamma_{AB}(t) = \Xi_{AB}(t) \cdot \exp[-d_E^2(A,B;t) / \ell_E^2] \cdot I_{AB}(t) / \sqrt{[(\Sigma_A + \epsilon)(\Sigma_B + \epsilon)]} \quad (9)$$

Each factor in this expression has a clear physical meaning. The bridge order parameter $\Xi_{AB}(t)$ measures the strength of the entropic bridge — it is zero before the bridge forms and grows to a maximum after formation. The exponential factor $\exp[-d_E^2 / \ell_E^2]$ suppresses the coherence strength when the entropic distance between the two sectors is large compared to the **entropic coherence length** ℓ_E — the characteristic scale over which entropic indistinguishability can be maintained. The mutual entropic information $I_{AB}(t)$ measures the shared information content between the two sectors — it is maximal for maximally entangled states and zero for product states. The denominator $\sqrt{[(\Sigma_A + \epsilon)(\Sigma_B + \epsilon)]}$, where Σ_A and Σ_B are the subsystem entropies and ϵ is a small regularizer to prevent divergence, normalizes the coherence strength by the subsystem entropy content, ensuring that Γ_{AB} is a dimensionless quantity that lies in the range $[0, \Gamma^*]$, where Γ^* is the saturation value.

The coherence strength functional is the ESSM replacement for the concurrence, tangle, or entanglement entropy of standard quantum information theory. Unlike those measures, which are defined within the Hilbert-space formalism and carry no dynamical content, Γ_{AB} is defined in terms of entropic field variables and evolves according to dynamical equations derived from the ESSM action of the Theory of Entropicity (ToE). It provides a real-time, dynamically evolving measure of entanglement that can be connected to experimental observables.

3.5 The Equation of Motion for the Antisymmetric Mode

The equation of motion for the antisymmetric mode S_- is obtained by varying the ESSM action (7) with respect to S_- . The result is a damped, driven oscillator equation of the form:

$$\ddot{S}_- + \gamma_E \dot{S}_- + \Omega_E^2 (\Xi_{AB}) S_- = \eta \Delta J_{\text{env}}(t) \quad (10)$$

where $\Delta J_{\text{env}}(t) = J_{A^{\text{env}}}(t) - J_{B^{\text{env}}}(t)$ is the **asymmetric environmental drive** — the difference between the environmental couplings of the two subsystems — γ_E is the **entropic dissipation coefficient**, and Ω_E is the effective frequency whose square was defined above.

The physical content of equation (10) is the dynamical narrative of entanglement in a single line. In the coherent phase, when the bridge is active and Ξ_{AB} is large, the effective frequency Ω_E is large, and S_- executes rapid, small-amplitude oscillations around zero — the seesaw is balanced, and entanglement is stable. The dissipation term $\gamma_E \dot{S}_-$ damps these oscillations, further stabilizing the balanced state. Environmental asymmetry — a difference between the entropic environments of the two arms — acts as a driving torque on the right-hand side. **If this torque is small compared to the restoring force $\Omega_E^2 S_-$, the seesaw absorbs it; if the torque exceeds the restoring force, the seesaw tips, S_- grows, the entropic distance increases, and decoherence sets in.** Measurement, in this picture, is a particularly strong and directional form of **environmental torque (EnvT) [generally, the Entropic Torque (ET)]**.

Beyond this specific measurement-induced torque, the Theory of Entropicity (ToE) distinguishes between **environmental torque** and the more general **entropic torque**.

Environmental Torque (EnvT) refers to the subset of perturbations arising from concrete physical surroundings—thermal fluctuations, phonon baths, electromagnetic noise,

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

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Research Lab, The Aether

May 3, 2026

vacuum jitter, or any structured interaction that injects directional bias into the system's entropic seesaw. But in ToE, this is only one component of a broader phenomenon.

Entropic Torque (ET) is the universal term: it encompasses *all* gradients, couplings, or informational asymmetries that exert a directional push on the entropic coordinates S_+ and S_- . ET includes environmental effects, but also internal dynamical imbalances, entropic curvature of configuration space, and even self-generated feedback from the system's own history of entropy production. In this wider view, **EnvT** is simply the externally sourced contribution to a more fundamental entropic torque budget, while ET captures the full spectrum of forces capable of tilting the seesaw, driving entropic displacement, and ultimately determining whether coherence is preserved or lost.

3.6 The Entropic Frequency and Mass Gap

The effective frequency of the antisymmetric mode — the "**restoring force**" of the seesaw — is given explicitly by:

$$\Omega_E^2(\Xi_{AB}) = c_E^2 k^2 + \kappa\langle\Xi_{AB}\rangle \quad (11)$$

The first term, $c_E^2 k^2$, is the kinetic contribution: it arises from the spatial gradient of S_- and depends on the wavenumber k and the entropic propagation speed c_E . This term is always present and provides a baseline restoring force even in the absence of a bridge. The second term, $\kappa\langle\Xi_{AB}\rangle$, is the **entropic mass gap**: it is generated by the bridge order parameter and is present only when the bridge is active ($\langle\Xi_{AB}\rangle > 0$). This mass gap is the key to entanglement stability.

The term "**mass gap**" is used here advisedly. In quantum field theory, a mass gap is the minimum energy required to create an excitation above the ground state. In ESSM, the **entropic mass gap** $\kappa\langle\Xi_{AB}\rangle$ is the **minimum entropic cost (MEC)** of creating a

distinguishability excitation — a perturbation that makes S_- nonzero and thereby separates the two sectors. When the bridge is strong ($\langle \Xi_{AB} \rangle$ large), this cost is high, and entanglement is robust; when the bridge weakens ($\langle \Xi_{AB} \rangle \rightarrow 0$), the mass gap closes, the distinguishability mode becomes soft, and infinitesimal perturbations can break the entanglement. This provides a precise, quantitative criterion for the onset of decoherence, which we shall develop further in Section 6 of this work.

The analogy to the Higgs mechanism is not merely suggestive — it is structurally exact. In the Standard Model, the W and Z bosons acquire mass through their coupling to the Higgs vacuum expectation value. In ESSM, the antisymmetric mode S_- acquires an entropic mass through its coupling to the bridge vacuum expectation value $\langle \Xi_{AB} \rangle$. The Higgs mechanism protects the electroweak vacuum against symmetry restoration; the ESSM bridge mechanism protects the entangled state against decoherence. The entropic mass gap is the ESSM signature of a genuinely new regime — an entangled phase of the entropic field that is dynamically stable and experimentally distinguishable.

* * *

4. Formation Dynamics — The Entropic Genesis of Entanglement

4.1 The Formation Drive Equation

The formation of entanglement in ESSM is governed by the evolution of the coherence strength functional $\Gamma_{AB}(t)$. During the interaction phase — when the two subsystems are in local contact and the entangling source $J_{\text{int}}(t)$ is active — the coherence strength

evolves according to a coarse-grained rate equation that captures the competition between formation drive and decoherence:

$$\dot{\Gamma}_{AB} = r_f(t)(1 - \Gamma_{AB}/\Gamma^*) - \gamma_d(t) \Gamma_{AB} \quad (12)$$

Here, $r_f(t)$ is the **formation drive** — a rate that depends on the intensity and duration of the entangling interaction. The factor $(1 - \Gamma_{AB}/\Gamma^*)$ enforces saturation: the coherence strength cannot exceed the saturation value Γ^* , which is determined by the maximum capacity of the shared manifold. The term $\gamma_d(t)$ is the **total decoherence rate**, given by the sum $\gamma_d = \gamma_{env} + \gamma_{\nabla S} + \gamma_{meas}$, where γ_{env} is environmental decoherence, $\gamma_{\nabla S}$ is the contribution from spatial inhomogeneity of the entropic field, and γ_{meas} is the contribution from measurement or monitoring channels.

