Quantum is Composite

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The wave-particle duality of light and matter remains a cornerstone of quantum mechanics. The Standard Model of particle physics defines both the photon and the electron as strictly elementary, indivisible point particles. In this paper, we propose a composite model of quanta wherein these purported elementary particles are composed of multiple, underlying vibratory entities. We introduce a *topological wave-packet framework* and examine how this sub-structural hypothesis can naturally recover wave-particle duality by explaining the wave and the particle phenomena of light simultaneously without changing models, address theoretical singularities, and propose potential testable predictions. We also consider the physical reason and origin of the relativity of mass and energy, and the physical meaning of Planck's constant within this framework.

Key words: quantum particles; continuity; composite; topological envelope; reconciliation of wave-particle duality; relativity of mass and energy; physical meaning of Planck's constant

I. INTRODUCTION

While Newton's corpuscular theory posited light as discrete streams of particles, a model highly successful in explaining geometric (ray) optics, Young's double-slit experiment necessitated a wave-mechanical description to account for interference and diffraction phenomena. Moreover, the photoelectric effect, elucidated by Einstein, and the kinematics of Compton scattering inextricably required light to possess quantized, discrete properties–photons. Later, de Broglie extended this duality to matter, proposing that particles such as electrons exhibit wave-like behavior, characterized by the wavelength $\lambda = h/p$, where h is Planck's constant and p is momentum. It is therefore of fundamental interest to explore the true nature of light. Is it a wave, a particle, both or neither? Is it elementary or composite? We begin with recalling the double-slit experiment and its variants, and their explanation according to quantum mechanics and information theory (fringe-path distinguishability). We then propose a topological framework of wave-packets and, based on this framework, reconcile and eliminate wave-particle duality. Moreover, we explore the relativistic energy-momentum relation and the variation of mass with velocity in the light of our proposed framework. We also provide physical meaning of Planck's constant.

The phenomena of Young's double-slit experiment [1, 2] and the delayed choice quantum erasure (DCQE) experiment [3–7] are integral to the framework of quantum mechanics. The double-slit experiment prompted Feynman to remark that it contains the *only mystery* of the discipline [8]. When light is shown through a single narrow slit, a normal intensity pattern is observed on the screen, maximum in the centre and decreasing towards both ends. However, when light is shown through two adjacent narrow slits (many photons at once or a single photon one after another) [9–12], interference pattern is observed on the screen. When *which-way* information [13, 14] is sought by placing a detector beyond the slits, the interference pattern vanishes. The same is observed with electrons [15–18], neutrons [19, 20], atoms [21–23], and even macromolecules[24, 25]. And, in the delayed-choice quantum erasure experiment, whether the interference pattern is observed or not depends on which detector the *idler* photon passed through.

In standard quantum mechanics, a particle like a photon or an electron is not a tiny billiard ball; its state is described by a wavefunction ($|\psi\rangle$), the probability amplitude. The absolute square of this wavefunction, $|\,|\psi\rangle\,|^2$, gives the probability density of finding the particle at a specific location. Quantum mechanics explains the above phenomena in the following manner.

Single-Photon Double-Slit Interference. When a single photon is fired at a double slit, its wavefunction propagates through space as a wave. The wavefront reaches both slits simultaneously. Instead of choosing one path, the wavefunction splits and passes through both slits. On the far side, the two emerging components of the same wavefunction ($|\psi_1\rangle$ and $|\psi_2\rangle$) overlap and interfere with each other, creating regions of constructive and destructive probability amplitudes. When the photon hits the screen, the wavefunction *collapses*, and the photon registers as a single, localized dot. While a single photon cannot show a pattern by itself, its landing position is governed by the probability distribution:

$$\begin{aligned} P(x) &= |\,|\psi_1(x)\rangle + |\psi_2(x)\rangle\,|^2 \\ &= |\,|\psi_1\rangle\,|^2 + |\,|\psi_2\rangle\,|^2 + 2\mathrm{Re}(\psi_1^*\psi_2). \end{aligned} \tag{1}$$

The last term, $2\mathrm{Re}(\psi_1^*\psi_2)$, is the *interference term*. When we fire thousands of photons one after another, this

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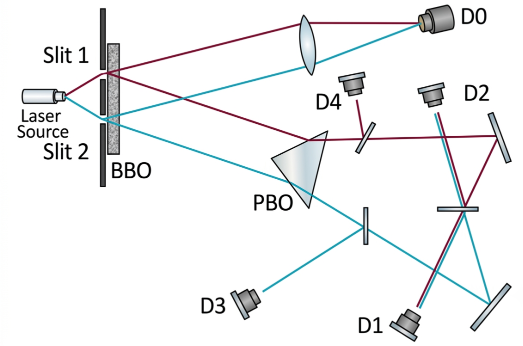

FIG. 1. Schematic diagram of the delayed-choice quantum erasure experiment. For details, see the text.

underlying probability distribution builds up into the classic fringe pattern. The photon, in essence, interferes with itself.

Loss of Interference with Which-Way Information. When we introduce a detector to determine which slit the photon went through, we force the system to interact with an environment. To gain the *which-way* information, the photon must physically interact with the detector. This interaction causes *quantum entanglement* [26] between the photon and the detector. The total state is no longer just the photon; it is a combined system:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\big(|\psi_1\rangle|D_1\rangle + |\psi_2\rangle|D_2\rangle\big). \tag{2}$$

Because the detector states $|D_1\rangle$ and $|D_2\rangle$ are orthogonal (perfectly distinguishable), the mathematical interference term drops to zero when calculating the probability distribution on the screen. As a result, the wavefunction loses its phase coherence–a process called *quantum decoherence* [27]. The pattern on the screen reverts to a simple, classical sum of two independent single-slit patterns ($P(x) = ||\psi_1\rangle|^2 + ||\psi_2\rangle|^2$).

