Empirical demonstration of worldline-mediated correlations: Born from causal accessibility, microscopic and macroscopic entanglement, and the reflection "smoking gun"

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(Dated: January 22, 2026)

We present a unified, experimentally relevant formalism linking (i) a causal-accessibility derivation of Born's rule, (ii) macroscopic entanglement arising from constrained global configurations (Matrioska $\Delta C \leftrightarrow \Delta M \leftrightarrow \Delta L$), and (iii) the De Giuseppe Paradox, highlighting how spacetime configurations of worldlines can generate apparent retrocausal correlations without violating relativity. Detection amplitudes are expressed as sums over causal channels, $\psi(R) = \sum_i c_i\, \alpha_i(R)$, with probabilities $P(R) = |\psi(R)|^2$ as expectations of a positive accessibility operator. Phase-preserving reflection of single photons on arbitrary interfaces serves as a direct empirical signature of worldline-mediated coherence, already consistent with high-visibility interference and Hong–Ou–Mandel data. Time-dependent reflectivity modulation and entangled-photon cross correlations provide experimentally accessible protocols to distinguish worldline selection from naive local re-emission. This integrated framework unifies fundamental probability, macroscopic entanglement, and operationally detectable worldline effects, offering a falsifiable route to probe the global geometry of quantum histories and the ontological necessity of worldlines.

1. Motivation. Quantum amplitudes interfere; Born's rule assigns probabilities as squared moduli. Standard approaches accept these as foundational. We show how both Born's rule and interference phenomena admit a unified causal-accessibility representation, and how constraints on admissible global configurations ("matrioskas") produce macroscopic non-factorizability. This yields a unified account for interference, entanglement and—crucially—phase-preserving single-photon reflection across diverse materials. The latter provides an empirical locus where ontologies differ and where experiment can decide.

2. Causal-accessibility amplitudes and Born's rule. Let $\{C_i\}$ denote a finite set of causal channels (frames / worldline light-cones) that can contribute to registering an event in spacetime region R. For each channel define a complex cone-to-region amplitude

$$\alpha_i(R) = \langle R|\Pi_{C_i}(R)|C_i\rangle,$$

with $\Pi_{C_i}(R)$ a positive causal projection operator (integral of a frame-filtered local measurement density over R). For a preparation encoded by coefficients $c_i \in \mathbb{C}$ define the global accessibility amplitude

$$\psi(R) = \sum_i c_i\, \alpha_i(R),$$

and a positive accessibility operator

$$\hat{A}(R) = \sum_{i,j} |C_i\rangle\, \overline{\alpha_i(R)}\alpha_j(R)\, \langle C_j|\,.$$

The detection probability then arises naturally:

$$P(R) = \frac{\langle\Psi|\hat{A}(R)|\Psi\rangle}{\sum_{R'}\langle\Psi|\hat{A}(R')|\Psi\rangle} = \frac{|\psi(R)|^2}{\sum_{R'}|\psi(R')|^2}.$$

Theorem (Born from causal accessibility): Under minimal assumptions (light-cone coverage, linear superposition of amplitudes along causal channels, and operational detection), Born's rule emerges as the squared modulus of the global accessibility amplitude.

3. Configurational emergence time τ_C. The causal-accessibility construction above presupposes that the global configuration contributing to R is physically established as a single operational entity. We therefore introduce a *configurational emergence time* τ_C, defined as the minimal temporal scale required for a set of causal channels $\{C_i\}$ to become jointly selectable as a coherent global accessibility structure.

Operationally, the accessibility amplitudes acquire an implicit temporal condition,

$$\alpha_i(R) \;\equiv\; \alpha_i(R;\tau), \qquad \alpha_i(R;\tau < \tau_C) = 0,$$

so that no global accessibility amplitude is physically defined before τ_C. For $\tau \geq \tau_C$, the amplitudes recover the standard form used above and Born's rule applies unchanged.

The quantity τ_C is *not* a propagation time, measurement time, or decoherence time; rather, it characterizes the minimal duration required for a spacetime configuration to become an admissible element of the global operational configuration space.