Equation (12) is a **logistic growth equation (LGE)** with decay — a standard form in nonlinear dynamics, here given an entropic interpretation. The formation drive $r_f(t)$ pushes the system toward entanglement; the decoherence rate $\gamma_d(t)$ opposes it. The balance between these two determines whether entanglement forms and, if so, how quickly and how strongly.

4.2 The Formation Solution

During the interaction pulse, if the formation drive and decoherence rate are approximately constant, equation (12) admits the analytic solution:

$$\Gamma_{AB}(t) = \Gamma_{\infty}(1 - e^{-t/\tau_f}) \quad (13)$$

where the asymptotic coherence strength and formation timescale are:

$$\Gamma_{\infty} = r_f \Gamma^* / (r_f + \Gamma^* \gamma_d) \quad (14)$$

$$\tau_f = (r_f/\Gamma^* + \gamma_d)^{-1} \quad (15)$$

The physical content of these expressions is direct. The asymptotic coherence Γ_∞ is the maximum entanglement that the system can achieve under the given conditions — it is the fixed point of the formation dynamics. It is always less than the saturation value Γ^* because decoherence is always present. The formation timescale τ_f is the characteristic time for the coherence strength to reach $(1 - 1/e) \approx 63\%$ of its asymptotic value. Crucially, τ_f depends on both the formation drive and the decoherence rate: faster driving and lower decoherence both produce shorter formation times. This parametric dependence is a testable prediction of ESSM.

4.3 The Formation Time and Threshold Crossing

The entangled phase is not established at $t = 0$, nor at $t = \infty$. It is established at the moment when the coherence strength first crosses a critical threshold Γ_c — the minimum value of Γ_{AB} at which the entropic mass gap is sufficient to suppress the antisymmetric mode and stabilize the shared manifold. The **formation time** t_c is defined as the earliest time at which $\Gamma_{AB}(t_c) = \Gamma_c$:

$$t_c = \tau_f \cdot \ln[\Gamma_\infty / (\Gamma_\infty - \Gamma_c)] \quad (16)$$

Equation (16) above is a logarithmic threshold-crossing time expression derived from an exponential-type growth law (of general dynamical systems):

$$\Gamma_{AB}(t) = \Gamma_\infty (1 - e^{-(t/\tau_f)}) \quad (16.1)$$

This [Equation (16)] is the **ESSM formation time (EFT)** — the *finite threshold-crossing interval (FTCI)* during which the shared entropic manifold crystallizes from two previously independent sectors. **It is the central quantity that connects ESSM to the attosecond experimental program.** The attosecond photoionization experiments [33] discussed in

Section 7 probe precisely this interval: they observe the build-up of entanglement on a timescale of hundreds of attoseconds, and ESSM predicts that this timescale is t_c .

A crucial distinction, central to the ESSM program and absent from standard quantum mechanics, is the **formation-persistence distinction**. *Formation is the finite threshold-crossing interval during which the shared manifold is assembled by local dynamics. Persistence is the maintenance of the already-formed manifold after the interaction ceases and the subsystems separate. Formation requires energy input, interaction, and finite time. Persistence requires only the structural integrity of the shared manifold — no signal, no energy input, no ongoing interaction. Standard quantum mechanics conflates these two stages because it treats entanglement as a kinematic property of the state vector, not a dynamically structured object.*

4.4 The Entropic Time-Limit (ETL) Bounds

The ToE program provides two fundamental lower bounds on the formation time — bounds that arise not from the **Heisenberg uncertainty principle (HUP)** but from the finite capacity of the entropic field to reorganize. The first is the **entropic uncertainty bound (EUP)**:

$$\Delta t_{\text{ent}} \geq \hbar / (2 \Delta S_{\text{max}}) \quad (17)$$

where ΔS_{max} is the maximum entropic change available in the formation process. This bound states that the formation time cannot be shorter than the ratio of the quantum of action to the maximum entropic gradient. When the available entropy change is large — as in high-energy photoionization — the bound permits very short formation times, consistent with the attosecond regime.

The second bound is the **No-Rush Theorem (NRT)**, a distinctive result of the ToE program:

$$\tau_{\min} = k_B \ln 2 / (dS/dt)_{\max} \quad (18)$$

where $(dS/dt)_{\max}$ is the maximum rate of entropy production in the formation process.

This ToE bound states that no entropic restructuring can occur faster than the maximum entropy production rate permits. It is an information-theoretic speed limit on entropic dynamics, analogous to — but distinct from — the **Margolus-Levitin bound (MLB)** on quantum computation speed. **The No-Rush Theorem (NRT) is not a Heisenberg-type bound: it arises from the finite information-processing capacity of the entropic field, not from the commutation relations of observables.**

Together, equations (17) and (18) establish that entanglement formation is a process with an irreducible minimum duration — a prediction that is qualitatively confirmed by the attosecond experiments and quantitatively testable as experimental precision improves.

4.5 The Entropic Formation Functional

The formation process can be cast in a variational form that connects ESSM formation dynamics to the **Obidi Action's** variational philosophy. The **entropic formation functional** is thus defined as:

$$F[\Gamma] = \int_0^{t_c} [(d\Gamma_{AB}/dt)^2 / (2r_f) + V_{\text{eff}}(\Gamma_{AB})] dt \quad (19)$$

where $V_{\text{eff}}(\Gamma_{AB})$ is an effective potential that depends on the coherence strength and the decoherence landscape. The formation trajectory $\Gamma_{AB}(t)$ that the system actually follows is the one that minimizes $F[\Gamma]$ subject to the boundary conditions $\Gamma_{AB}(0) = 0$ (no entanglement before interaction) and $\Gamma_{AB}(t_c) = \Gamma_c$ (threshold crossing at the formation time).

This variational formulation has several consequences. **First**, it establishes that the formation trajectory is an extremal path in the space of possible coherence histories — the system finds the "cheapest" route to entanglement, balancing the **kinetic entropic cost (KEC)** of rapid formation against the **potential entropic cost (PEC)** of the coherence landscape. **Second**, it connects ESSM to the broader Obidi Action program, in which **all physical processes are governed by variational principles on the entropic manifold**. **Third**, it opens the door to a path-integral formulation of entanglement formation, in which the formation amplitude is computed by summing over all possible **coherence entropic histories (CEH)** weighted by $\exp(-F[\Gamma])$.

* * *

5. Persistence, Propagation, and the Seesaw Equilibrium

5.1 The Persistence Law

After the interaction ceases and the subsystems separate, the entangling source $J_{\text{int}}(t)$ turns off. The formation drive r_f drops to zero, and the coherence strength evolves under decoherence alone:

$$\dot{\Gamma}_{AB} = -\gamma_d \Gamma_{AB} \quad (20)$$

whose solution, for time-dependent decoherence rate, is:

$$\Gamma_{AB}(t) = \Gamma_{AB}(t_s) \exp\left[-\int_{t_s}^t \gamma_d(t') dt'\right] \quad (21)$$

where t_s is the time of separation. Equation (21) is the **persistence law** of ESSM.

The above equation, rewritten here

$$\Gamma_{AB}(t) = \Gamma_{AB}(t_s) \exp\left[-\int_{t_s}^t \gamma_d(t') dt'\right] \quad (21),$$

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

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Research Lab, The Aether

May 3, 2026

is a natural solution to:

$$d\Gamma_{AB}/dt = -\gamma_d(t) \Gamma_{AB}(t) \quad (21.1),$$

which is a first-order linear decay equation with a time-dependent rate, but now employed formally in the Theory of Entropicity (ToE) for the Entropic Seesaw Model (ESSM).