Delayed-Choice Quantum Eraser. The delayed-choice experiment uses entangled pairs of photons (see Fig. 1): a *signal photon* (sent to the slits and then to a primary screen D_0) and an *idler photon* (sent through a maze of beam splitters to various detectors). The idler detectors are set up such that some detectors (D_1 and D_2) *erase* or scramble the path information, making it impossible to know which slit the signal photon took. Other detectors (D_3 and D_4) preserve the *which-way* information. The paradox here is that the choice of whether to erase or keep the path information can happen *after* the signal photon has already hit the primary screen. If we look at the total aggregate data of all signal photons on the screen, it always looks like a patternless blob. No interference is visible. However, if we use a technique called *coincidence counting*–meaning we only plot the signal photons whose corresponding idler photons hit detector D_1 or D_2 (erased path)–an interference pattern emerges. If we plot only those that hit D_3 or D_4 (known path), a scatter pattern emerges. Though a popular claim of the DCQE experiment is that *future changes the past!*, there is no retrocausal changing of the past [7]. The total pattern on the screen always lacks interference. The interference pattern is *hidden* within the joint correlations of the two entangled photons, and uncovered only by looking at the idler data.

II. INFORMATION-BASED FRAMEWORK

All three above phenomena can also be eplained in a unified way (see Table I) with the rule: *Interference and information are mutually exclusive*. This framework corresponds to the information-based wave-particle duality. Whether an interference pattern appears depends entirely on the availability of path information *anywhere else in the universe*, regardless of whether a human looks at it. This is rigorously quantified by the Englert-Greenberger-Yasin (EGY) relation [28, 29]:

$$\mathcal{V}^2 + \mathcal{P}^2 \leq 1, \tag{3}$$

where $\mathcal{V}$ is *visibility* (the contrast or sharpness of the interference pattern; wave-like behavior) and $\mathcal{P}$ is *predictability* (the degree of *which-way* path information available; particle-like behavior).

III. TOPOLOGICAL WAVE-PACKET FRAMEWORK

Today, quantum electrodynamics (QED) and the Standard Model treat the photon (a gauge boson) and the electron (a lepton) as zero-dimensional, structureless point particles. They are deemed mathematically *elementary*, incapable of being fractured into constituent parts. However, the assumption of zero-dimensionality introduces inherent mathematical singularities, often requiring complex renormalization techniques to yield physical predictions.

The assumption that photons and electrons are indivisible elementary entities is an extrapolation based on current empirical limits. Physicists are working on disclosong the structure and size of photons recently [30–32]. In this section, we abandon the point-particle assumption of quantum particles (photon, electron, neutron, etc.) and present a composite structure framework (a similar perspective is found in the Indian scriptures as well [33–35]) which explains not only the wave-phenomena (double-slit interference, the wavefunction collapse, and the delayed-choice quantum erasure experiment) but also the particle aspects of light (Einstein's photoelectric and Compton effects, pair production) in a unified way. This model shares conceptual resemblance with String Theory (which replaces point particles with one-dimensional vibrating strings) and *preon* models (which propose sub-components for

Scenario	Path Information ($\mathcal{P}$)	Visibility ($\mathcal{V}$)	Resulting Physical Phenomenon
Standard Double Slit	$\mathcal{P} = 0$ (Completely unknown)	$\mathcal{V} = 1$ (Maximum)	The system contains zero information about the path. The wave amplitudes must be summed, creating a *pure interference pattern*.
Active Detection	$\mathcal{P} = 1$ (Perfectly known)	$\mathcal{V} = 0$ (Zero)	The interaction with the detector transfers path information to the environment. The phase relation is destroyed, and the pattern *completely disappears*.
Delayed-Choice Eraser	$\mathcal{P}$ is variable depending on sub-sorting	$\mathcal{V}$ is variable depending on sub-sorting	Total $\mathcal{P} = 1$ globally, so the raw screen shows no interference. But by sorting data by idler detectors, we selectively isolate subsets where $\mathcal{P} = 0$ (restoring $\mathcal{V} = 1$) or $\mathcal{P} = 1$ (restoring $\mathcal{V} = 0$).

TABLE I. A unified explanation of the double-slit interference, the wavefunction collapse, and the delayed-choice quantum erasure experiment using the Englert-Greenberger-Yasin (EGY) relation. The universe enforces a strict accounting of information. If a particle propagates through a system without leaving a trace of its path on any other quantum state, it behaves as a delocalized wave and exhibits interference. The moment that path information is encoded into another system (a detector, an entangled twin photon, or even a stray air molecule), the wave-like coherence is localized, and it behaves as a classical particle.

quarks and leptons). Our framework does not align with Ref. [36] because a photon is composite. The key postulate of our framework is: *Quantum particles such as photons, electrons, etc. are not elementary, mathematical zero-dimensional points. They are structured, extended wave-packets whose constituent vibrating entities explore stationary (optimal) paths non-locally, but instantly collapse (condense or withdraw its components like a touch-me-not plant) to a single "point" during an external interaction with a potential barrier and conserve their topological information.* This postulate can be broken down into sub-postulates, for later convenience, as below.

(P1) *Heterogeneous Wave-Packet.* Quantum particles are composite, localized wave packets confined within a *topological envelope* [37]. They consist of distinct, fundamental vibrating entities with specialized functions: *binding entities* (which maintain internal cohesion), *momentum entities* (which drive translation and rotation), and *action entities* (which interact with external fields). The propagation speed of the overall envelope through 3D space differs from the internal vibrational frequencies of its constituent entities. An electron or a photon is an emergent phenomenon–a specific, stable configuration of these vibrating sub-entities bound together by fundamental forces that operate at scales far below the current electroweak limit.