4. Matrioska entanglement. Microscopic (and macroscopic) entanglement arises when global admissible configurations ($\Delta C \leftrightarrow \Delta M \leftrightarrow \Delta L$) impose constraints on the joint states of subsystems A and B. Operationally, this means that measurements on A and B exhibit correlations that cannot be reproduced by independent local states alone. Let $\gamma \in \mathcal{A}(\Delta C, \Delta M, \Delta L)$ denote an admissible configuration produced by a preparation protocol P, inducing a joint probability (or density) μ with marginals

μ_A and μ_B. If the joint law is ε-nonfactorizable,

$$D(\mu, \mu_A \otimes \mu_B) > \varepsilon > 0,$$

then A and B exhibit operationally detectable entanglement-like correlations. For continuous-variable Gaussian realizations, this is certified quantitatively by logarithmic negativity

$$E_N = \max\left(0, -\ln 2\tilde{\nu}_-\right) > 0,$$

where $\tilde{\nu}_-$ is the minimal symplectic eigenvalue of the partially transposed covariance matrix, and by mutual information

$$I(A:B) = S(\mu_A) + S(\mu_B) - S(\mu_{AB}) > 0.$$

This compact formalism shows how macroscopic preparation protocols exploiting Matrioska constraints $(\Delta C, \Delta M, \Delta L)$ can produce measurable non-factorizable correlations—i.e., entanglement—without requiring any microscopic mediator, providing a clear operational and quantitative route to macroscopic entanglement.

5. Temporal admissibility of Matrioska configurations. The admissible set $\mathcal{A}(\Delta C, \Delta M, \Delta L)$ must additionally satisfy a temporal emergence condition. For each configuration $\gamma \in \mathcal{A}$, we associate a configurational time $\tau_C(\gamma)$ such that

$$\gamma \text{ is operationally accessible } \iff \tau \geq \tau_C(\gamma).$$

Below this threshold, the global constraints $(\Delta C, \Delta M, \Delta L)$ are not yet jointly enforceable, and no non-factorizable joint law can be physically realized, even if formally allowed by the Hamiltonian description.

This provides a sharp criterion distinguishing merely kinematically allowed entanglement from operationally emergent entanglement, at both microscopic and macroscopic scales.

6. Reflection as a smoking gun for worldlines. Single-photon reflection on glass, metal, or water preserves amplitude, phase, and coherence across angles and materials. Standard classical or QED explanations compute the amplitude identically but interpret propagation differently:

7. Configurational time of an interface. Within the worldline-selection picture, an optical interface (glass, metal, water) functions as a collective spacetime object only after reaching its configurational emergence time τ_C^{int}. Phase-preserving reflection occurs exclusively for $\tau \geq \tau_C^{\text{int}}$, once the interface behaves as a single globally admissible boundary condition.

This explains the observed material-independence of single-photon reflection: microscopic differences are averaged out once the interface has emerged as a unified spacetime configuration. No microscopic re-emission timing needs to be invoked, consistent with sub-picosecond experimental response.

- *Local re-emission:* photon is absorbed by atoms and re-emitted with correct phase.
- *Worldline selection:* the photon follows only admissible causal paths that connect source to detector; reflection is the projection onto accessible worldlines.

Existing high-visibility interference experiments (e.g., Hong–Ou–Mandel, single-photon double-slit, delayed-choice setups) already contain the "smoking gun": the exact phase preservation across interfaces requires nonlocal causal consistency, which is naturally captured by the worldline formalism. By modulating interface properties in a time-dependent, phase-sensitive manner (e.g., fast electro-optic reflectivity changes), one can distinguish the ontologies: only worldline selection predicts coherent redistribution in the reflected amplitude instantaneously across the causal set.

8. Experimental protocol.

1. Prepare single-photon or entangled photon pairs with high coherence length.
2. Direct one photon at an interface (glass, metal, or water) whose reflectivity can be modulated at sub-nanosecond scales.
3. Interfere the reflected photon with a stable reference arm.
4. Measure interference visibility as a function of modulation; deviations from naive re-emission predictions confirm worldline-mediated coherence redistribution.
5. Cross-correlate with second photon in an entangled pair to test nonlocal causal consistency in macroscopic reflection setups.

9. Predictions and falsifiability.

- Standard QED amplitudes reproduce all statistical outcomes; the difference is ontological: the worldline formalism predicts deterministic phase preservation across globally accessible paths even under fast boundary modulations.
- Existing datasets with stable high-visibility interference already suggest this behavior; the proposed time-resolved modulation tests the conjecture directly.
- The framework unifies Born rule derivation, macroscopic entanglement, and worldline consistency into a single empirically accessible formalism.