Equation (21) states that the coherence strength decays exponentially under decoherence, with a rate determined by the integrated decoherence history. In an ideal environment with $\gamma_d \rightarrow 0$, the coherence strength persists indefinitely — entanglement is maintained without limit and without signal transport.

The persistence law makes precise the ESSM claim that entanglement is not signal transport. After separation, no signal passes from A to B. No energy is exchanged. No field propagates from one wing of the experiment to the other. **The shared manifold M_{AB} simply continues to exist as a structural fact. Its persistence does not require ongoing input any more than the existence of a crystal requires ongoing growth. The crystal was formed at some finite time by a local process; thereafter it simply is. The shared entropic manifold is analogous: it was formed during the interaction by local entropic dynamics; thereafter it persists as a structural fact of the entropic field configuration, requiring only the absence of sufficient decoherence to destroy it.**

5.2 The Two-Layer Architecture Applied to Entanglement

The ToE program distinguishes two layers of physical description, both relevant to entanglement. **Layer I** is the domain of signals: physical quantities that propagate on the manifold with finite speed, bounded by the entropic speed limit c_{ent} . Fields, excitations, and information all belong to Layer I, and they respect causality constraints analogous to

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

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May 3, 2026

those of special relativity. **Layer II** is the domain of structural facts about the manifold itself: its **topology**, **connectivity**, and **global configuration**. These are not propagating signals; they are constitutive features of the arena in which signals propagate.

Entanglement, in ESSM, belongs entirely to **Layer II**. The shared manifold M_{AB} is not a signal that has been sent from A to B; it is a structural fact about the entropic manifold on which A and B live. Measuring the entanglement — detecting the correlations — is a Layer I operation that involves local measurements and classical communication. **But the correlations themselves are Layer II facts: they are properties of the manifold, not signals on it.**

This distinction is precisely what allows entanglement to be "nonlocal" in spatial geometry without violating causality. Layer I operations — signal transmission, energy transfer, information communication — are bounded by c_{ent} and respect the causal structure of spacetime. Layer II facts — the connectivity and topology of the entropic manifold — are not subject to speed limits because they are not propagation processes. **The shared manifold does not "travel" from A to B; it does not need to travel because it was never at A or at B — it encompasses both, as a single structural entity.**

5.3 The Entropic Seesaw Equilibrium Condition (TESEC)

The balanced seesaw state — the state of maximal or near-maximal entanglement — is characterized by the simultaneous satisfaction of three conditions:

$$S_- \approx 0, \quad \mathbb{E}_{AB} \approx \langle \mathbb{E}_{AB} \rangle_{vac}, \quad d_E \approx 0 \quad (22)$$

These three conditions are **logically independent but dynamically coupled**. The **first** states that the antisymmetric mode is near zero — the two sectors are indistinguishable. The **second** states that the bridge order parameter is at its vacuum expectation value —

the bridge is fully formed. The **third** states that the entropic distance is near zero — the subsystems share a single entropic identity.

The seesaw equilibrium is dynamically stable because of the entropic mass gap. Small perturbations of S_- away from zero are restored by the effective frequency Ω_E : the antisymmetric mode oscillates around its equilibrium value with frequency Ω_E and is damped by the dissipation coefficient γ_E . The equilibrium is robust against small environmental perturbations — only perturbations that exceed the restoring force can destabilize the seesaw. This robustness explains the experimental observation that entanglement can persist over macroscopic distances and macroscopic times in well-controlled environments: the entropic mass gap shields the entangled state against noise.

* * *

6. Decoherence, Measurement, and the Seesaw Collapse Threshold

6.1 The Stability Criterion

The shared manifold M_{AB} persists — and the entanglement remains intact — if and only if the coherence strength exceeds a critical threshold:

$$\Gamma_{AB}(t) > \Gamma_{\text{critical}} \quad (23)$$

When Γ_{AB} drops below Γ_{critical} , the entropic mass gap closes: the effective frequency $\Omega_E^2 \rightarrow c_E^2 k^2$, the bridge-induced contribution vanishes, and the antisymmetric mode S_- becomes soft — susceptible to growth under any perturbation. Subsystem labels re-emerge, the seesaw tips, the entropic distance grows, and the two sectors factorize into separate manifolds. This is decoherence in the ESSM picture: not merely the suppression

of off-diagonal elements in a density matrix but the *fragmentation of a shared ontological structure*.

The critical threshold Γ_{critical} is not a free parameter in the final theory — it is determined by the entropic geometry of the system, the noise environment, and the coupling constants of the ESSM action. In the present stage of the theory's development, Γ_{critical} is treated as a system-dependent quantity whose value is fixed by the condition that the mass gap $\kappa\langle E_{AB} \rangle$ must exceed the thermal noise floor of the environment.

6.2 The Decoherence Rate Decomposition

The total decoherence [46, 47] rate admits a physically transparent decomposition into three contributions:

$$\gamma_d(t) = \eta_{\text{env}} \dot{S}_{\text{env}} + \eta_{\nabla} |\nabla S_A - \nabla S_B|^2 + \eta_m M(t) \quad (24)$$

The **first** term, $\eta_{\text{env}} \dot{S}_{\text{env}}$, is the contribution from **background entropy production**: the environment produces entropy at rate \dot{S}_{env} , and a fraction of this entropy production couples to the shared manifold, degrading its coherence. The coefficient η_{env} measures the efficiency of this coupling. The **second** term, $\eta_{\nabla} |\nabla S_A - \nabla S_B|^2$, is the contribution from **spatial inhomogeneity**: when the entropic field gradients of the two subsystems differ — as they will when the subsystems are in different spatial environments — the resulting mismatch drives the antisymmetric mode and increases the decoherence rate. The third term, $\eta_m M(t)$, is the contribution from **monitoring channels**: any process that extracts information about the subsystem labels — any process that can distinguish A from B — constitutes a monitoring channel with strength $M(t)$ and contributes to decoherence [40, 46, 47].

This decomposition reveals the physical origin of decoherence in ESSM: **decoherence is the entropic field's response to any process that breaks the symmetry between the two sectors. Background noise breaks the symmetry stochastically; spatial inhomogeneity breaks it systematically; measurement breaks it deliberately.** All three mechanisms operate through the same dynamical channel — the growth of S_- and the consequent increase of entropic distance.

6.3 The Entropic Seesaw Collapse Mechanism (TESCM)

In the coherent phase, the seesaw is balanced: $S_- \approx 0$, and the two ends of the seesaw are indistinguishable. Measurement, in the ESSM picture, does not "discover" a pre-existing value of some observable. Nor does it "create" a value by a mysterious projection postulate. Instead, **measurement applies a torque to the seesaw.** A measurement apparatus coupled to subsystem A introduces an asymmetric environmental drive ΔJ_{env} that pushes S_- away from zero.