(P2) *Multi-Path Exploration and Non-Local Continuity.* The path of an individual constituent entity depends on its properties (nature) and the properties [of the components] of the medium in which it propagates. Among the multiple paths available, it will opt the path of *stationary action*. Hence, when travelling from Point A to Point B, the packet's envelope expands. Crucially, these entities are not detached; they remain unbrokenly linked across space by a non-local, elastic topological field (the binding network).

(P3) *Resonant Feedback and Critical Collapse.* When a packet encounters an opposing potential field or boundary, it does not merely collide classically. It establishes an instantaneous, resonant *lock-and-key* feedback loop based on its internal vibrational frequency. If resonance is achieved, the entire non-locally extended envelope instantly collapses radially inward to the point of interaction. If resonance fails, the packet is reflected, deflected, or transmitted as a whole.

(P4) *Conservation of Topological Information.* The phase coherence and structural balance of the internal entities are strictly conserved. If any part of the extended binding network interacts with an external system (such as a detector), the path information becomes permanently encoded into that environment, fracturing the internal phase relations of the packet.

A. Eliminating Wave-Particle Duality

With the help of the above postulates, we can explain the wave and the particle phenomena of light simultaneously (see Appendix A–D and Fig. 2). In classical physics, while the wave-like phenomena (continuous, extended behavior) require a wave front to spread across space, the particle-like phenomena (localized, quantized behavior) require light to concentrate its energy instantly at a single point. In our framework, the wave-like phenomenon corresponds to the *expansion of the topological envelope* and the *multi-path exploration of its internal entities* (P1 & P2), and the particle-like phenomenon is explained by *resonant feedback and critical collapse* (P3)–the packet behaves like a particle only at the moment of interaction.

Our topological framework reconciles and eliminates the *wave-particle duality* through a shift in perspective. Wave and particle are descriptions of how internal components of light react to different environments:

(i) *Light is always a wave packet.* It never magically transitions from a smooth wave to a solid sphere. Its fundamental nature is static: an extended, composite topological envelope.

(ii) *Wave behavior is the journey.* When light travels through space or interacts with macro-objects (slits, lenses, polarizers), we observe the continuous, extended propagation of its envelope and the multi-path distribution of its internal entities.
(iii) *Particle behavior is the destination.* When light interacts with subatomic potential fields (atoms, electrons), it triggers a resonant feedback loop. The non-local, elastic nature of the binding entities forces the *entire extended packet* to instantly gather its energy and collapse to a point.

B. Theoretical Implications

Our proposed framework provides a visual, mechanical, and intuitive way to think about wave-particle duality. By replacing abstract wavefunctions with physical, heterogeneous *vibrating entities*, it successfully replicates: (i) Feynman paths (by distributing entities across available stationary trajectories), (ii) Decoherence (by mechanically disrupting the packet's constituent balance via external potentials), and (iii) Quantized collisions (by treating interactions as localized envelope impacts).

If this axiomatic system is true, several profound secondary conclusions follow naturally:

Remark 1. (Emergent Quantization from Boundary Constraints) Quantization is not an inherent, fundamental discretization of spacetime or fields. Instead, it is an *emergent eigenvalue problem* arising entirely from the lock-and-key resonance criteria (P3). Energy and momentum are transferred in discrete blocks because the topological envelope can only undergo binary transitions (full radial collapse or coherent scattering).

Remark 2. (Finite Lower Bound for Gravitational and Inertial Mass) Since mass in this framework corresponds to the energy required by the *binding entities* to hold the topological envelope together against the translational expansion of the *momentum entities*, mass must be fundamentally related to the tension of the non-local network. This implies a minimum stable envelope size, below which a particle would lose structural cohesion and dissipate, yielding a fundamental lower limit on rest mass.

Remark 3. (Relativistic Energy-Momentum Relation) Since mass is redefined as a structural balance between internal binding and momentum entities, this model can mathematically derive the relativistic energy-momentum relation $E^2 = (pc)^2 + (m_0c^2)^2$ (see Appendix E). In this framework, Einstein's energy-momentum relation is not an abstract consequence of four-dimensional spacetime geometry. Instead, it is a *mechanical load-bearing balance equation* for a localized topological envelope. The total energy squared is split purely between the work done by the *binding entities* to keep the particle from exploding outward (m_0c^2), and the work done by the *momentum entities* to drive it forward through the medium (pc).

Remark 4. (Variation of Mass with Velocity) If we look at the mechanical stresses experienced by the internal entities, this structural wave-packet model can also account for relativistic changes in mass (see Appendix F & G). By tracking how the total internal field frequency Ω shifts during translation, we can derive standard Lorentzian mass increase and explore the unconventional *mass decrease* behavior proposed by Kumar [38].

Remark 5. (Non-Signaling Quantum Entanglement without Hidden Variables) Two entangled particles are simply two distinct resonance centers sharing a single, continuous, non-local elastic binding network $K(\mathbf{x}, \mathbf{y})$ across space. When either particle undergoes a resonant lock-and-key collapse (P3), the entire shared network instantly experiences the radial constraint. This explains why updates appear instantaneous without requiring superluminal signals across an empty vacuum; the *medium* connecting them is the extended particle itself.

Remark 6. (Intrinsic Thermodynamic Arrow of Time via Phase Fracture) Postulate (P4) introduces an explicit mechanism for irreversibility. When an extended binding network interacts with an open environment, the encoding of path information *fractures* the internal phase relations. Because recovering this phase information requires gathering the state of the entire global environment, the system exhibits an intrinsic structural entropy increase, providing a physical origin for the arrow of time at the single-particle level.