10. Operational links to energy and mass. Local energy densities $\hat{H}(x)$ and causal projection operators $\Pi_{C_i}(R)$ define expected accessible energy in R:

$$\mathbb{E}[E_R] = \int_R d^3x \ \mathrm{Tr}\left(\rho\,\mathcal{E}_{F_i}[\hat{H}(x)]\right),$$

so that $m_R = \mathbb{E}[E_R]/c^2$. This provides a direct connection between worldline-mediated probabilities, energy localization, and gravitational sourcing, linking to De Giuseppe Theory.

The De Giuseppe constant K_D

We introduce a universal proportionality constant K_D, termed the *De Giuseppe constant*, which sets the conversion scale between total accessible configurational energy and configurational emergence time.

For a given configuration, the emergence time is defined as

$$\tau_C = \frac{K_D}{E_{\mathrm{bound}} + E_{\mathrm{grav}}}\,F_C,$$

where E_{bound} is the total binding energy maintaining the configuration, E_{grav} the accessible gravitational energy contribution, and $F_C \in (0, 1]$ a dimensionless configurational coherence factor encoding geometric completeness.

Physically, K_D has dimensions of action and represents the minimal spacetime action required for a global configuration to become operationally selectable as a single entity. It does not correspond to a new force or interaction, but to a universal emergence threshold linking energy localization, causal accessibility, and time.

Operationally, K_D formalizes an **energy $\times$ time criterion for the observability of a configuration**: a configuration only becomes effectively realized or measurable once the product of its accessible energy and K_D exceeds the threshold set by τ_C.

Equivalently, τ_C can be interpreted as the characteristic **emergence time** of a structure given its internal energy content; K_D sets the universal scale for this relation. This makes explicit the connection between energy, causal accessibility, and temporal realization in physical systems.

THE "SMOKING GUN": EMPIRICAL SIGNATURES OF NONLOCAL COHERENCE

We now highlight the key empirical evidence — the "smoking gun" — that distinguishes a purely local re-emission view from the global, worldline-based description of reflection and interference. These results are already well-established and do not require proposing new experimental setups.

Core empirical fact

Single-photon and few-photon interference experiments reveal that photons reflected from standard optical interfaces preserve phase and polarization coherence with reference beams to a degree incompatible with independent, local re-emission events. In particular:

- Interference visibility remains near unity across a broad range of materials, angles, and polarizations.
- Coherence is maintained even when reflection involves multiple atomic layers and scattering centers.
- Two-photon interference (Hong–Ou–Mandel) shows high visibility dips regardless of material microstructure, demonstrating that phase relationships are preserved across separate optical paths.

Implications for local re-emission models

A naive local re-emission hypothesis predicts that microscopic absorption and subsequent emission should introduce random phase shifts or delays, leading to:

- Reduced single-photon interference visibility proportional to the number of microscopic emitters involved.
- Material-dependent variations in two-photon interference, reflecting differences in atomic response times and local dynamics.
- Observable dwell times in reflection beyond what is imposed by light-speed propagation.

None of these effects are observed in high-visibility single- and two-photon experiments, providing direct empirical contradiction to the local re-emission account.

Consistency with worldline-based description

The observed phase preservation is naturally explained if reflection corresponds to a globally admissible photon worldline constrained by boundary conditions. In this framework:

- Coherence is maintained up to the causal limits set by geometry, independent of microscopic material details.
- Two-photon correlations (HOM dips) remain robust across interfaces because worldlines are globally selected to preserve the admissible phase structure.

- No additional dwell times or stochastic phase perturbations are required, consistent with observed sub-picosecond temporal response.

Quantitative illustration (from existing data)

Let V denote interference visibility:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}.$$

Published experiments show $V \gtrsim 0.9$ in single-photon MZI setups and HOM dips with comparable depth, independent of material microstructure. For a local re-emission model with characteristic microscopic response time $\tau_{\rm resp}$, one would expect

$$V_{\rm L} \lesssim V_0 \exp\left[-(2\pi f_{\rm micro}\tau_{\rm resp})^2 \right] \ll 1,$$

which is clearly violated by measured data. This is the smoking-gun signature: phase and coherence are maintained beyond what local emission can account for.

Summary

Existing single- and two-photon interference results already falsify the naive local re-emission hypothesis. Coherence across interfaces and high HOM visibility constitute clear, experimentally verified "smoking guns," confirming that any realistic model of reflection must incorporate globally constrained photon histories, consistent with the worldline-selection perspective.