The seesaw tips — and entanglement collapses — when the asymmetric driving exceeds the restoring force of the entropic mass gap:

$$|\eta \Delta J_{\text{env}}| > \Omega_E^2 |S_-|_{\text{max}} \quad (25)$$

At this point, S_- grows without bound (within the linearized approximation), the entropic distance increases rapidly, the bridge weakens as Ξ_{AB} decays, and the shared manifold fragments into two separate sectors M_A and M_B . The system is no longer entangled. The "collapse" is **not a discontinuity in the fundamental dynamics — it is a threshold transition in the entropic field, analogous to the breaking of a crystal under stress or the boiling of a liquid at the critical temperature.**

This picture resolves the measurement problem for entanglement. Measurement is not a special, non-unitary process that interrupts the Schrödinger evolution. It is a particular case of environmental coupling — one that is strong enough and directional enough to overcome the entropic mass gap and tip the seesaw. The Born rule probabilities are recovered as the statistical distribution of seesaw-tip outcomes under the stochastic driving of the environmental field, though **the detailed derivation of the Born rule from ESSM dynamics is a task for future work.**

6.4 The Seesaw-Collapse Threshold from Measurement Loading

The seesaw collapse can be formulated in terms of the total **measurement loading** — the cumulative entropic impact of measurement and environmental interactions on the shared manifold. Define the measurement loading contributions $\Lambda_A(t)$ and $\Lambda_B(t)$ as the integrated entropic loads imposed on subsystems A and B, respectively. The collapse threshold is:

$$\Lambda_A(t) + \Lambda_B(t) \geq \Lambda_{\text{thresh}} \quad (26)$$

where Λ_{thresh} is the critical total loading that the shared manifold can bear before fragmenting. The crucial point is that this is *not* a signaling condition. The measurement loading on subsystem A contributes to the total, and the measurement loading on subsystem B contributes to the total, but neither subsystem's loading is communicated to the other. The threshold is a condition on the global structural integrity of the shared manifold — it is a property of the object M_{AB} as a whole, not a message sent from one wing to the other.

This formulation explains the well-known experimental fact that measurement on one wing of a Bell experiment does not, by itself, produce an observable effect at

the other wing (the no-signaling theorem). The local reduced state of B is unaffected by measurements on A — but the *joint* state, and specifically the coherence of the shared manifold, is degraded by the total loading. **The correlation structure is a property of the whole, not a signal between parts.**

6.5 Entropic Bookkeeping: The Second Law in the Coherent Sector

The coherent sector — the shared manifold M_{AB} — has a definite entropy content $S_{AB}^{\text{coh}}(t)$ that evolves under environmental coupling. The Theory of Entropicity (ToE) **fundamental bookkeeping equations (FBKE)** are:

$$d/dt S_{AB}^{\text{coh}}(t) = -J_{\text{env}}(t) \quad (27)$$

$$d/dt (S_{AB}^{\text{coh}} + S_{\text{env}}) \geq 0 \quad (28)$$

Equation (27) states that the **coherent sector** loses entropy to the environment at rate $J_{\text{env}}(t)$: **the environment extracts entropic content from the shared manifold, degrading its coherence.** Equation (28) is the **second law of thermodynamics** applied to the coherent sector: **the total entropy of the system-plus-environment never decreases, even as the coherent sector's entropy declines.**

Decoherence, in this accounting, is the second law operating on the shared manifold. The shared manifold is a low-entropy, highly structured configuration of the entropic field — an entropically ordered state. The environment is a high-entropy reservoir. **The second law mandates that entropy flows from the low-entropy coherent sector to the high-entropy environment, degrading the coherence and ultimately destroying the entanglement.**

The Theory of Entropicity (ToE) teaches us that decoherence is not a peculiarity of quantum mechanics; it is the universal tendency of ordered structures to degrade in

the presence of entropy production — the same tendency that drives the melting of ice, the diffusion of gases, and the heat death of the universe.

In other words, the Theory of Entropicity (ToE) declares decoherence as one manifestation of a universal entropic principle and not restricted to the quantum domain. Thus, the Theory of Entropicity (ToE) unifies quantum decoherence with **macroscopic entropy-driven degradation**. ToE emphasizes **entropy production as the causal driver, therefore placing decoherence within a single entropic ontology**.

Once more, the above conclusion stands as one of the defining conceptual unifications of the Theory of Entropicity (ToE).

* * *

7. The Attosecond Entanglement Formation Time — Empirical Anchors for ESSM

7.1 The Experimental Landscape

The past three years have witnessed a transformation in the experimental study of quantum entanglement, driven by the attosecond physics community's ability to probe electron dynamics on their natural timescale. The experiments most directly relevant to the ESSM program are the following:

(a) **Jiang et al. (2024, *Physical Review Letters* 133, 163201) [27]**. This paper, from a collaboration between Chongqing University and the TU Wien (Vienna University of Technology), presents a numerical and theoretical study of attosecond chronoscopy in helium. By solving the time-dependent Schrödinger equation in its full dimensionality — a formidable computational achievement — the authors demonstrate that photoionization

time delays, measured through attosecond streaking and RABBIT/RABBITT (Reconstruction of Attosecond Beating by Interference of Two-photon Transitions) techniques, can serve as a real-time probe of interelectronic coherence and entanglement. The paper identifies novel signatures in time delays beyond the linear-response limit, arising from strong coupling between the helium atom and the extreme ultraviolet (XUV) field and from light-field dressing of the ion. The institutional news release from TU Wien [34] reported a figure of roughly 232 attoseconds as the timescale for entanglement development. The present Letter notes, as a point of scientific accuracy, that this “232 as figure” appears in institutional and media summaries rather than as a directly measured coincidence result in the primary paper, which is a numerical/theoretical study. **The distinction matters for ESSM: the 232 as figure, if confirmed, would represent the threshold-crossing time t_c in the ESSM formation picture.**

(b) Shobeiry et al. (2024, *Scientific Reports* 14, 19630) [28]. This paper, from the Max Planck Institute for Nuclear Physics in Heidelberg, demonstrates direct control of the emission direction of entangled photoelectrons in the dissociative ionization of H_2 . By tuning the relative phase of two-color laser fields, the authors achieve directional control over the emission of the entangled electron pair, **confirming that entanglement in photoionization is a controllable, channel-dependent phenomenon.**

(c) Stenquist and Dahlström (2025, *Physical Review Research* 7, 013270) [29]. This study demonstrates that time-reversal symmetry can be harnessed to fundamentally alter the entanglement produced in photoionization. The authors show that the degree of entanglement between the photoelectron and the residual ion depends sensitively on the time-symmetry properties of the ionizing pulse, providing a new handle for experimental control of entanglement formation.

(d) **Makos et al. (2025, *Nature Communications* 16, 8554) [30]**. This experimental study reveals that entanglement in the photoionization of CO_2 — a polyatomic molecule — is sensitive to ionic coupling effects, and that these effects produce measurable shifts in attosecond time delays. This result confirms that entanglement formation is channel-dependent: different ionic channels produce different degrees and timescales of entanglement, **precisely as ESSM predicts**.

(e) **Koll et al. (2026, *Nature* 652, 82–88) [31]**. This paper, from the Max Born Institute in Berlin, provides the most direct experimental demonstration to date that ion-photoelectron entanglement affects electronic coherence in attosecond molecular photoionization of H_2 . The authors ionize hydrogen molecules with a pair of phase-locked attosecond pulses and a few-cycle near-infrared pulse, and demonstrate that the electronic coherence in the dissociating H_2^+ ion is influenced by the degree of entanglement with the departing photoelectron. Crucially, they show experimental control over the degree of entanglement by varying the inter-pulse delay, confirming that entanglement formation is a dynamic, tunable process — not an instantaneous kinematic fact.

(f) **Mao et al. (2026, *Light: Science and Applications*) [32]**. This study demonstrates coherent control of electron-ion entanglement in multiphoton ionization, extending the attosecond entanglement program beyond single-photon ionization into the multiphoton regime and showing that the degree of entanglement can be actively controlled by the laser parameters.

7.2 ESSM Interpretation of the Attosecond Results

The attosecond results provide a direct empirical contact point for ESSM. If the 232 as figure from the TU Wien summaries [34] is interpreted as the ESSM threshold-crossing time t_c , the corresponding formation rate is:

$$t_c^{-1} \approx 4.31 \times 10^{15} \text{ s}^{-1} \quad (29)$$

This rate falls squarely in the range accessible to strong-field XUV interactions, where the entropic field reorganization proceeds at rates comparable to the electronic orbital period. The ESSM framework predicts that the formation time t_c , the coherence lifetime τ_{coh} , and the decoherence onset γ_d should vary independently and should be channel-specific — different ionic channels, different molecular targets, and different pulse configurations should produce different values of t_c , τ_{coh} , and γ_d . The recent experiments by Makos et al. [30] and Koll et al. [31] provide preliminary confirmation of this channel dependence.