Remark 7. (Physical Meaning of Planck's Constant) Under the topological envelope framework, Plancks constant (h) is redefined from a simple scalar of proportionality into the fundamental invariant of structural coherence (see Appendix H). It quantifies the dynamic equilibrium of the heterogeneous entities, serves as the elastic modulus for non-local spatial dilation, acts as the critical threshold for resonant collapse, and represents the minimum indivisible unit of conserved topological information during environmental interaction.

C. Testable Theoretical Predictions

If photons and electrons are composite structures, there must be a spatial scale at which this sub-structure becomes manifest. Converting this hypothesis from mathematical speculation to empirical science requires pursuing several theoretical predictions:
(i) Form Factors at Ultra-High Energies: Just as the Rutherford and deeply inelastic scattering experiments revealed the sub-structure of the atom and the proton respectively, collisions at energies near the Planck scale ($\sim 10^{19}$ GeV) should reveal a non-zero physical radius for the electron. This would manifest as deviations in expected scattering cross-sections.
(ii) Excited States and Resonances: If the electron is

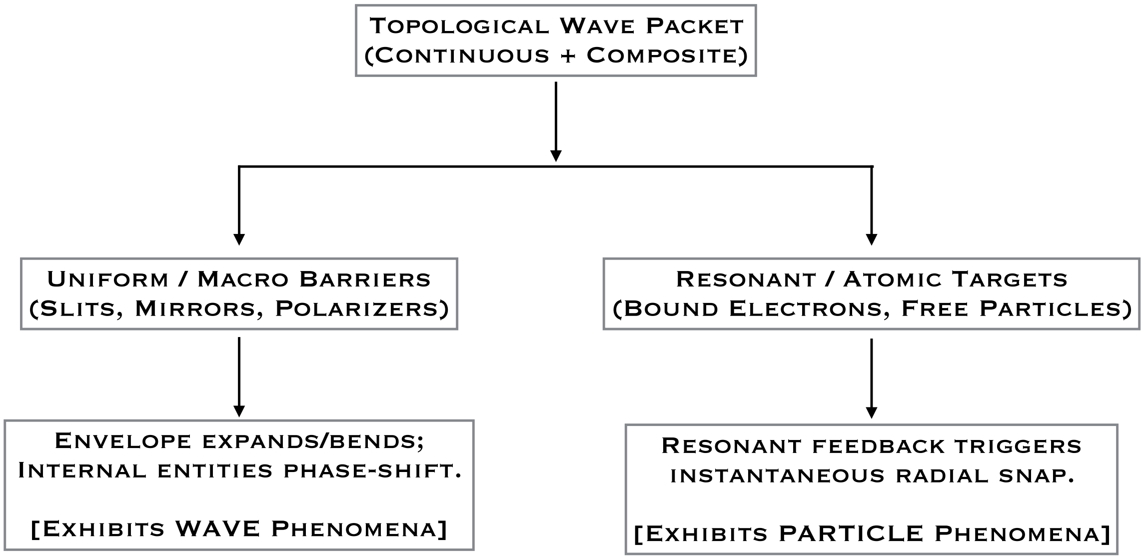

FIG. 2. Reconciliation of wave and particle duality of light. By defining the photon as an extended object with a non-local internal binding network and a resonant collapse mechanism, the wave-particle paradox disappears. Light doesn't have two conflicting natures; it has one singular, sophisticated structure that naturally satisfies the conditions of both wave and particle experiments.

composed of vibrating entities, introducing sufficient energy to the system should excite these oscillators into higher harmonic states. This would result in the creation of heavier, highly unstable *cousins* of the electron. (While the muon and tau particles already exist as heavier generations of leptons, a true composite model might predict a much denser continuum of resonance states).
(iii) Spontaneous Decay: Truly elementary particles do not decay. If the electron is composite, it may have a finite, albeit extraordinarily long, half-life, eventually decaying into its sub-components or lighter particles.

IV. CONCLUSION

The classification of photons and electrons as indivisible point particles has served as a highly robust and predictive framework for over a century. However, viewing these entities as composite systems of interacting, vibrating sub-components offers a compelling paradigm shift. By assigning a physical ontology to the wave-like and particle-like behaviors observed in nature, this sub-structural vibratory hypothesis contextualizes quantum duality not as a paradoxical abstraction, but as the emergent dynamics of an underlying, structured reality yet to be experimentally resolved. Exploring this sub-structural frontier may ultimately provide the crucial link needed to move beyond the Standard Model and resolve the persistent problems of modern physics. Our topological wave-packet framework requires just one central postulate (equivalently, four sub-postulates) that explains all wave and particle phenomena to date, and eliminates wave-particle duality. Occam's razor strongly favours our framework.

