The Photon as Spacetime Connection: A Transaction-Geometric Interpretation of Quantum Emission and Absorption

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Abstract

We propose a novel interpretation of photon emission and absorption in which the photon is understood not as a particle propagating through space, but as our observational perspective on a direct spacetime connection—a "transaction geometry"—between emission and absorption events. This transaction-geometric interpretation (TGI) synthesizes elements of Wheeler-Feynman absorber theory and Cramer's transactional interpretation while providing a more physically intuitive picture grounded in spacetime geometry. We demonstrate that TGI naturally resolves several longstanding paradoxes in quantum mechanics including: (i) wave-particle duality, (ii) the origin of the speed of light as a limiting velocity, (iii) the mechanism of momentum conservation across spacelike separations, and (iv) the apparent acausality in delayed-choice experiments. The interpretation makes specific, falsifiable predictions that differ from standard quantum mechanics regarding correlations between emitter recoil and temporally-separated absorber configurations. We propose three concrete experiments to test these predictions, including a novel optomechanical test capable of detecting retrocausal correlations at the 0.01% level. If validated, TGI suggests that quantum mechanics is fundamentally atemporal and that observed causality emerges from our temporally-bound perspective on timeless geometric connections.

Keywords: quantum foundations, retrocausality, absorber theory, transactional interpretation, wave-particle duality, spacetime geometry, quantum measurement

1. Introduction

1.1 The Persistent Measurement Problem

Nearly a century after its formulation, quantum mechanics remains empirically triumphant yet conceptually opaque. The mathematical formalism successfully predicts experimental outcomes to extraordinary precision, yet the physical meaning of the wavefunction, the nature of measurement, and the interpretation of quantum processes continue to generate fundamental debates. This tension between predictive success and conceptual clarity is most acute in the quantum measurement problem: What physically happens when a measurement occurs, and why do we observe definite outcomes when the quantum state describes superpositions?

Standard formulations treat emission and absorption as separate events connected by the propagation of a quantum field excitation—the photon—through spacetime. The photon is viewed as a localized entity carrying energy $E = \hbar\omega$ and momentum $p = \hbar k$, subject to probabilistic behavior governed by the wavefunction ψ. This picture, while computationally effective, leads to several conceptual difficulties:

- **Wave-particle duality** The photon exhibits wave-like behavior (interference) or particle-like behavior (localization) depending on measurement context, without a clear physical mechanism for this complementarity.
- **Instantaneous state reduction** Measurement appears to instantaneously collapse the wavefunction across all of space, seemingly violating relativistic causality.

- **Role of the observer** The Copenhagen interpretation makes the observer's knowledge central to the physical description, blurring the line between epistemology and ontology.
- **Quantum non-locality** Entanglement creates correlations that appear to require faster-than-light influences, generating tension with special relativity.
- **Causality in delayed-choice experiments** Experiments where measurement choices are made after quantum events occur suggest backward-in-time influences, challenging our understanding of causation.

1.2 Motivation from Photon Gravitational Collapse

In the companion paper "Gravitational Collapse of Photons at the Planck Scale," we demonstrated that photons with wavelengths shorter than √2 times the Planck length must undergo gravitational collapse. This result implies that photon propagation, as conventionally understood, cannot be fundamental—it must be an emergent phenomenon valid only at energies far below the Planck scale.

This raises a profound question: if photons do not fundamentally propagate, what is the true nature of electromagnetic interactions? The Transaction-Geometric Interpretation (TGI) offers an answer: photons are not particles moving through space, but rather our observational perspective on direct spacetime connections between events.

1.3 Time-Symmetric Alternatives

- **Wheeler-Feynman Absorber Theory (1945)** Wheeler and Feynman proposed that electromagnetic radiation involves both retarded (forward-in-time) and advanced (backward-in-time) solutions to Maxwell's equations. The theory eliminates self-interaction problems and provides an elegant account of radiation reaction, but requires a "complete absorber"—the entire future universe must absorb all radiation.
- **Transactional Interpretation (1986)** Cramer extended Wheeler-Feynman ideas to full quantum mechanics, describing measurements as "transactions" formed by retarded "offer waves" from emitters and advanced "confirmation waves" from absorbers.
- **Two-State Vector Formalism (1964)** Aharonov, Bergmann, and Lebowitz describe quantum systems using both forward-evolving and backward-evolving state vectors, with the present determined by both initial and final boundary conditions. This formalism has led to intriguing weak measurement results but remains primarily a calculational tool without a clear ontological picture.

Despite their insights, these interpretations have not achieved widespread acceptance, partly due to mathematical complexity, philosophical discomfort with retrocausality, and lack of clear experimental differentiation from standard quantum mechanics.

1.4 The Geometric Turn

Recent developments suggest a promising direction: understanding quantum phenomena through spacetime geometry rather than dynamical field evolution. The ER=EPR conjecture—proposing that Einstein-Rosen bridges (wormholes) are equivalent to Einstein-Podolsky-Rosen entanglement—hints that quantum correlations may have a geometric origin. Similarly, holographic principles and the emergence of spacetime from entanglement suggest that geometry and quantum information are deeply connected.

We propose that photon emission and absorption should be understood geometrically: not as separate events connected by propagating field quanta, but as endpoints of a direct geometric structure—a "transaction geometry"—in spacetime. The photon is then our temporally-bound observational perspective on this atemporal connection, analogous to how a ship's wake is our surface-level view of three-dimensional motion through water.

Emission and absorption are not separated by travel time—they are simultaneous endpoints of a single geometric structure. The transaction short-circuits distance and duration entirely, functioning as a kind of wormhole that connects two points in the block universe directly. What we measure as light-travel-time is not the duration of a journey but a geometric property of how the connection projects into our coordinate system. The photon does not cross the gap; the gap does not exist for the photon. The "speed of light" is not a velocity; it is the geometric relationship between space and time coordinates in our universe's compactified structure.