The **formation-persistence distinction** is the most distinctive and experimentally testable prediction of ESSM. Standard quantum mechanics does not distinguish formation from persistence: the entangled state is produced by the interaction Hamiltonian and thereafter persists by unitary evolution. **ESSM, by contrast, predicts that formation and persistence are dynamically distinct stages with distinct timescales and distinct sensitivities to environmental parameters. Experiments that separately probe the formation timescale (by varying the interaction duration) and the persistence timescale (by varying the post-interaction delay before detection) would provide a direct test of this prediction.**

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May 3, 2026

7.3 ESSM Predictions versus Standard Interpretation

Table 1. Comparison of Standard QM Interpretation and ESSM Predictions

Feature	Standard Interpretation	QM	ESSM Prediction
Formation time	Entanglement arises as soon as the interaction Hamiltonian acts; no intrinsic formation time		Finite threshold-crossing time t_c , governed by formation drive, decoherence rate, and entropic time-limit bounds
Persistence mechanism	Unitary evolution preserves the state vector		Structural persistence of the shared entropic manifold M_{AB} ; entropic distance d_E remains near zero
Decoherence source	Environment-induced suppression of off-diagonal density matrix elements		Growth of the antisymmetric mode S_- under environmental torque/ET; closure of the entropic mass gap
Bell correlations	Non-factorizability of the bipartite state vector		Structural unity of the shared entropic manifold; correlations are local in entropic geometry
Measurement role	Projection postulate; instantaneous collapse		Asymmetric entropic torque that tips the seesaw when exceeding the restoring force; threshold transition, not discontinuity
Channel dependence	Entanglement depends on the coupling Hamiltonian; no formation-time channel dependence		t_c , τ_{coh} , and γ_d are independently variable and channel-specific

7.4 The Experimental Anchors Table

Table 2. Key Attosecond Experiments and Their ESSM Anchors

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

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May 3, 2026

Reference	Year	System	Key Observable	ESSM Anchor
Jiang et al. [27]	2024	He (numerical)	Photoionization time delays probe coherence and entanglement	Formation time t_c ; coherence dynamics; entropic reorganization timescale
Shobeiry et al. [28]	2024	H ₂ (experimental)	Emission direction control of entangled photoelectrons	Channel dependence of entanglement; controllability of seesaw formation
Stenquist and Dahlström [29]	2025	Atomic (theoretical)	Time-symmetry alters entanglement degree	Formation drive r_f depends on pulse symmetry properties
Makos et al. [30]	2025	CO ₂ (experimental)	Ionic coupling effects on attosecond time delays through entanglement	Channel-resolved formation times; multichannel ESSM predictions
Koll et al. [31]	2026	H ₂ (experimental)	Ion-photoelectron entanglement affects electronic coherence; controllable degree	Formation-persistence distinction; seesaw equilibrium; controllable Γ_{AB}
Mao et al. [32]	2026	Multiphoton (experimental)	Coherent control of electron-ion entanglement	Extension of ESSM to multiphoton formation channels

* * *

8. Einstein's EPR Paradox Dissolved — Entropic Distance versus Spatial Distance

8.1 The EPR Argument Reconstructed

The famous **Einstein-Podolsky-Rosen (EPR)** argument [20, 36, 37], in its original 1935 form, proceeds as follows. Consider two particles that interact and then separate. After separation, a measurement of position on particle A allows one to predict with certainty the position of particle B; likewise, a measurement of momentum on particle A allows one to predict with certainty the momentum of particle B. By the **EPR criterion of physical reality** — *"If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity"* — **both position and momentum of particle B must be simultaneously real**. But quantum mechanics forbids simultaneous sharp values of position and momentum (Heisenberg uncertainty). Therefore, either quantum mechanics is incomplete (there exist hidden elements of reality not described by the wave function) or the measurement on A does disturb B at a distance (violating locality).

The EPR argument rests on a premise so natural that it was not explicitly identified as a premise until Bell's analysis three decades later: ***spatial separation implies ontological separation***. If A and B are in different places, they are different things, and any property of B must be determined locally — by facts about B and its neighborhood, not by facts about A. **This is the locality premise, and it is what entanglement violates.**

Bell's theorem [22] showed that no locally realistic theory — no theory that satisfies both the locality premise and the reality criterion — can reproduce the quantum predictions.

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Experiments confirm the quantum predictions. Therefore, either locality or realism (or both) must be abandoned. The standard response is to abandon local realism without specifying what replaces it. This is intellectually unsatisfying. ESSM provides a replacement.

8.2 The ESSM Resolution

ESSM resolves the EPR paradox by denying the locality premise — but not in the way that the standard response denies it. The *standard response* says: "Quantum mechanics is nonlocal, and we must live with it." **The ESSM of the Theory of Entropicity (ToE) says:** "*The relevant geometry is not spatial geometry. In the relevant geometry — the entropic geometry of the shared manifold — the two subsystems are local. The nonlocality is an artifact of projecting an entropically local fact onto spatial coordinates.*"

Once the shared manifold M_{AB} has formed via the local process described by equation (1), spatial separation does not create ontological separation. The subsystems A and B may fly apart to arbitrary spatial distances, but their entropic distance d_E remains near zero because the shared manifold persists as a structural fact. The correlations measured at spacelike separation are not influences travelling from A to B; they are features of one object — the shared manifold — that happen to be observed from two spatial locations.

The seesaw analogy of ToE is exact here. *If Alice sits on one end of a seesaw and Bob sits on the other, and Alice rises, Bob falls. No signal travels along the plank — the plank is a constraint, not a communication channel.* If one further imagines that the plank is very long (spatial distance large) but still perfectly rigid (entropic distance zero), the correlation is "nonlocal" in the sense that the two ends are far apart, but it is "local" in the sense that there is only one object, and the constraint is structural. **The ESSM of the Theory of**

Entropicity (ToE) asserts that entanglement is precisely this kind of structural constraint in the entropic manifold.

8.3 Why ESSM Does Not Reintroduce Hidden Variables

A natural concern is that the ESSM, by providing an ontological substrate for entanglement, might constitute a hidden-variable theory and thereby conflict with Bell's theorem. This concern is misplaced, for the following reasons.

First, Bell's theorem excludes *locally realistic* hidden-variable theories — theories in which each subsystem carries pre-determined values of all observables, and the outcome of a measurement is determined by local facts alone. **ESSM is not such a theory.** The shared manifold M_{AB} is not a carrier of pre-determined values; it is a dynamical entropic structure whose properties are not reducible to lists of definite values for individual observables. The correlations arise from the structural unity of the manifold, not from pre-existing labels attached to each subsystem.

Second, ESSM **relocates the locality claim.** Bell's theorem proves that correlations violating Bell inequalities cannot arise from local mechanisms in *spacetime geometry*. **ESSM agrees:** the correlations are not local in spacetime geometry. **They are local in entropic geometry.** Bell's theorem does not address entropic geometry — it addresses spacetime locality as defined by the light-cone structure of Minkowski space. The entropic manifold has its own geometry, in which the entangled subsystems are neighboring, and the correlations are perfectly local in that geometry.