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[33] "The most fundamental, indivisible particle is termed *Paramanu* [this is not Dalton's atom], and a combination of sixty paramanus constitutes an *Anu* [molecule]. A combination of two anus forms a *Dvyanuka* [binary molecular compound], which corresponds to *Vayu* [this is not tangible air]; three dvyanukas constitute *Agni* [this is not tangible fire]; four dvyanukas constitute *Jala* [this is not tangible water]; five dvyanukas constitute *Prithvi* [this is not tangible earth]. Alternatively, three dvyanukas form a *Trasarenu* [a tertiary molecular cluster], and its duplication gives rise to observable macroscopic matter, such as earth." [Dayanand Saraswati, *Satyartha Prakasha*, Ch. 8]
[34] "Each photon comprises approximately 360 types of *parmanus* (subtle vibrating entities, specifically, Prana and Chhanda)–which possess infinitesimal mass and exhibit gravitational force." [Agnivrata Naishthika, *Vaidic Rashmi Vigyanam*, Ch. 6, Pg. 240]
[35] "Negatively charged subatomic particles are predominated by *Soma (Marut)* entities, whereas positively charged particles are predominated by *Agni (Prana)* entities...It is noteworthy that particle formation or synthesis is impossible without the coupling (binary interaction) of Prana and Marut vibrating entities. Both categories of these charged particles fall under the classification of the primordial fire element (Agni Mahabhuta)...The constituent count of paramanus (i.e., Prana or Chhanda entities) within these charged particles is marginally higher than that in photons (which contain approximately 360 types) but remains lower than that in a Jala molecule (which contains approximately 480 types)." [Agnivrata Naishthika, *Vaidic Rashmi Vigyanam*, Ch. 6, Pg. 241]
[36] I. C. O. Rukan, J. Gulla, and J. Skaar, *Truncated photon*, Phys. Rev. Lett. , (2026).
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Appendix

Based on the postulates of our topological wave-packet framework in Sec. III, we explain wave and particle phenomena of light, and relativity of mass and energy below. To formalize and describe the physics implied by postulates (P1) through (P4), we construct a mathematical framework. Let a quantum particle be defined by a localized topological envelope $\mathcal{E}(t) \subset \mathbb{R}^3$ with a well-defined boundary $\partial\mathcal{E}(t)$. We map the internal state of the packet to a composite multi-component field vector:

$$\mathbf{\Psi}(\mathbf{x},t) = \begin{pmatrix} \psi_b(\mathbf{x},t) \\ \psi_m(\mathbf{x},t) \\ \psi_a(\mathbf{x},t) \end{pmatrix} \begin{matrix} \text{(Binding Entity)} \\ \text{(Momentum Entity)} \\ \text{(Action Entity)} \end{matrix} \tag{4}$$

Each entity has characteristic internal vibrational frequencies $\omega_b, \omega_m, \omega_a$, while the center-of-mass velocity of the envelope is $\mathbf{v}_e = \dot{\mathbf{x}}_c$. By virtue of (P1), $\mathbf{v}_e \neq \omega_i$.

A. Reflection and Refraction

In the old view, light waves bounce off a mirror or bend in water due to wave-front altering speeds; or classical photons choose paths of least time. In our framework, when the expanded envelope of the packet encounters the dense potential boundary of a new medium (like glass or a mirror), its internal *action entities* interact with the boundary's field (P3). Because the boundary is uniform, no single point achieves unique resonance to trigger a critical collapse. Instead, the boundary's potential field shifts the phase and direction of the *momentum entities*. The packet remains intact and is either glanced/deflected (reflection) or transmitted with a altered internal velocity (refraction), strictly preserving the continuity of the binding network.

Let the medium be characterized by a localized structural parameter field $\mu(\mathbf{x})$. The total action S of the constituent entities propagating inside the expanding envelope from space-time point A to B is given by:

$$S = \int_A^B \mathcal{L}_{int}\left(\mathbf{\Psi}, \partial_\mu \mathbf{\Psi}, \mu(\mathbf{x})\right) d^4x + \iint_{\mathcal{E}} K(\mathbf{x},\mathbf{y}) \psi_b(\mathbf{x}) \psi_b^*(\mathbf{y})\, d^3x\, d^3y, \tag{5}$$

where $K(\mathbf{x},\mathbf{y})$ represents the non-local kernel of the *elastic binding network* (P2).

Refraction: When crossing a boundary where $\mu(\mathbf{x})$ shifts discontinuously, the system minimizes action ($\delta S = 0$). To preserve the elastic cohesion of the internal binding network, the internal momentum frequency ω_m alters its coupling with spatial translation. This yields a modified variational principle across the interface boundary:

$$\begin{aligned} &\delta \textstyle\int (\mathbf{k}_m \cdot d\mathbf{x} - \omega_m dt) = 0 \\ &\implies n_1 \sin\theta_1 = n_2 \sin\theta_2, \end{aligned} \tag{6}$$

where the refractive index $n \propto \frac{\omega_m(\mu)}{\mathbf{v}_e}$. The bending is a structural adaptation of the envelope to prevent phase-shearing between the components.

Reflection: If the boundary potential $V(\mathbf{x})$ fails to satisfy the lock-and-key resonance integral:

$$\mathcal{R} = \left| \int_{\partial\mathcal{E}} \psi_a(\mathbf{x},t) \cdot V(\mathbf{x})\, d^3x \right| < \mathcal{R}_{crit}, \tag{7}$$

the interaction fails (P3). The envelope behaves as an unbroken topological barrier, reversing the momentum vector of ψ_m to conserve total structural energy and balance (P4), leading to specular reflection.

B. Diffraction and Interference

In the old view, a wave bends around obstacles and passes through both slits to interfere with itself. In our framework, when the packet encounters a barrier with narrow openings (slits), the envelope is physically constrained. The internal constituent entities explore available paths simultaneously (P2), passing through open spaces while remaining elastically linked by the non-local binding network. Behind the barrier, the differing internal speeds of these entities create a spatial grid of constructive and destructive phase relationships. The wave pattern is actually just the geometric layout of this non-local binding network as it propagates.

Single-Photon Double-Slit Interference: When a single photon packet is emitted, its envelope expands across both slits. Following (P2), its constituent vibrating entities travel through Slit A and Slit B simultaneously, maintaining their elastic, non-local connection. On the far side of the slits, the components emerging from Slit 1 and Slit 2 overlap. Because the internal vibrating entities travel at different speeds than the envelope (P1), they arrive at the screen with spatial phase differences. This creates a geometric grid of constructive and destructive resonance fields. When the leading edge of the packet establishes a structural resonance with an atom on the screen (P3), the entire spread-out network instantly collapses to that single point, registering a localized hit. Over time, these hits map out the underlying resonant grid, forming interference fringes.