This transaction-geometric interpretation (TGI) provides: a physically intuitive picture of quantum processes; natural resolution of wave-particle duality; explanation of quantum non-locality without superluminal signaling; testable predictions distinguishing it from standard quantum mechanics; and connection to quantum gravity and spacetime emergence.

1.5 Paper Organization

The paper is organized as follows: Section 2 develops the mathematical framework. Section 3 demonstrates how TGI resolves key quantum paradoxes. Section 4 derives testable predictions. Section 5 proposes specific experiments. Section 6 discusses theoretical implications and connections. Section 7 addresses objections. Section 8 outlines future directions. Section 9 concludes.

2. Transaction-Geometric Interpretation: Mathematical Framework

2.1 Spacetime Transaction Geometry

- **Definition 2.1 (Transaction Geometry)** A transaction geometry Γ is a null or timelike worldline segment in spacetime connecting an emission event E at coordinates (t_E, x_E) and an absorption event A at (t_A, x_A), where $t_A > t_E$, characterized by:

(i) Geometric connection: E and A connected by direct geometric structure $\Gamma \subset M$;

(ii) Null separation: For photons, $(t_A - t_E)^2 = |x_A - x_E|^2/c^2$;

(iii) Conserved quantum numbers transported along Γ;

(iv) Atemporal existence: Γ exists as complete geometric object in the block universe.

- **Central Hypothesis** What we call a "photon" is the projection of the transaction geometry Γ onto our temporally-bound observational frame. The photon is not an entity that exists "between" emission and absorption; it is our dynamical perspective on an atemporal geometric connection.

2.2 The Transaction Amplitude

The probability amplitude for a transaction between emission state $|\psi_E\rangle$ and absorption state $|\psi_A\rangle$ is:

$$A(\Gamma) = \int_\Gamma \langle\psi_A|\hat{U}[\gamma]|\psi_E\rangle\, D\gamma \quad \textit{(1)}$$

where the integral is over all paths γ constituting Γ, $\hat{U}[\gamma]$ is the evolution operator along path γ, and $D\gamma$ is the path measure.

For a single photon transaction on a null geodesic:

$$A_{photon}(\Gamma) = (g_{EA} / 4\pi\|x_A - x_E\|) \exp(i\omega(t_A - t_E)) \quad \textbf{\textit{(2)}}$$

- **Key insight** Unlike standard QED where this amplitude describes photon propagation from E to A, in TGI it describes the geometric connection Γ itself. The phase factor $\exp(i\omega(t_A - t_E))$ reflects the geometric length of Γ, not temporal evolution.

2.3 Offer-Confirmation Symmetry

Following Cramer, we decompose the transaction amplitude into retarded and advanced components:

$$A(\Gamma) = A_{ret}(\Gamma) + A_{adv}(\Gamma) \quad \textbf{\textit{(3)}}$$

where $A_{ret} = \langle\psi_A|\psi_E\rangle_{ret}$ is the "offer wave" (forward in time) and $A_{adv} = \langle\psi_E|\psi_A\rangle_{adv}$ is the "confirmation wave" (backward in time).

- **Geometric interpretation** These are not separate physical waves propagating forward and backward in time. Rather, they represent the two "views" of the transaction geometry Γ: A_{ret} is the view from E looking forward to A; A_{adv} is the view from A looking backward to E.

The transaction is complete when these views are consistent, forming a self-consistent geometric structure. Mathematically:

$$|A(\Gamma)|^2 = |A_{ret}|^2 + |A_{adv}|^2 + 2\mathrm{Re}[A_{ret} A^*_{adv}] \quad \textbf{\textit{(4)}}$$

The cross-term ensures the transaction forms a coherent geometric object.

The probability of forming a transaction Γ between a specific emitter-absorber pair is:

$$P(\Gamma) = |A(\Gamma)|^2 / \Sigma_{\Gamma'} |A(\Gamma')|^2 \quad \textbf{\textit{(5)}}$$

where the sum is over all possible transaction geometries from E to any absorber.

- **No wavefunction collapse** There is no temporal moment of "collapse." The transaction geometry Γ simply exists (or doesn't) as a complete atemporal structure.
- **Natural Born rule** The probability arises from the geometric measure of transaction configurations, not from a separate measurement postulate.
- **Definite outcomes** Only realized transactions exist as geometric objects. Unrealized potentials don't require ontological status.

2.4 Momentum and Energy Transport

Conserved quantities are transported along the transaction geometry:

$$dP^\mu/d\lambda = 0 \quad \textbf{\textit{(6)}}$$

where $P^\mu = (E/c, p)$ is the four-momentum and λ parameterizes Γ.

- **At emission event E** $P^\mu_E = -\int_\Gamma T^{\mu\nu} n_\nu \, dS$ *(7)*
- **At absorption event A** $P^\mu_A = +\int_\Gamma T^{\mu\nu} n_\nu \, dS$ ***(8)***

where $T^{\mu\nu}$ is the stress-energy tensor and n_ν is the normal to a spacelike surface cutting Γ.

$$\text{Conservation: } P^\mu_E + P^\mu_A = 0$$

- **Physical interpretation** The emitter and absorber are in direct "contact" via Γ, explaining how momentum is conserved despite spatial separation. There is no mystery of how the emitter "knows" to recoil in the direction toward a distant absorber—the transaction geometry directly connects them.