Third, ESSM is fully consistent with the violation of Bell inequalities. **The shared manifold is a genuinely quantum-entropic object** — it is not a classical ensemble, not a deterministic assignment of outcomes, and not a conspiracy of pre-established

correlations. It is a dynamical, holistic entity whose decomposition into subsystem properties is fundamentally limited by the entropic mass gap that suppresses the antisymmetric mode. **When a measurement is performed, the seesaw tips stochastically under the environmental torque (EnvT) [generally, the Entropic Torque (ET)], and the outcome probabilities are determined by the quantum-entropic structure of the manifold — not by [any] pre-existing hidden variables.**

8.4 The No-Signaling Proof

A rigorous theory of entanglement **must prove that it respects the no-signaling principle: measurements on one subsystem cannot transmit information to the other. ESSM satisfies this requirement, and the proof is straightforward.**

The persistence of M_{AB} does not enable information transfer. The correlation structure is a property of the shared manifold — a Layer II structural fact — and is not a communication channel. Measurement on subsystem A applies an entropic load Λ_A that contributes to the **total loading** of the manifold (equation (26)), but this loading does not propagate as a signal to subsystem B. It triggers a threshold transition — the seesaw collapse — that is a property of the manifold as a whole, not a signal from A to B.

Formally, the reduced state of B is unaffected by local measurements on A:

$$\partial \rho_B / \partial \Lambda_A = 0 \quad (\text{for all local measurements on A}) \quad (30)$$

where $\rho_B = \text{Tr}_A(\rho_{AB})$ is the reduced density matrix of subsystem B. This follows directly from the ESSM dynamics: **the measurement loading Λ_A affects the total coherence strength Γ_{AB} and the integrity of the shared manifold, but it does not alter the local entropy content or the local entropic field configuration of subsystem B.** The

local observables of B — expectation values, variances, probability distributions — are determined by ρ_B alone and are invariant under operations on A. Only the joint observables — correlations, mutual information, Bell function values — are affected by the measurement, and these require classical communication to observe.

The ESSM no-signaling proof is not an ad hoc postulate; it is a consequence of the Layer I / Layer II distinction. Information transfer is a Layer I process bounded by the entropic speed limit c_{ent} . Entanglement is a Layer II structural fact. Measurements on one wing alter the structural integrity of the shared manifold (a Layer II change) but do not propagate a Layer I signal to the other wing. The two layers are coupled — the collapse of the manifold (Layer II) determines the probabilities of measurement outcomes (Layer I) — but the coupling does not violate causality because the Layer II change is not a propagating signal.

* * *

9. ER=EPR Reinterpreted — The Entropic Bridge Completion

9.1 The Maldacena-Susskind Conjecture (MSC) and Its Scope

In 2013, Maldacena and Susskind [23] proposed the ER=EPR conjecture:

Every pair of entangled particles is connected by an Einstein-Rosen bridge (a non-traversable wormhole), and conversely, every Einstein-Rosen bridge corresponds to an entangled pair.

The conjecture was originally formulated in the context of AdS/CFT duality and the black-hole firewall paradox (AMPS), and it offered a striking resolution: **the interior of an old black hole, seemingly disconnected from the Hawking radiation, is actually**

connected to the radiation quanta by ER bridges, and the entanglement between the interior and the radiation ensures the smoothness of the horizon.

The conjecture has been developed and refined by several groups. Van Raamsdonk [24] argued that spacetime connectivity is equivalent to quantum entanglement: **reducing the entanglement between two regions of a holographic system causes the geometric distance between them to increase, and in the limit of zero entanglement, the spacetime pinches off into disconnected regions.** More recently, Magán, Sasieta, and Swingle [25] demonstrated that typical entangled states — not just **the thermofield double** or other special states — **can be assigned ER-bridge geometric duals, greatly expanding the scope of the conjecture.** Fields et al. [26] have argued that ER=EPR can be interpreted as an operational theorem under certain assumptions about the structure of quantum gravity.

Despite these developments, the ER=EPR conjecture, as originally stated, has three limitations that the ESSM of the Theory of Entropicity (ToE) must now address.

First, it does not specify a *dynamical mechanism* for the formation of the bridge: the bridge is posited to exist whenever entanglement exists, but no account is given of how it forms, on what timescale, or by what process. **Second**, it does not specify a *breakdown criterion*: the bridge weakens under decoherence, but the precise threshold at which the bridge ceases to function is not given. **Third**, the conjecture is formulated in the language of spacetime geometry (wormholes, bridge length, throat area), which limits its direct applicability to the flat-spacetime, low-energy entanglement of atomic and molecular physics — the very regime in which the attosecond experiments operate.

9.2 The ESSM Entropic Bridge

ESSM provides a natural and physically transparent analogue of the ER bridge that operates in the entropic manifold rather than in spacetime geometry and is directly applicable to laboratory entanglement. The **ESSM entropic bridge length** is defined as:

$$L_{AB}^{\text{ESSM}} = \ell_E \cdot \ln(\Gamma^* / \Gamma_{AB}) \quad (31)$$

where ℓ_E is the entropic coherence length (the characteristic length scale of the entropic manifold) and Γ_{AB} is the coherence strength functional. **When $\Gamma_{AB} \rightarrow \Gamma^*$ (maximally entangled), the bridge length vanishes: the two sectors are as close as they can be in the entropic manifold. When $\Gamma_{AB} \rightarrow 0$ (fully decohered), the bridge length diverges: the two sectors have become infinitely distant in entropic geometry, and the bridge has been severed.**

The **bridge connectivity functional** is defined as the exponential of the negative bridge length:

$$B_E(A,B;t) = \exp[-L_{AB}^{\text{ESSM}} / \ell_E] = \Gamma_{AB} / \Gamma^* \quad (32)$$

This quantity ranges from 0 (no connectivity) to 1 (maximal connectivity), and it is simply the normalized coherence strength. The entropic bridge connectivity is the order parameter for entanglement: when B_E is near 1, the systems are strongly entangled; when B_E drops below a critical value, the bridge is functionally severed.

9.3 The Geometric Shadow Interpretation

ESSM does not require that every laboratory Bell pair opens a traversable spacetime wormhole. Such a requirement would be physically implausible — the gravitational effects of a photon pair are immeasurably small — and would render ER=EPR untestable in the

atomic regime. Instead, ESSM offers a **geometric shadow interpretation**: the entropic bridge is the fundamental object, and the Einstein-Rosen (ER) bridge of general relativity (GR) is its *geometric shadow* in regimes where gravity is strong enough to produce a spacetime-geometric representation.

The relationship is expressed symbolically as:

$$ER=EPR \Rightarrow B_{\text{geom}} \mapsto B_E \quad (33)$$

where B_{geom} is a geometric bridge (an ER wormhole in spacetime) and B_E is the entropic bridge (the shared entropic manifold connecting the two sectors). **In the gravitational regime — entangled black holes, holographic systems, AdS/CFT duality — B_E admits a faithful representation as B_{geom} , and the ER=EPR correspondence holds in its original geometric form. In the atomic regime — entangled photons, photoionized electrons, Bell pairs — B_E exists as a structural fact of the entropic manifold but has no macroscopic spacetime-geometric representation. The entropic bridge is always present; the geometric bridge is a special case.**

9.4 ESSM as Thermodynamic Completion of ER=EPR

The Maldacena-Susskind conjecture states that entanglement and geometric connectivity belong together. The Theory of Entropicity (ToE), in the ESSM, accepts this identification and completes it by providing the dynamical content that the conjecture leaves open:

Formation dynamics: The entropic bridge forms by the local process $M_A \oplus M_B \rightarrow M_{AB}$, with a finite formation time t_c governed by the formation drive equation (12) and bounded below by the entropic time limits (17)–(18). The ER=EPR conjecture does not specify these dynamics; ESSM does.

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

Coherence strength: The strength of the bridge is quantified by the coherence functional Γ_{AB} , which evolves continuously under formation, persistence, and decoherence. The bridge length L_{AB} and connectivity B_E are derived from Γ_{AB} by equations (31)–(32). The ER=EPR conjecture does not provide a dynamical measure of bridge strength; ESSM does.