As the packet moves forward, (P2) states the envelope volume expands: $\frac{d}{dt}\text{Vol}(\mathcal{E}) > 0$. When it encounters a double slit, the non-local elastic binding network $K(\mathbf{x},\mathbf{y})$ ensures that the physical packet does not split into independent parts [39]; rather, the singular envelope *fluidly* deforms and simultaneously passes through both slits S_1 and S_2. The phase evolution of the momentum entity ψ_m along any path within the extended envelope is coherent. The structural profile at the screen is dictated by the global spatial minimization of action for the unified network:

$$\Psi_{total}(\mathbf{x}_{screen}) = \psi_m(\mathbf{x}_{S1}) e^{iS[\gamma_1]} + \psi_m(\mathbf{x}_{S2}) e^{iS[\gamma_2]}. \tag{8}$$

Detection and Vanishing of Interference: A detector is placed at one of the slits to determine which path the photon takes. This detector projects an active potential field. As the extended constituent entities pass through the slits, the portion traveling through the monitored slit interacts with the detector's field. According to (P4), this interaction encodes the path information into the detector, which mechanically disrupts and drains the delicate phase balance of the *binding entities*. The elastic connection between the entities in Slit A and Slit B is fractured. *Because they are no longer phase-coherent, they cannot form a unified resonant grid behind the slits.* The packet behaves as a localized stream, yielding a classical, non-interfering scatter pattern on the screen.

Delayed-Choice Quantum Eraser: A source generates an entangled pair of packets: a *signal packet* (sent to the slits and a screen) and an *idler packet* (sent to a distant maze of beam splitters and detectors). Because the two packets are entangled, their individual non-local binding networks (P2) are elastically tied to one another as a singular, macro-extended system. When the signal packet hits the screen, it forms a patternless blob because the total system's path information is still available via the traveling idler packet. The choice is made when the idler packet finally hits a detector: If it hits a *path-revealing* detector, the non-local network collapses in a way that confirms a distinct trajectory, matching the signal photons that formed the scatter pattern. If it hits an *erasing* detector (where paths scramble), a phase shift is instantaneously transmitted through the continuous binding network (P2) back to the recorded impact point of the signal photon. By sorting the screen data based on which idler detector clicked (coincidence counting), we isolate the subsets of packets whose networks remained perfectly phase-coherent, revealing the hidden interference pattern.

If a detector interacts with the binding network at slit S_1, an environmental coupling term $\mathcal{L}_{env}(\mathbf{\Psi}, \phi_{det})$ is introduced. Per (P4), the path information becomes macroscopically encoded:

$$\mathbf{\Psi} \otimes |0\rangle_{env} \longrightarrow \begin{pmatrix} \psi_{b,1} \\ \psi_{m,1} \\ \psi_{a,1} \end{pmatrix} \otimes |1\rangle_{env} + \begin{pmatrix} \psi_{b,2} \\ \psi_{m,2} \\ \psi_{a,2} \end{pmatrix} \otimes |0\rangle_{env}. \tag{9}$$

This encoding acts as a phase-fracturing operator $\hat{\mathcal{F}}$. It introduces a stochastic phase shift $\Delta\phi \in [0, 2\pi]$ between the components, wiping out the stationary action coherence ($\langle e^{i\Delta\phi} \rangle = 0$).

If a downstream configuration *erases* this environmental record before a resonance collapse (P3) occurs on the screen, the phase relations along the elastic network are restored, recovering the fringe pattern.

C. Polarization

Light consists of transverse electromagnetic waves vibrating in specific directional planes. The vibrating entities within the packet (P1) possess specific spatial orientations or directional axes of vibration relative to the envelope's direction of travel. When the packet encounters a polarizing filter (a crystal lattice with a directional potential field), entities vibrating perpendicular to the filter's alignment are absorbed or blocked (P3). Only the constituent entities vibrating parallel to the filter's field pass through. The emerging packet is *pruned*–its internal entities now vibrate in a single, unified geometric plane.

Polarization is modeled as the spatial orientation vector $\hat{\mathbf{n}}$ of the internal vibrational axes of the action entities ψ_a. When encountering a polarizing grid oriented along $\hat{\mathbf{p}}$, the lock-and-key mechanism (P3) evaluates an orientation-dependent resonance condition:

$$\mathcal{R}(\theta) = \mathcal{R}_0 \, |\hat{\mathbf{n}} \cdot \hat{\mathbf{p}}| = \mathcal{R}_0 \cos\theta. \tag{10}$$

If $\mathcal{R}(\theta) \geq \mathcal{R}_{crit}$, the packet passes through, and its internal orientation vector dynamically updates to align perfectly with $\hat{\mathbf{p}}$ to maintain internal structural balance (P4). The probability of a successful *key* engagement scales quadratically ($\cos^2\theta$) due to the projection of the action entity's internal vibrational energy field.

D. Photoelectric & Compton Effects and Pair Production

Photoelectric Effect. Light packets (photons) strike a metal plate to liberate bound electrons, which are trapped by the metal's internal potential barrier. Increasing the intensity of light merely increases the *quantity* of individual wave packets sent per second. However, according to (P3), electron ejection relies entirely on the *lock-and-key* resonant feedback loop. The internal vibrational frequency of the photon's *action entities* (P1) must match or exceed the resonant frequency of the bound electron. If the frequency is below the threshold, the packet cannot establish resonance and simply glances off or converts to heat–no matter how many packets we send. If the frequency is high enough, a single packet instantly achieves resonance, collapses its entire envelope energy into the electron (P3), and ejects it with (almost) zero time delay.