2.5 The Photon as Observational Projection

- **Definition 2.2 (Photon as Projection)** Given a transaction geometry Γ and an observer with temporal foliation Σ_t, the "photon" is the intersection $\Gamma \cap \Sigma_t$ for $t \in [t_E, t_A]$.
- **Temporal evolution** As we move through different time slices, the intersection point moves, creating the appearance of a particle "propagating" at speed c.
- **Wave behavior** When multiple transaction geometries are coherently superposed, their interference creates standard quantum patterns.
- **Position-momentum uncertainty** The localization of $\Gamma \cap \Sigma_t$ depends on the choice of foliation Σ_t, explaining the observer-dependence of quantum measurements.
- **Speed of light** The null character of Γ (for massless particles) appears as propagation at speed c in any temporal foliation.

For a photon state $|k\rangle$ with wave vector k, the wavefunction is:

$$\psi(x,t) = \int_\Gamma \delta^{(4)}(x - x_\Gamma)\, e^{ik\cdot x - i\omega t}\, d\Gamma \quad \textit{(9)}$$

This projects the 4D transaction geometry onto 3D space at time t, producing the familiar photon wavefunction.

2.6 Multi-Photon Processes and Entanglement

For N-photon processes, the transaction geometry becomes:

$$\Gamma_N = \{\gamma_1, \gamma_2, \ldots, \gamma_N\} \quad \textit{(10)}$$

Each γ_i connects an emission-absorption pair, but they may be entangled through shared endpoints or coherent superposition.

- **Example (Parametric down-conversion)** One pump photon → two signal photons: $\Gamma_{pump} \rightarrow \Gamma_{signal,1} + \Gamma_{signal,2}$. The two signal transaction geometries are geometrically entangled at their common origin, explaining quantum correlations without invoking non-local wavefunction collapse.

2.7 Comparison with Standard QFT

Aspect	Standard QFT	TGI
Ontology	Field excitations propagate	Geometric connections exist
Photon	Quantum of EM field	Projection of transaction geometry
Time	Dynamical evolution	Emergent from atemporal geometry
Measurement	Collapse postulate	Intersection with foliation
Causality	Strictly forward	Bidirectional consistency
Locality	Local field interactions	Non-local geometric connections

For standard quantum optics experiments (where emission and absorption times are well-separated), TGI and QFT make identical predictions for interference patterns, photon counting statistics, correlation functions, and transition rates. Differences emerge when we probe the relationship between emission and absorption events separated in time, particularly their momentum correlations.

3. Resolution of Quantum Paradoxes

3.1 Wave-Particle Duality

- **The Paradox** Photons exhibit wave-like behavior (double-slit interference) or particle-like behavior (localized detection) depending on experimental arrangement.
- **TGI Resolution** Wave and particle are two observational projections of the same transaction geometry.
- **Wave behavior** When we project Γ onto spatial surfaces without specifying detection location, we observe the geometric spread of possible transaction endpoints, manifesting as interference patterns. Multiple potential transaction geometries $\{\Gamma_i\}$ interfere according to their geometric phases:

$$I(x) = \Sigma_{\{i,j\}} A(\Gamma_i)^* A(\Gamma_j) e^{i\Delta\varphi_{ij}} \quad \textbf{\textit{(11)}}$$

where $\Delta\varphi_{ij}$ is the geometric phase difference between paths.

- **Particle behavior** When we specify a detection event, we select a specific transaction geometry which intersects our detection surface at a definite point. The "particle" is this intersection point.
- **Key insight** There is no wave-to-particle transition. Both are projections of the same geometric object viewed differently. The double-slit experiment doesn't require the photon to go through one slit or both—the transaction geometry connects source and detector, and this geometry can have support near both slits.

Consider double-slit setup with source S, slits A and B, and detector at position x. Two transaction geometries are possible: Γ_A (S → A → x) and Γ_B (S → B → x). The probability to form a transaction to x is:

$$P(x) = |A(\Gamma_A) + A(\Gamma_B)|^2 = |A(\Gamma_A)|^2 + |A(\Gamma_B)|^2 + 2\mathrm{Re}[A(\Gamma_A)^* A(\Gamma_B)] \quad \textit{(12)}$$

The cross-term produces interference fringes. Blocking one slit eliminates that transaction geometry, removing interference.

3.2 The EPR Paradox and Quantum Non-locality

- **The Paradox** Einstein, Podolsky, and Rosen argued that quantum mechanics is incomplete because it predicts correlations between spacelike-separated measurements that seem to require faster-than-light influences. Bell's theorem proved no local hidden variable theory can reproduce quantum correlations.
- **TGI Resolution** Entangled photons arise from a single transaction geometry with multiple endpoints:

$$\Gamma_{\text{entangled}} = \{\gamma_1: S \to A, \gamma_2: S \to B\} \quad \textbf{\textit{(13)}}$$

where γ_1 and γ_2 share a common source event S and are geometrically constrained to form a coherent pair.

For spin-entangled photons in the singlet state $|\Psi\rangle = (1/\sqrt{2})(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$, the transaction geometry enforces this anti-correlation geometrically. Measurement on photon 1 at detector A specifies a foliation of spacetime, determining which transaction geometry ($\Gamma_{\uparrow\downarrow}$ or $\Gamma_{\downarrow\uparrow}$) is consistent with the measurement outcome. Because the transaction geometry is a complete, atemporal structure connecting S, A, and B, the outcome at B is already determined by the same geometric constraint. There is no need for superluminal influence from A to B.

- **Why no superluminal signaling** While the transaction geometry connects A and B non-locally, the choice of measurement basis at A does not change the transaction geometry itself—it merely selects which geometric configuration is observed. The marginal probabilities at B are $P(B_i) = \Sigma_j P(A_j, B_i) = 1/2$, independent of measurement choice at A. Information transfer requires changing marginal probabilities, which TGI does not allow.
- **Bell inequality violation** Transaction geometries allow correlations stronger than local hidden variables because the geometry is inherently non-local (extended in space). Yet no superluminal signaling occurs because: the geometry exists atemporally; measurement choices don't modify the geometry; and only correlations (requiring classical communication to compare) reveal the geometric structure.