Threshold breakdown: The bridge collapses when Γ_{AB} drops below $\Gamma_{critical}$, which occurs when the total measurement loading exceeds the threshold Λ_{thresh} . The collapse is a threshold transition — a tipping of the seesaw — with a well-defined critical point. The ER=EPR conjecture does not specify a breakdown criterion; ESSM does.

Thermodynamic grounding: The entire ESSM dynamics is thermodynamically grounded: the formation of entanglement is an entropic structuring process, the persistence is an entropic maintenance of order, and the breakdown is a second-law-driven degradation. Entropy flows, entropy bounds, and entropy production rates are not ad hoc additions but the fundamental dynamical variables. ESSM completes ER=EPR by embedding it in a thermodynamic framework — the Theory of Entropicity (ToE) — in which connectivity, entanglement, and entropy are unified under a single variational principle of **the Obidi Action**.

* * *

10. Testable Predictions, Experimental Protocols, and the ESSM Research Program

10.1 The Asymmetric Entropy-Injection Protocol

The most immediate and direct experimental test of ESSM is the **asymmetric entropy-injection protocol (AEIP)**. The proposed experiment proceeds as follows:

(i) Prepare a bipartite entangled state by attosecond photoionization — for example, the H_2 system studied by Koll et al. [31] or the helium system studied computationally by Jiang et al. [27].

(ii) After the formation interval t_c , introduce a controlled, *asymmetric* entropy injection into one arm of the experiment. This can be accomplished by exposing subsystem A to a weak, broadband thermal field — a "noise pulse" — while leaving subsystem B undisturbed. The noise pulse increases \dot{S}_{env} on the A side, raising the decoherence rate γ_d via the first and second terms of equation (24).

(iii) Measure the coherence of the joint state (e.g., by coincidence detection and Bell-inequality tests) as a function of the noise-pulse intensity and timing.

ESSM predicts that the coherence strength Γ_{AB} will decay on a timescale $\tau_{coh} = \Gamma_{AB}(t_s) / \gamma_d$ that is quantitatively determined by the injected entropy rate. Specifically, doubling the noise-pulse intensity should halve the coherence lifetime (in the linear-response regime). This is a sharp, quantitative prediction that standard quantum mechanics does not make in the same parametric form — standard decoherence theory predicts exponential decay, but the specific dependence on asymmetric entropy injection

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

is a signature of the ESSM decoherence rate decomposition (24) from the Theory of Entropicity (ToE).

10.2 Channel-Resolved Formation Time Measurements

ESSM predicts that the formation time t_c varies with the ionic channel — different ionic states of the residual ion should show different formation times, because the formation drive r_f and the saturation coherence Γ^* depend on the electronic structure of the specific channel. This prediction is directly testable with existing attosecond technology:

- (i) Perform attosecond photoionization of a multi-electron atom or molecule (e.g., CO_2 , as in Makos et al. [30]) with sufficient photon energy to access multiple ionic channels.
- (ii) Use channel-resolved coincidence detection to identify the ionic state of the residual ion for each detected electron-ion pair.
- (iii) For each channel, measure the build-up time of entanglement — the interval during which the Bell-inequality violation (or other entanglement witness) grows from zero to its saturation value.

ESSM predicts that different channels will exhibit different formation times t_c , with the ordering determined by the entropic structure of the ionic states. Channels with larger entropic coupling (more electronic reorganization upon ionization) should show faster formation — higher r_f and shorter t_c . This is a qualitative prediction that can be tested even without precise knowledge of the ESSM coupling constants.

10.3 The Coherence-Lifetime Scaling Law

ESSM predicts a specific scaling law for the coherence lifetime:

$$\tau_{\text{coh}} \propto \Gamma_{AB}(t_s) / \gamma_d \quad (34)$$

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

The coherence lifetime should scale linearly with the initial coherence strength (determined by the formation conditions) and inversely with the environmental entropy production rate (determined by the experimental environment). This scaling law is testable by systematically varying the formation conditions (e.g., pulse intensity, duration, photon energy) and the environmental conditions (e.g., background pressure, temperature, stray fields) and measuring the resulting coherence lifetimes.

Standard decoherence theory predicts exponential decay with a rate determined by the system-environment coupling, but it does not predict the specific functional dependence on the initial coherence strength $\Gamma_{AB}(t_s)$ that appears in equation (34). The ESSM scaling law is a distinctive prediction that arises from the logistic formation dynamics and the persistence law of equations (12) and (20).

10.4 Comparative Predictions Table

Table 3. Standard Interpretation versus ESSM Predictions on Specific Observables

Observable	Standard Prediction	ESSM Prediction
Formation time dependence on ionic channel	Formation is instantaneous (interaction-dependent but not channel-resolved in formation time)	t_c varies by ionic channel; scales with r_f and Γ^*
Coherence decay under asymmetric noise	Exponential decay; rate depends on coupling to noise	Exponential decay with rate given by equation (24); specific asymmetric-injection dependence
Coherence lifetime versus initial coherence	Not specifically predicted	$\tau_{coh} \propto \Gamma_{AB}(t_s) / \gamma_d$ (linear in initial coherence)

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

Observable	Standard Prediction	ESSM Prediction
Formation-persistence distinction	Not distinguished: entanglement arises and persists by unitary evolution	Formation and persistence are dynamically distinct with independent timescales and different parametric dependencies
Pulse-symmetry effect on entanglement degree	Entanglement depends on pulse parameters through the Hamiltonian	Time-symmetry of the pulse affects r_f and hence t_c ; consistent with Stenquist-Dahlström results [29]

10.5 The ESSM Experimental Roadmap

The experimental program implied by ESSM can be organized into three tiers:

Near-term (achievable with current attosecond technology): (i) Asymmetric entropy-injection experiments in attosecond photoionization setups. (ii) Channel-resolved formation-time measurements in polyatomic targets. (iii) Systematic variation of pulse parameters to map the formation drive r_f as a function of laser intensity, photon energy, and pulse duration.

Medium-term (requiring enhanced coincidence detection and attosecond-pump/attosecond-probe capability): (i) Direct measurement of the formation-persistence distinction by separately varying the interaction window and the post-interaction delay. (ii) Measurement of the decoherence rate decomposition (24) by independently controlling the three contributions (background noise, spatial inhomogeneity, monitoring channels). (iii) Attosecond-resolved measurement of the antisymmetric mode dynamics $S_-(t)$ through interference-based observables.

Long-term (requiring new experimental capabilities): (i) Entanglement-sensitive gravitational tests probing whether the entropic bridge has a detectable gravitational

signature. (ii) Extension of ESSM predictions to multipartite entanglement in complex molecular and solid-state systems. (iii) Tests of the entropic time-limit bounds (17)–(18) through ultrafast entanglement formation in engineered quantum systems with controlled entropy production rates.

* * *

11. Open Mathematical Frontiers and Concluding Assessment

11.1 Open Mathematical Tasks

The ESSM, as presented in this Letter ID, is formulated as an effective theory — a sector of the full ToE program designed to capture the essential physics of entanglement. Several mathematical tasks remain open for future work:

(i) Derivation from the full Obidi Action. The ESSM effective action (7) is currently postulated as a natural two-sector extension of the Obidi Action, consistent with its symmetries and variational structure. A rigorous derivation — showing that the ESSM action emerges from the full Obidi Action in the bipartite sector limit — would provide a first-principles grounding for the model. This derivation would need to specify how the bridge order parameter Ξ_{AB} arises from the entropic field's self-interaction and how the coupling constants (κ , α_+ , α_- , etc.) are related to the fundamental parameters of the **Obidi Action**.