When an incoming radiation packet impinges on a bound atomic system, the lock-and-key mechanism depends on an exact frequency-matching feedback loop:

$$\mathcal{R}(\omega_a) = \int \psi_a(\mathbf{x}) \cdot \psi^*_{bound}(\mathbf{x}) \, d^3x \propto \delta(\omega_a - \omega_{atomic}). \tag{11}$$

If $\hbar\omega_a \geq \Phi$ (where Φ is the structural binding energy threshold of the target system), a resonant lock is instantly established.

By (P3), the entire non-locally extended envelope $\mathcal{E}$ instantly undergoes a *radial collapse* to the coordinate point of interaction $\mathbf{x}_0$:

$$\mathcal{E}(t) \xrightarrow{\text{Resonance}} \delta(\mathbf{x} - \mathbf{x}_0). \tag{12}$$

The action entities release their entire quantized packet energy into the binding network of the electron, liberating it. Because it is a discrete resonance-driven topological transition, no partial energy transfers can occur.

Compton Effect. A high-energy X-ray photon packet undergoes a high-velocity collision with a stationary, weakly bound electron. This event is a direct application of postulates (P1) and (P3). The incoming photon packet strikes the electron's potential field. During the impact, a portion of the photon's internal *momentum entities* is transferred to the electron, causing it to recoil. Because the photon packet has parted with some of its constituent momentum entities and kinetic energy, the internal vibrational rate of its remaining entities slows down. According to (P1), a slower internal vibrational frequency directly translates to a longer spatial wavelength (λ'). The angle of deflection dictates how much of the packet's internal structure was stripped away during the collision, perfectly accounting for the angular dependence of the wavelength shift.

If the incoming packet hits a free or weakly-bound electron, a perfect lock-and-key resonance for full absorption cannot be satisfied. Instead, a *partial resonant scattering* loop occurs. The momentum entities ψ_m transfer a fraction of their translational strain to the target electron. To conserve the overall structural balance (P4), the packet sheds energy, causing its internal vibrational frequency to drop ($\omega_a \to \omega_a'$). This manifests as a shift in wavelength governed by the spatial conservation of internal entity momentum:

$$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta). \tag{13}$$

Pair Production. Pair production represents a dramatic *topological rupture* of a highly energetic action packet ($\hbar\omega_a \geq 2m_e c^2$) interacting with the extreme gradient of a nuclear potential field ∇V_{nuc}. The external potential strains the internal binding network beyond its elastic limit. The structural balance (P4) forces a topological phase bifurcation. The single envelope $\mathcal{E}_{photon}$ fractures along its internal vibrational nodes:

$$\mathcal{E}_{photon} \longrightarrow \mathcal{E}_{electron} \cup \mathcal{E}_{positron}. \tag{14}$$

The fundamental entities split and reorganize into two distinct, stable, self-contained topological envelopes, trapping a portion of the spatial field energy into permanent localized internal binding rotations (rest mass).

E. Relativistic Energy-Momentum Relation

To derive the relativistic energy-momentum relation from this framework, we must look at how the binding entities and momentum entities co-exist within the topological envelope $\mathcal{E}$. By analyzing below the structural mechanics implied by our postulates, we can map the derivation through the interplay of localized internal cohesion (rest mass) and external spatial translation (momentum).

Orthogonality of Internal Entities. Postulate (P1) asserts that the packet consists of distinct entities with specialized functions. Let us look at the two primary drivers of the packet's state: (i) The Binding Entity (ψ_b): This entity maintains internal cohesion. It oscillates at an intrinsic, isotropic frequency ω_b to keep the topological envelope from dissolving. Because it is purely responsible for keeping the particle together, its oscillation exists even when the packet is at absolute rest ($v_e = 0$). (ii) The Momentum Entity (ψ_m): This entity drives translation through 3D space. It establishes a directional spatial wavevector $\mathbf{k}_m$ along the axis of propagation, dictating how the packet shears through the external medium.

Because the binding entity operates *internally* to maintain a 3D localized envelope and the momentum entity operates *externally* to drive directional translation, these two vibrational modes are structurally orthogonal within the binding network.

Structural Balance Invariant. Postulate (P4) states that the structural balance of the internal entities is strictly conserved. For the extended topological field to remain stable during translation, the total rate of internal action variation–which we will call the total packet frequency Ω–must dynamically reconcile these two orthogonal stresses (the internal cohesive cycling and the external translational cycling).

Mathematically, because these modes are orthogonal, their frequencies combine in quadrature to determine the total field stress of the moving packet:

$$\Omega^2 = \omega_b^2 + \omega_{trans}^2, \tag{15}$$

where ω_{trans} is the frequency component contributed by the translation drive. In a vacuum medium where the characteristic propagation speed of field perturbations is c, the translational frequency is directly proportional to the spatial wavevector: $\omega_{trans} = c|\mathbf{k}_m|$. Substituting this into our structural balance equation yields the fundamental frequency invariant of the envelope:

$$\Omega^2 = \omega_b^2 + c^2|\mathbf{k}_m|^2. \tag{16}$$

Deriving Envelope Velocity via Stationary Action. According to Postulate (P2), the individual entities opt for the path of stationary action ($\delta S = 0$). For a composite wave packet traveling from Point A to Point B, the center-of-mass of the envelope ($\mathbf{v}_e$) must track the region of constructive phase coherence across the elastic binding network. This means the overall envelope velocity matches the group velocity of the combined field:

$$\mathbf{v}_e = \nabla_{\mathbf{k}_m}\Omega. \tag{17}$$

Taking the gradient of our invariant equation $\Omega = \sqrt{\omega_b^2 + c^2|\mathbf{k}_m|^2}$ with respect to $\mathbf{k}_m$, we get

$$\mathbf{v}_e = \frac{1}{2\sqrt{\omega_b^2 + c^2|\mathbf{k}_m|^2}} \cdot (2c^2\mathbf{k}_m) = \frac{c^2\mathbf{k}_m}{\Omega}. \tag{18}$$