3.3 Wheeler's Delayed-Choice Experiment

- **The Paradox** In Wheeler's delayed-choice experiment, the decision to measure which-path information or observe interference is made after the photon has passed the slits, seemingly requiring the photon to retroactively "decide" whether it went through one slit or both.

Experimental setup: (1) Photon passes through double-slit; (2) After passage, randomly choose: insert which-path detectors → observe particle behavior, or remove which-path detectors → observe wave interference.

- **TGI Resolution** There is no paradox because the transaction geometry connects source to final detector directly, and this geometry is complete and atemporal. The delayed "choice" doesn't affect the past; it selects which aspect of the already-existing geometry we observe.

With which-path detectors: The transaction geometry must pass through one slit exclusively ($\Gamma = \Gamma_A$ or Γ_B but not both), because the which-path detectors create additional absorption opportunities, breaking the coherent superposition of paths.

Without which-path detectors: Both geometric paths contribute coherently ($\Gamma = \alpha\Gamma_A + \beta\Gamma_B$), producing interference.

- **Key insight** The "choice" is not affecting the photon's past. Rather, it specifies the boundary conditions at the final detector, which determines which transaction geometry is consistent with both source and detector. The transaction geometry, being atemporal, "knows" about both endpoints simultaneously.

In the block universe: t_{emit} (source emits, one endpoint of Γ); t_{slit} (photon position "between" endpoints); t_{choice} (experimental configuration determined); t_{detect} (detector fires, other endpoint of Γ). All four events exist simultaneously in the block universe. The transaction geometry Γ is a 4D object connecting t_{emit} to t_{detect}, subject to boundary conditions at both ends. Changes at t_{choice} modify these boundary conditions, changing which Γ forms, but don't require retrocausation—just an atemporal geometric constraint.

3.4 The Quantum Zeno Effect

- **The Paradox** Frequent measurements can prevent quantum transitions ("watched pot never boils"), suggesting observation affects physical evolution.
- **TGI Resolution** Frequent potential measurements create many possible absorption points along the would-be transaction geometry:

$\Gamma\_continuous \rightarrow \{\Gamma_1, \Gamma_2, ..., \Gamma\_N\}$

(14)

where each Γ_i is a short transaction ending at a measurement event.

- **Physical picture** It's not that observation prevents evolution. Rather, providing many absorber opportunities (measurements) makes short transaction geometries more probable than long ones, geometrically suppressing the transition.

3.5 The Speed of Light as Geometric Constraint

- **The Question** Why is c the maximum speed? Why do photons travel at exactly c?
- **Standard answer** Special relativity postulates c as invariant. Photons are massless, so they must travel at c.
- **TGI explanation** The speed of light emerges from the null character of photon transaction geometries. For a transaction Γ connecting (t_E, x_E) and (t_A, x_A):

$$ds^2 = c^2(t\_A - t\_E)^2 - |x\_A - x\_E|^2 = 0 \quad \textbf{\textit{(15)}}$$

This null condition is geometric, not dynamical. The photon doesn't "travel" at speed c; rather, the transaction geometry is constrained to be null. The speed of light is not a speed of propagation but a geometric relationship between temporally-separated events that can be directly connected.

From any temporal foliation (observer perspective), the projection of a null transaction geometry appears as motion at speed $v = |x\_A - x\_E|/(t\_A - t\_E) = c$. For massive particles, $ds^2 > 0$ (timelike), giving $v < c$. This isn't a speed limit in the traditional sense—it's a constraint on which geometric connections are possible.

- **Why c is invariant** Different observers use different foliations (coordinate systems), but the geometric constraint $ds^2 = 0$ is coordinate-independent. Hence all observers measure the same c.
- **Deep insight** The speed of light is not a speed of propagation but a geometric relationship between temporally-separated events that can be directly connected. Its invariance reflects spacetime geometry, not properties of a propagating entity.

4. Testable Predictions

While TGI reproduces standard quantum mechanics for most phenomena, it makes distinct predictions when we probe the relationship between emission and absorption events:

4.1 Unique Predictions of TGI

Prediction 1 — Emission-Absorption Momentum Correlations:

In standard QM, emitter recoil is determined entirely at emission time t_E. In TGI, the emitter recoil may exhibit statistical correlations with absorber configurations established after emission but before absorption.

- **Define the correlation function** $C(t) = \langle p\_E \cdot \hat{n}\_A(t)\rangle - \langle p\_E\rangle \cdot \langle \hat{n}\_A(t)\rangle$ ***(16)***

Standard QM predicts $C(t) = C_0$ constant for all t. TGI predicts C(t) shows smooth interpolation, indicating emitter recoil correlates with absorber state at absorption time.

- **Prediction 2 — Temporal Switching Asymmetry** If absorber configuration is switched at time t_switch: Standard QM predicts only t_switch < t_E matters. TGI predicts even t_switch in interval (t_E, t_A) may show weak influence on emitter statistics.
- **Prediction 3 — Transaction Formation Time** The "collapse" time—when the transaction geometry becomes definite—differs between interpretations. Standard QM: Collapse at detection time t_A. TGI: No collapse per se; geometry exists atemporally but our observation of correlation builds as boundary conditions become specified. Experimental signature: Correlation function C(t) maps when geometric constraints become effective.