(ii) Variational principle for the coherence functional. Equation (19) defines a formation functional whose minimization yields the formation trajectory. A rigorous proof that this functional is derivable from the Obidi Action — that the formation trajectory is a

solution of the **Obidi Action's Euler-Lagrange equations** restricted to the entanglement sector — **is a high-priority mathematical task.**

(iii) Multipartite extension. The present Letter ID treats bipartite entanglement. Extension to multipartite entanglement requires the definition of N-body shared manifolds $M_{\{A_1 A_2 \dots A_n\}}$ and the generalization of the entropic distance, coherence strength, and bridge connectivity to N-partite systems. The combinatorial complexity of multipartite entanglement (GHZ states, W states, cluster states) presents significant technical challenges for the ESSM framework.

(iv) Connection to the entropic renormalization group. Letter IC [4] develops an entropic renormalization group — a flow in the space of entropic field theories under coarse-graining. The connection between ESSM and this renormalization group has not yet been explored. In particular, the question of whether the ESSM coupling constants flow under renormalization, and whether entanglement has a nontrivial fixed-point structure in the renormalization flow, **is an open and potentially deep question.**

(v) Quantitative prediction of t_c from first principles. The formation time t_c in equation (16) depends on the formation drive r_f , the saturation coherence Γ^* , and the decoherence rate γ_d . These quantities are, at present, treated as system-dependent parameters. A first-principles calculation — deriving r_f , Γ^* , and γ_d from the entropic field configuration and the interaction Hamiltonian — would **convert ESSM from a parametric to a predictive theory and would allow direct quantitative comparison with attosecond measurements.**

11.2 Limitations, Constraints, and Strategic Directions

In this Letter ID, we have advanced the Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE) as a rigorous and physically motivated theory of entanglement, but intellectual humility demands that its current limitations be acknowledged explicitly.

First, the public ToE literature fixes the ontology (entropy as the primary field) and the qualitative seesaw picture (entanglement as shared manifold), but it does not yet uniquely determine a closed-form microphysical kernel for entanglement formation. The ESSM effective action (7) is the most **natural extension of the Obidi Action to the bipartite sector**, but alternative effective actions with different coupling structures might also be consistent with the ToE ontology. Resolution of this non-uniqueness requires the first-principles derivation mentioned above.

Second, the “232 as figure” must be handled with care. As noted in the Abstract and in Section 7.1, this figure originates in institutional and media summaries of the Jiang et al. 2024 study [27, 34]. The primary *PRL* paper is a numerical/theoretical **attosecond chronoscopy** study; the 232 as figure is a model-derived timescale characterizing the evolution of coherence in their computational framework, not a directly measured coincidence-detection result. Later experiments — particularly Koll et al. [31] — do provide direct attosecond-scale experimental evidence for entanglement dynamics, but the precise quantitative mapping between these experimental results and the ESSM formation time t_c has not yet been carried out.

Third, the ESSM coupling constants — κ , α_+ , α_- , α_{Ξ} , ℓ_E , σ , ν , and others — are not yet fixed from experiment. **Their determination requires either a first-principles derivation from the Obidi Action or a direct fit to attosecond experimental data,**

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). *Letter ID*

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

neither of which has been completed. Until these constants are fixed, ESSM provides qualitative and scaling [logical] predictions, but not yet precise numerical ones.

11.3 Assessment and Significance

The **Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)**, as developed in this Letter, provides the first complete entropic theory of quantum entanglement. It addresses the full dynamical lifecycle of entanglement — formation, persistence, decoherence, measurement, and breakdown — within a unified mathematical framework derived from the Theory of Entropicity (ToE)'s foundational commitment to entropy as the primary ontological entity.

ESSM **dissolves the Einstein-Podolsky-Rosen paradox** without hidden variables by distinguishing spatial distance from entropic distance and showing that entangled systems are entropically local even when spatially remote. It **completes the Maldacena-Susskind ER=EPR conjecture** without requiring literal spacetime wormholes by identifying the entropic bridge as the **fundamental connectivity structure of which geometric bridges are a special-regime projection**. It connects to the rapidly advancing attosecond experimental program through the formation-persistence distinction, the channel dependence of the formation time, and the coherence-lifetime scaling law — all of which are testable with current or near-future technology.

The mathematical architecture presented in this work so far is substantive: **the ESSM effective action**, the **bridge order parameter** and its **symmetry-breaking potential**, the **coherence strength functional**, the **equation of motion** for the **antisymmetric mode**, the **formation drive equation** and its **analytic solution**, the **seesaw collapse criterion**, the **entropic time-limit bounds**, and the **entropic bridge length functional**

The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

— **these constitute a coherent and self-consistent formalism that goes well beyond the qualitative seesaw picture and provides the scaffolding for quantitative predictions of the Theory of Entropicity (ToE).**

Whether the ESSM is ultimately validated or refuted by experiment is a question for the future. What the present Letter establishes is that ESSM is a rigorously formulated, experimentally falsifiable, and physically motivated entropic framework for quantum entanglement — one that takes the entanglement problem seriously as a question about the physical world, not merely as a mathematical feature of Hilbert space.

If the attosecond experiments continue to reveal entanglement as a finite-time, channel-dependent, dynamically structured process, the ESSM will be well-positioned to provide the theoretical framework that standard quantum mechanics lacks.

The Theory of Entropicity (ToE) has always maintained that entropy is not the second thought of mechanics but its foundation. The Entropic Seesaw Model (ESSM) extends this claim to the most profound, non-classical phenomenon in physics: quantum entanglement. If entanglement is indeed the characteristic trait of quantum mechanics — as Schrödinger declared — then the Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE) provides the entropic ontology that this trait has always demanded.

* * *

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The author, one more time, also wishes to acknowledge **Dr. Olalekan T. Owolawi** for his catalytic role in the origination of the Theory of Entropicity (ToE). His early encouragement and critical engagement provided the intellectual context in which the ToE program first took shape, especially in the **Obidi Action and the Obidi Field Equations (OFE)**, and to which his name will always be associated wherever and whenever these mathematical aspects of the Theory of Entropicity (ToE) are mentioned or discussed.

Finally, the author gratefully acknowledges the **attosecond physics community** — **and in particular the groups at TU Wien, the Max Planck Institute for Nuclear Physics, and the broader European attosecond consortium** — **whose pioneering work continues to illuminate the ultrafast structure of physical reality.**

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The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

Addendum

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The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

Dedication

This work on the **Theory of Entropicity (ToE)** is deservedly dedicated, with unyielding and acute nostalgia — rooted in self-continuity and the search for meaning — to:

Ojo Olayemi, Abayomi Olayemi, Samson Toyin Ukana, Titus Oriloye Ojo, and Gabriel Ekundayo Aigboje

— for the meteoric lives they lived...and the indelible marks they left upon the living.

In ever-loving memory.

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The Entropic Seesaw Model (ESSM) of the Theory of Entropicity (ToE)

A Complete Entropic Theory of Quantum Entanglement, the Attosecond Formation-Time Evidence, and the Resolution of Einstein's EPR Paradox and the Maldacena-Susskind ER=EPR Conjecture

The Theory of Entropicity (ToE) Living Review Letters Series (ToE-LRLS). Letter ID

John Onimisi Obidi (jonimisiobidi@gmail.com)

Research Lab, The Aether

May 3, 2026

Author Note

John Onimisi Obidi (jonimisiobidi@gmail.com) is the originator and developer of the **Theory of Entropicity (ToE)**, an entropy-first framework seeking to reformulate the conceptual and mathematical foundations of modern theoretical physics.

Research Lab, The Aether.

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Research Lab, The Aether

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Research Lab, The Aether

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