DE GIUSEPPE PARADOX: FORMAL STATEMENT, NECESSITY OF WORLDLINES, AND THE ROLE OF f

Before introducing the formal mathematical setup, it is instructive to illustrate the De Giuseppe Paradox with a concrete example, integrating the precise spacetime configuration formalism. Consider a spacecraft (A) transporting a set of bricks towards a wall being simultaneously constructed by a second agent (B) at a point M. Let the delivery endpoint be Y. The scenario is:

- A departs from x carrying bricks at relativistic velocity $v < c$. The journey to Y lasts **4 hours proper time** for A.

- B constructs the wall at M at a later coordinate time $t_B(M)$. Due to time dilation and relativity of simultaneity, B observes **10 years elapse** while A experiences 4 hours.

- At the midpoint M, A has experienced **2 hours** while B sees **5 years** elapsed. The worldlines of A and B intersect here in such a way that the bricks A carries have not yet arrived at M, yet B is already building the wall.

- Consequently, from a spacetime configuration perspective, the bricks appear **simultaneously present** both on A's spacecraft and incorporated into the wall constructed by B. No local light-cone is violated, but the ontological co-existence creates the paradoxical effect.

We define a *spacetime configuration function* f as follows:

$$f\big((x_M,t_M),(x_Y,t_Y)\big) = \begin{cases} 1, & \text{if a retrocausal loop emerges (apparent paradox),} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

where x_M, t_M are the coordinates of the wall construction and x_Y, t_Y the delivery point coordinates. Explicitly, the loop condition can be written:

$$f((x_M,t_M),(x_Y,t_Y)) = 1 \iff \mathrm{Bricks}_{\rm wall}(t_B(M)) \wedge \mathrm{Bricks}_{\rm A}(t_A(Y)),$$

This indicates that, in certain reference frames, the bricks are simultaneously "present" both in the wall and on the spacecraft without violating any local light-cone constraints. Small perturbations in x_M or t_M can switch f to 0, eliminating the retrocausal appearance.

Formally, the spacetime interval between wall and delivery point is:

$$\Delta s^2 = c^2(t_Y - t_M)^2 - (x_Y - x_M)^2,$$

and the emergent retrocausality condition requires:

$$\Delta t_B(M \to Y) < \Delta t_A(Y \to M),$$

in B's frame, producing an apparent loop while fully respecting Special Relativity. This operationalizes the concrete paradox: the wall can exist "before" A's bricks arrive in certain frames, generating an ontological tension that is frame-dependent but causally consistent locally.

Mathematical setup

Let $(\mathcal{M}, g)$ denote the Minkowski spacetime (or, more generally, a local Lorentzian 4-space). Let Γ be the space of smooth curves $\gamma : \mathbb{R} \supset I \to \mathcal{M}$ that are future-directed and timelike or null (worldlines). Each $\gamma \in \Gamma$ represents the history of a localized object or excitation.

Define the *operational configuration space* Ω as the set of global assignments of worldlines and macroscopic parameters (positions of apparatus, times of action, etc.). Each $\mathcal{C} \in \Omega$ encodes a complete arrangement of events and devices.

Introduce the configurational function

$$f : \Omega \to \{0, 1\},$$

defined so that

$$\begin{aligned} &f(\mathcal{C}) = 1 \\ &\quad \Longleftrightarrow \mathcal{C} \text{ contains a closure of causal accessibility (a "loop")} \\ &\qquad \text{generating apparent retrocausal correlations.} \end{aligned} \tag{2}$$

More concretely, $f(\mathcal{C}) = 1$ if there exist events $e_i, e_j \in \mathcal{C}$ and frames F_A, F_B such that

$$t_{F_A}(e_i) < t_{F_A}(e_j) \quad \text{and} \quad t_{F_B}(e_j) < t_{F_B}(e_i),$$

while all local causal cones remain respected.

Configurational time and loop admissibility

Not every configuration $\mathcal{C} \in \Omega$ with suitable geometry is physically realizable. We therefore refine the loop condition by introducing a configurational time $\tau_C(\mathcal{C})$ associated with the establishment of the global worldline arrangement.

The loop condition becomes

$$f(\mathcal{C}) = 1 \iff \big(\mathcal{C} \text{ contains a causal closure}\big) \wedge (\tau \geq \tau_C(\mathcal{C})).$$

For $\tau < \tau_C(\mathcal{C})$, the apparent retrocausal loop cannot emerge, even if the spacetime geometry would allow it kinematically. The De Giuseppe Paradox is therefore *selective*: it arises only for configurations that have reached their configurational emergence time.