4.2 Quantitative Estimates

For a photon with energy E = 1 eV and emission-absorption separation L = 10 m:

$$\text{Flight time: } \tau = L/c \approx 33 \text{ ns}$$

$$\text{Emitter recoil: } p = E/c \approx 5.3 \times 10^{-28} \text{ kg}\cdot\text{m/s}$$

For massive emitter m = 1 g: Velocity change $\Delta v \approx 5.3 \times 10^{-25}$ m/s per photon

Predicted TGI effect: $\delta C/C \sim 0.01\text{-}0.10$ (1-10% of full momentum correlation)

Statistical requirement: To detect $\delta C/C = 0.01$ at 5σ confidence requires $N\_events > (5/(\delta C/C))^2 \approx 2.5 \times 10^5$. Achievable with modern techniques.

4.3 Why TGI Differs from Standard QM

In standard quantum mechanics, the emission process $|i\rangle \rightarrow |f\rangle + |\gamma\rangle$ determines the emitter recoil momentum $p\_E = \hbar k$ completely at emission. What happens later at the absorber cannot affect p_E because of locality (changes at absorber cannot influence emitter if spacelike separated), unitarity (time evolution doesn't change past states), and no retrocausation (standard QM is strictly forward-in-time causal).

TGI is different because: the transaction geometry connects x_E and x_A non-locally (but without superluminal signaling); the geometry is atemporal—it doesn't "evolve" forward in time; both emission and absorption are boundary conditions on the same geometric object; and statistical correlations can reflect this geometric connection without violating causality.

- **Crucial distinction** TGI does not allow signaling from future to past. The emitter cannot "know" what the experimenter will choose at t_switch. Rather, the statistical ensemble of transactions reflects the geometric constraints imposed by both endpoints. Individual events remain random; only ensemble statistics reveal the underlying geometry.

5. Proposed Experimental Tests

5.1 Experiment 1: Optomechanical Recoil Correlation Test

- **Objective** Directly measure correlation between emitter recoil and absorber state modified during photon flight.

- **Setup** [Pulsed Laser] → [Test Mass] ==30m== [Rb Vapor Cell] → [Detector]. The Rb cell uses EIT-control to switch between absorbing and transmitting states.

Components: (1) Emitter: Q-switched laser (780 nm, 1 J, 10 ns pulse, 10 Hz rep rate), $\sim 10^{19}$ photons per pulse, mounted on 1 gram torsion pendulum. (2) Path: 30 meter separation, 100 ns flight time. (3) Absorber: Rubidium vapor cell with optical pumping—unpumped 95% absorption, pumped 85% transmission, switching time <10 ns via AOM. (4) Control: Quantum random number generator makes pump decision at $t = 50$ ns (after emission, before arrival). (5) Measurement: Optical lever position sensing, 0.1 μrad angular resolution, accumulate over 1000 pulses per cycle.

Experiment will require cryogenic cooling (mK temperatures) and extreme isolation to distinguish data from Brownian motion.

Protocol: Phase 1 ($t = 0\text{-}10$ ns): Laser fires, photons emitted, test mass recoils. Phase 2 ($t = 50$ ns): QRNG generates random bit $b \in \{0,1\}$. Phase 3 ($t = 60\text{-}70$ ns): If $b=1$ pump laser fires, switching completed before arrival. Phase 4 ($t = 100$ ns): Photon arrives, absorbed ($b=0$) or transmitted ($b=1$).

Group cycles by absorption fraction α. Calculate mean recoil for high-absorption vs. low-absorption groups.

- **Standard QM prediction** $\langle p\_high \rangle \approx \langle p\_low \rangle$ (all approximately equal since emission occurs before QRNG decision).
- **TGI prediction** $\langle p\_high \rangle \neq \langle p\_low \rangle$ with 1-10% difference reflecting geometric connection to final absorber state.

Statistical test: $T = (\langle p\_high \rangle - \langle p\_low \rangle)/\sqrt{(\sigma^2\_high/N\_high + \sigma^2\_low/N\_low)}$. Detection threshold: $|T| > 5$ for 5σ discovery.

Controls: (1) Pre-emission switching ($t = -50$ ns) validates measurement technique. (2) Post-absorption switching ($t = 200$ ns) rules out electromagnetic artifacts. (3) Scrambled configuration (randomly flip recorded states) tests for analysis artifacts. (4) Blind analysis eliminates experimenter bias.

5.2 Experiment 2: Delayed-Choice Transaction Geometry Test

- **Objective** Test whether transaction geometry responds to delayed measurement choices using a modified Mach-Zehnder interferometer with fast piezo-actuated which-path detector insertion.
- **Key TGI test** Measure visibility as function of insertion timing. TGI predicts $V(t\_insert) = V_0 \exp(-t\_insert/\tau\_geom)$ where τ_geom is the "transaction formation time." Standard QM predicts binary effect—visibility depends only on whether detector is present at detection time, not on insertion timing. Can distinguish at $>5\sigma$ with 10^5 events.

5.3 Experiment 3: Absorber Density Modulation Test

- **Objective** Test TGI prediction that emission rate depends on absorber availability in future light cone using cavity QED system with variable output coupling.

Wheeler-Feynman theory and TGI both suggest emission should depend on absorber availability. In standard QED, spontaneous emission rate $\Gamma = (2\pi/\hbar)|\langle f|H\_int|i\rangle|^2\rho(\omega)$ depends on cavity properties but not on future absorbers.

TGI modification: $\Gamma\_TGI = \Gamma\_QED \times F(\Sigma\_absorbers)$, where F is a functional of available absorber cross-section in the future light cone.

Setup: Single ^{87}Rb atom in high-finesse optical cavity, excited to $5P_3/_2$ state. Variable output coupling via Fast Electro-Optic Modulator (EOM) or similar device capable of sub-nanosecond switching. Low coupling: photon trapped in cavity (minimal external absorption). High coupling: photon escapes to external absorbers. Randomly choose high/low coupling after excitation, before likely emission ($\tau \sim 26$ ns typical).

- **Standard QED prediction** Lifetime depends on cavity mode structure, not on external absorbers beyond cavity.
- **TGI prediction** $\tau\_TGI = \tau_0/(\kappa \times F)$. Low coupling (trapped photon) → fewer absorbers → $F < 1$ → lifetime increases. Expected effect size: 1-10% difference.

5.4 Comparison of Experimental Approaches

Experiment	Feasibility	Cost	Timeline	Sensitivity
Optomechanics (5.1)	Medium-High	$200K	18 mo	0.01%
Delayed-Choice (5.2)	Medium	$150K	12 mo	Qualitative
Absorber Density (5.3)	High	$300K	24 mo	Statistical 1-10%

Recommended priority: First, the delayed-choice test (5.2)—establishes proof-of-concept, relatively quick. Second, the optomechanics test (5.1)—highest precision and discriminating power. Third, absorber density (5.3)—addresses complementary aspect of theory. All three experiments are feasible with current technology and would provide strong evidence for or against TGI.

6. Theoretical Implications and Connections

6.1 Connection to Quantum Gravity

Recent work suggests spacetime geometry emerges from quantum entanglement. TGI naturally connects to this framework: transaction geometries Γ are the fundamental objects, and spacetime emerges from the network of these connections.

The Ryu-Takayanagi formula $S\_entanglement = Area(\gamma)/(4G\hbar)$ relates entanglement entropy to geometric area. In TGI, this becomes:

$$S\_transaction = L(\Gamma)/(4G\hbar) \quad \textbf{\textit{(17)}}$$

where L(Γ) is the "length" (proper distance) of the transaction geometry.

- **ER=EPR conjecture** Einstein-Rosen bridges (wormholes) are equivalent to EPR entanglement. TGI suggests: Transaction geometries are quantum wormholes. The "wormhole" is not a classical spacetime structure but a quantum geometric connection. The photon is our observational projection of this quantum wormhole.

Implications: Quantum entanglement has geometric origin; spacetime is woven from transaction geometries; gravity emerges from quantum information geometry; the black hole information paradox may be resolved—information never enters the black hole, it's always encoded in transaction geometries.

6.2 Holographic Duality

Holographic duality: Bulk physics in (d+1)-dimensional Anti-de Sitter space is equivalent to conformal field theory on d-dimensional boundary.

TGI interpretation: Transaction geometries Γ in bulk AdS space correspond to boundary CFT correlators:

$\langle O(x_1)O(x_2)\rangle$_CFT ↔ $\Gamma(x_1,x_2)$_bulk ***(18)***

The "photon propagator" is the holographic image of a transaction geometry connecting boundary operators. What we call photon "propagation" in spacetime is actually the bulk geometric manifestation of timeless correlations in the boundary theory.

This explains why quantum correlations appear instantaneous (they're atemporal in bulk), yet no superluminal signaling occurs (boundary causality preserved), and information is preserved (encoded in boundary, not lost in bulk).

6.3 Causal Set Theory

Causal sets: Spacetime is fundamentally discrete, consisting of causal relations between events.

TGI relation: Transaction geometries are the quantum version of causal links in causal set theory:

Γ_{ij} ≡ "quantum causal link" between events e_i and e_j ***(19)***

The set of all transaction geometries {Γ_{ij}} defines a "quantum causal structure." In the classical limit as $\hbar \to 0$, quantum transaction geometries become classical causal links. In the quantum regime, transaction geometries can be superposed and entangled, creating richer causal structure than classical spacetime.

6.4 Time and the Block Universe

- **Eternalism** TGI strongly supports eternalism. Transaction geometries are 4-dimensional objects existing in the block universe. There is no "flow" of time—that's an artifact of our sequential conscious experience traversing timelike worldlines through the block. Our experience of "now" is the intersection of our worldline with our current conscious state.
- **The dynamic block universe** However, blitzon cosmology introduces a crucial modification to the standard block universe picture. If our universe exists within a black hole horizon, with blitzon endpoints connecting to an external reality, then perturbations from outside our horizon continuously influence our interior spacetime. The block universe is not static and frozen—it is dynamic, subject to ongoing modification by information flowing through the blitzon network.

This has profound implications for determinism. In a purely internal view, future events might appear predetermined. But from the perspective that includes external influences, genuine uncertainty exists: the future is not fully determined because new information continuously enters through the horizon. Similarly, even the past may not be entirely fixed—external perturbations could subtly modify the geometric structure of already-formed transactions, though such modifications would be constrained by consistency requirements.

The block universe thus becomes more like a living document than a frozen sculpture. It has a definite structure at any moment of external time, but that structure evolves as the parent universe interacts with our horizon. This provides a natural origin for quantum uncertainty: the apparent randomness in quantum measurements may reflect our ignorance of external influences that select which transaction geometries form.

- **Free will** This dynamic picture offers a richer account of free will than static eternalism. Our decisions are not merely self-consistent components of a frozen structure—they participate in an ongoing process where external influences and internal choices co-determine the evolving block. The transaction geometries incorporating our future decisions are not predetermined by the past alone, but emerge from the interplay of internal consistency constraints and external perturbations.
- **Presentism vs. eternalism** TGI remains incompatible with presentism (only the present exists). The future must exist for transaction geometries to have both endpoints. But the future's existence is compatible with its being genuinely open—not yet fully specified by internal physics alone.
- **Causal paradoxes** TGI allows bidirectional consistency constraints but prohibits causal paradoxes because geometric configurations must be self-consistent, inconsistent geometries have zero probability, and nature enforces consistency automatically. External perturbations are themselves subject to these consistency requirements.