Formal statement of the paradox

De Giuseppe Paradox (formal). There exist configurations $\mathcal{C} \in \Omega$ with $f(\mathcal{C}) = 1$ that are physically consistent with Special Relativity (i.e., no superluminal signals are required), for which correlations appear in certain frames as violations of intuitive causal order (apparent retrocausality).

Why worldlines are unavoidable

Definition .1 (Persistence of an object) *A persistent physical object is represented by a smooth map*

$$X : \mathcal{I} \subset \mathbb{R} \to \mathcal{M}, \qquad \tau \mapsto X(\tau),$$

with $\dot{X}$ timelike (i.e., a worldline parametrized by proper time τ).

Theorem .1 (Necessity of worldlines in SR) *In Special Relativity, the ontological representation of a persistent object requires the existence of a timelike worldline: without a continuous representation, proper time, past/future light cones, and local energy-momentum conservation cannot be consistently assigned to that object.*

Proof sketch. SR operationally defines proper time, local causal cones, and frame-dependent simultaneity. Persistence requires a monotonically parameterized curve through events. Conserved quantities (energy, momentum, charge) require support along such curves (worldlines or worldtubes). Without a worldline, Lorentz transformations cannot consistently relate observers describing the same object, breaking identity across time. Hence worldlines are ontologically necessary for representing persistent entities in SR.

Role of f in identifying geometric intersections

The function f encodes exactly those global configuration properties that allow light cones to intersect and form apparent causal loops without introducing superluminal signaling. Concretely:

- $f(\mathcal{C}) = 0$ if the configuration is trivial (all events have concordant causal order in relevant frames) — no apparent retrocausal correlations emerge.
- $f(\mathcal{C}) = 1$ if the global geometry of worldlines and timing creates a *configurational closure* (e.g., A's bricks are simultaneously "described" as present both on the spacecraft and in the wall built by B in some frames), resulting in apparent causal ambiguity.

Consequences and predictions

1. **Sensitivity to extreme configurations.** Because f depends discontinuously on small spatial/temporal shifts (see $\delta x, \delta t$ in Paradox 2.0), configurations with $f = 1$ are *fragile*: minor perturbations eliminate the loop. This provides an operational criterion to falsify physical interpretations postulating extra entities.
2. **Phenomenological unification.** Many seemingly nonlocal quantum phenomena (interference, entanglement, delayed-choice) can be reformulated as cases where $f(\mathcal{C}) = 1$ for certain choices of worldlines and boundary conditions. This underlies the operational De Giuseppe program (see Sec.).

3. **No-signaling preserved.** Even when $f(\mathcal{C}) = 1$, all actual communication remains constrained within local light cones; retrocausality is informational (reordering of observations) and does not allow controllable signaling to the past.

Brief epistemic discussion

The paradox does not require modifying the metric or local equations; it only requires recognizing that the *global geometry* of worldlines and experimental boundary conditions can produce phenomenology that, in reduced descriptions or specific frames, appears to violate ordinary causality. The function f is the mathematical tool to isolate those regions of Ω and construct testable predictions.

Section conclusion

In summary: within SR, worldlines are the only ontologically consistent vehicle for representing persistent objects; the configurational function f identifies when the global geometry of these worldlines produces non-intuitive temporal effects ("apparent retrocausality"). This explains why the De Giuseppe Paradox is not a relativistic algebra error, but a geometric-ontological consequence of representing physical histories in $\mathcal{M}$.

8. Conclusion. We have shown that (i) Born's rule arises naturally as the expectation of a positive causal-accessibility operator, (ii) configuration-space constraints produce rigorously definable macroscopic entanglement, and (iii) single-photon reflection and interference experiments provide a "smoking gun" for worldline-mediated correlations. Finally, the introduction of the configurational emergence time τ_C and the De Giuseppe constant K_D elevates the framework from a purely kinematic reinterpretation to a physically predictive structure. Quantum mechanics operates in the regime $\tau \geq \tau_C$; below this threshold, no global accessibility amplitude, entanglement, or causal loop is physically defined. This provides a sharp temporal boundary for the applicability of quantum probabilities and worldline-mediated correlations. This integrated formalism is mathematically rigorous, operationally meaningful, and experimentally falsifiable, offering a high-impact route for testing foundational ontologies.

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