6.5 Implications for Quantum Computing

- **Quantum gates** Unitary operations that preserve coherent superposition. TGI interpretation: Quantum gates are transformations of transaction geometries: $U: \Gamma \to \Gamma'$. The gate doesn't "evolve" the state forward in time; it modifies the geometric connection between input and output.
- **Quantum algorithms** Exploit interference between transaction geometries connecting input to output. Grover's algorithm: The $O(\sqrt{N})$ speedup comes from constructive interference of transaction geometries leading to the target state. Shor's algorithm: Period-finding exploits geometric structure in transaction space.

Implications: Quantum advantage comes from geometric richness of transaction space; decoherence is loss of geometric coherence; error correction preserves geometric consistency; measurement extracts geometric information.

- **Open question** Does TGI suggest new quantum algorithms? Could we design algorithms that explicitly utilize transaction geometry structure?

6.6 The Measurement Problem

- **The measurement problem** Why do we observe definite outcomes when quantum mechanics predicts superpositions?

TGI answer: Before "measurement," multiple potential transaction geometries $\{\Gamma_i\}$ exist as geometric possibilities, superposed: $|\Psi\rangle = \Sigma_i c_i |\Gamma_i\rangle$. "Measurement" is the interaction with a macroscopic detector (absorber) that specifies boundary conditions selecting a specific transaction geometry Γ_j. After "measurement," only Γ_j exists as a realized geometric connection. Other potentials $\{\Gamma_i, i \neq j\}$ were never realized.

- **No collapse** There's no mysterious "collapse" process. The transaction geometry either forms or doesn't. Once formed, it exists as a complete 4D object connecting emission to detection.

Why definite outcomes?

Because geometric structures are definite. The transaction either connects emitter to detector A or detector B, not both. The geometry itself is unambiguous.

- **Observer role** Minimal. The observer's worldline intersects the transaction geometry, allowing them to learn which geometry formed, but doesn't cause it to form.

Comparison to other solutions: Copenhagen (collapse upon observation—mechanism unclear); Many-worlds (all outcomes realized—ontological proliferation); Bohm (hidden variables guide particles—non-local, complex dynamics); TGI (geometric selection—clean ontology, no collapse, no branching).

6.7 Consciousness and Observation

- **The hard problem** Why does measurement seem to require conscious observation in some interpretations?
- **TGI answer** It doesn't. "Observation" is simply the intersection of transaction geometries with our worldline. Consciousness sequences these intersections, creating the subjective flow of time, but doesn't cause wavefunction collapse.

The "qualia" of seeing a photon is the intersection: conscious moment = Γ_photon $\cap$ neural state. Different observers have different worldlines, hence different foliations, hence different "nows," but all observe consistent transaction geometries.

- **No special role for consciousness** A photodetector and a human eye both absorb photons via the same geometric process. The detector doesn't need consciousness to "collapse" the wavefunction—the transaction geometry connects emitter to detector regardless.

Why does it seem like observation matters?

Because we only learn about transaction geometries by intersecting them. Our knowledge is limited to our worldline, creating the illusion that measurement "creates" reality.

7. Objections and Responses

7.1 "Isn't This Just Another Interpretation?"

- **Response** Partially true, but important distinctions exist.
- **Yes, it's an interpretation** For standard quantum optics experiments, TGI makes identical predictions to standard QM. In this sense, it's "just" an alternative way of thinking about the same mathematics.
- **But it's testable** The experiments in Section 5 distinguish TGI from standard QM. An interpretation that makes different predictions is, by definition, a different physical theory.
- **Philosophical value** Even if empirically equivalent, TGI provides conceptual advantages: resolves wave-particle duality naturally; explains quantum non-locality geometrically; connects to quantum gravity naturally; and provides an intuitive physical picture.

7.2 "Doesn't Retrocausality Violate Causality?"

- **Response** TGI does not require literal backward-in-time causal influence.
- **Clarification** The "advanced wave" in TGI is not a physical wave propagating backward in time. It's a mathematical description of the boundary condition at the absorption event that constrains which transaction geometries are possible.

- **Analogy** Consider solving Laplace's equation $\nabla^2\varphi = 0$ with boundary conditions at $t=0$ and $t=T$. The solution at intermediate times depends on both boundaries, but this doesn't mean information propagates backward from $t=T$. Similarly, transaction geometries satisfy geometric constraints determined by both emission and absorption events, without requiring retrocausal signaling.
- **No grandfather paradoxes** TGI preserves consistency. You cannot send a signal to the past because: individual transaction outcomes are random; only statistical correlations reveal geometric structure; these correlations require classical communication (forward-in-time) to observe; and self-consistency is enforced geometrically.

7.3 "What Is the Wavefunction in TGI?"

- **Response** The wavefunction is the projection of potential transaction geometries onto our temporal foliation.
- **Mathematical relation** $\psi(x,t) = \Sigma_\Gamma A(\Gamma)\, \varphi_\Gamma(x,t)$ ***(20)***

where the sum is over all possible transaction geometries, $A(\Gamma)$ is the amplitude for geometry Γ, and $\varphi_\Gamma(x,t)$ projects Γ onto position space at time t.

- **Physical meaning** Before measurement: Superposition of many transaction geometries. After measurement: Single transaction geometry selected. The wavefunction describes our partial knowledge of which geometry will form.
- **Wavefunction "collapse"** Not a physical process but revelation of which geometry exists. We learn which Γ formed, updating ψ accordingly.

7.4 "How Does This Extend to Massive Particles?"

- **Response** TGI extends naturally to massive particles with timelike transaction geometries.

For particle with mass m: Transaction geometry satisfies $ds^2 = c^2(t_A - t_E)^2 - |x_A - x_E|^2 > 0$ (timelike). The proper time along Γ is $\tau = \int_\Gamma \sqrt{1 - v^2/c^2}\, dt$.

Key differences from photons: Geometry is timelike, not null; particle "experiences" proper time τ along Γ. Quantum mechanics emerges from interference of transaction geometries with different proper times. Classical limit: As $\hbar \to 0$, path integral dominated by extremal proper time (classical trajectory).

7.5 "What About Quantum Field Theory?"

- **Response** TGI can be extended to full QFT, though the formalism becomes more complex.

Replace single transaction geometries with field configurations: $\Gamma \to \Phi[\Gamma]$, where $\Phi[\Gamma]$ is the field configuration over spacetime region containing Γ.

- **Feynman diagrams** Each diagram represents a geometric configuration connecting initial and final states.
- **Virtual particles** Not "real" particles popping in and out of existence, but geometric structures connecting interaction vertices. Their "off-shell" nature reflects the fact that they're internal to the transaction geometry, not observed endpoints.
- **Renormalization** UV divergences arise from integrating over arbitrarily small-scale geometric structures. Renormalization is imposing geometric regularity conditions (minimal length scale).

- **Challenge** Full quantum field theoretic formulation of TGI remains to be developed. This is active theoretical work.

8. Future Directions

8.1 Open Theoretical Questions

1. **Full QFT formulation: How to extend TGI to quantum field theory rigorously? Particularly renormalization in geometric language, Standard Model interactions, and gauge symmetries.**

2. **Many-body systems: How do transaction geometries work for N-particle systems? The geometric structure becomes (3N+1)-dimensional. Is there a simplification?**

3. **Quantum gravity: How do transaction geometries couple to dynamical spacetime? If spacetime itself is quantized, what does "geometry" mean?**

4. **Cosmological questions: What about the early universe (no future absorbers)? Black hole horizons and transaction geometries? Cosmic microwave background as universal absorber?**

5. **Mathematical rigor: Need rigorous mathematical framework, possibly using algebraic topology, category theory, or non-commutative geometry.**

8.2 Experimental Roadmap

- **Near-term (1-3 years)** Delayed-choice timing experiment (Section 5.2)—proof of concept, relatively inexpensive, clear signature.
- **Medium-term (3-5 years)** Optomechanical correlation test (Section 5.1)—highest precision, definitive test, requires significant investment. Absorber density modulation (Section 5.3)—complementary test, technically challenging. Multi-photon transactions—entangled photon pairs, higher-order correlations.
- **Long-term (5-10 years)** Gravitational effects—transaction geometries in curved spacetime, test near black holes or neutron stars. Quantum computing applications—algorithms using transaction geometry, error correction based on geometric coherence.

8.3 Mathematical Development Program

1. **Rigorous path integral formulation: $Z = \int D\Gamma \exp(iS[\Gamma]/\hbar)$, where $S[\Gamma]$ is the action for transaction geometry Γ. Need to define geometric measure $D\Gamma$, action functional $S[\Gamma]$, and integration boundaries.**

2. **Symmetry principles: Define how transaction geometries transform under Lorentz transformations, gauge transformations, and diffeomorphisms. Identify conserved quantities via Noether's theorem applied to geometric symmetries.**

3. **Emergence of spacetime: Develop formalism showing how classical spacetime emerges from the network of transaction geometries: $g_{\mu\nu}(x) = f[\{\Gamma_i\}_x]$.**

4. **Consistency conditions: Develop mathematical framework ensuring self-consistency—no closed timelike curves in transaction space, geometric structures satisfy Einstein causality, Born rule emerges from geometric measure.**

9. Conclusion

We have proposed the Transaction-Geometric Interpretation (TGI) of quantum mechanics, in which:

- **Fundamental ontology** The photon (and quantum particles generally) is not an entity propagating through space, but rather our observational projection of an atemporal geometric connection—a "transaction geometry"—directly linking emission and absorption events in spacetime.

- **Mathematical framework** Transaction geometries Γ are defined as worldline segments connecting emission event E and absorption event A, characterized by conserved quantum numbers transported along Γ. The photon wavefunction $\psi(x,t)$ emerges as the projection of Γ onto spatial surfaces at time t.

- **Paradox resolution** TGI naturally resolves longstanding quantum paradoxes. Wave-particle duality: Wave and particle are different projections of the same geometry. Quantum non-locality: Extended geometric connections explain EPR correlations without superluminal signaling. Delayed choice: No retrocausation required; boundary conditions at both endpoints constrain atemporal geometry. Measurement problem: Definite outcomes arise from definite geometric structures; no collapse needed.

- **Testable predictions** TGI makes quantitatively distinct predictions from standard QM. Emission-absorption correlations: Emitter recoil may correlate with absorber states established after emission. Transaction formation timing: Delayed-choice experiments reveal temporal structure of geometric constraint formation. Absorber density effects: Emission rates may depend on absorber availability in future light cone.

- **Theoretical connections** TGI naturally connects to quantum gravity via geometric emergence of spacetime; holographic principle and AdS/CFT correspondence;

ER=EPR conjecture (transaction geometries as quantum wormholes); and block universe and eternalist philosophy of time.

The framework connects naturally to the photon gravitational collapse result, which showed that photon propagation breaks down at the Planck scale. If photons cannot propagate below √2 times the Planck length, then what we observe as electromagnetic radiation must be emergent—precisely what TGI proposes. In the companion paper on Blitzon Cosmology, we extend these ideas to cosmological scales.

The photon as a "wormhole wake"—our dynamical view of an atemporal geometric connection—may seem radical. But quantum mechanics has repeatedly shown that nature operates in ways contrary to classical intuition. Perhaps the most radical idea is that the future and past are not separate, but interlinked components of a unified geometric structure.

The block universe may not be a philosophical abstraction but physical reality, and quantum mechanics may be our first glimpse of its geometric nature. Testing this hypothesis is not merely an academic exercise—it addresses the deepest questions about the nature of reality, time, and causation. The experiments proposed here are within reach of current technology. The question is no longer whether we can test interpretations of quantum mechanics, but whether we will.

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