Rearranging this gives a direct relationship between the envelope's physical speed and its internal constituent frequencies:

$$\Omega\mathbf{v}_e = c^2\mathbf{k}_m. \tag{19}$$

This formula reveals the exact mechanism behind (P1): the overall envelope speed $\mathbf{v}_e$ is fundamentally modulated by the ratio of the spatial translation vector to the total internal vibrational frequency.

Action Entity Scaling and Final Synthesis. To convert these structural field frequencies into mechanical properties (Energy and Momentum), the *action entities* (ψ_a) act as the operational bridge (P1). They scale the internal frequencies by the fundamental constant of action, $\hbar$–
(i) Total Energy (E): The total action scaled frequency of the packet, $E = \hbar\Omega$. (ii) Momentum ($\mathbf{p}$): The action scaled spatial translation vector driven by the momentum entities, $\mathbf{p} = \hbar\mathbf{k}_m$. (iii) Rest Mass ($m_0$): When the envelope is stationary ($\mathbf{v}_e = 0$), the momentum wavevector $\mathbf{k}_m = 0$. The total remaining frequency is purely the cohesive cycling of the binding entity ($\Omega = \omega_b$). Therefore, *rest mass* is simply the structural energy of the binding network at rest divided by c^2: $m_0c^2 = \hbar\omega_b$.

Now, we multiply our structural balance invariant ($\Omega^2 = \omega_b^2 + c^2|\mathbf{k}_m|^2$) by $\hbar^2$:

$$(\hbar\Omega)^2 = (\hbar\omega_b)^2 + c^2(\hbar|\mathbf{k}_m|)^2. \tag{20}$$

Substituting our physical definitions (E, m_0, and $\mathbf{p}$) directly into the scaled invariant yields:

$$E^2 = (m_0c^2)^2 + c^2|\mathbf{p}|^2, \tag{21}$$

which elegantly rearranges to the classic relativistic energy-momentum relation:

$$E^2 = (pc)^2 + (m_0c^2)^2. \tag{22}$$

F. Relativistic Mass Increase as Structural Loading

In the previous section (Appendix E), we established the structural frequency invariant based on the orthogonality of the internal modes (P1 & P4):

$$\Omega^2 = \omega_b^2 + c^2|\mathbf{k}_m|^2.$$

According to postulate (P2), the envelope's center-of-mass moves at the group velocity v_e of the unified binding network. Differentiating Ω with respect to the spatial wavevector k_m yields:

$$v_e = \frac{\partial\Omega}{\partial k_m} = \frac{c^2k_m}{\Omega} \implies k_m = \frac{\Omega v_e}{c^2}. \tag{23}$$

Substituting this expression for k_m back into the structural balance invariant allows us to isolate the total internal frequency Ω as a function of the envelope's velocity through space:

$$\Omega^2 = \omega_b^2 + c^2\left(\frac{\Omega v_e}{c^2}\right)^2 = \omega_b^2 + \Omega^2\frac{v_e^2}{c^2}. \tag{24}$$

Gathering the Ω^2 terms to one side gives:

$$\Omega^2\left(1 - \frac{v_e^2}{c^2}\right) = \omega_b^2 \implies \Omega = \frac{\omega_b}{\sqrt{1 - \frac{v_e^2}{c^2}}}. \tag{25}$$

By applying the action scaling factor from the action entities (P1) ($E = \hbar\Omega$ and $m_0c^2 = \hbar\omega_b$), the effective operational mass ($m_{eff} = E/c^2$) transforms as:

$$m_{eff} = \frac{m_0}{\sqrt{1 - \frac{v_e^2}{c^2}}}. \tag{26}$$

Physical Interpretation. As the envelope velocity $v_e \to c$, the effective mass approaches infinity. Within this framework, this is not caused by a literal accumulation of *stuff*. Rather, as the momentum entities drive rapid spatial translation, they exert an extreme directional phase shear across the extended envelope. To prevent the elastic binding network from fracturing (P4), the total system frequency Ω must escalate. Relativistic mass increase is simply the *vibrational load-bearing response* required to maintain topological cohesion at high speeds.

G. Can Mass Decrease with Velocity?

In a recent paper [38], Kumar demonstrated that within generalized space-time coordinate transformations, velocity-dependent mass is not restricted to strictly increasing; depending on how reference frameworks are structurally equivalent, mass can decrease with velocity as well. We can naturally model this phenomenon by looking closer at postulate (P2): The path of an individual constituent entity depends on its properties (nature) and the properties of the components of the medium in which it propagates.

Modeling the Medium-Induced Mass Decrease. If the baseline cohesive frequency of the binding entity (ω_b) is treated as an absolute, isolated constant, we will always get a strict Lorentzian mass increase. However, if the packet propagates through a specialized medium

$\mu(\mathbf{x})$ or a background field that actively couples with the binding network, the baseline cohesion frequency becomes a function of the packet's translational momentum state, $\omega_b(k_m)$.

Let us generalize the internal binding frequency response to alter with the spatial momentum wavevector:

$$\omega_b(k_m) = \omega_0 \left(1 + \frac{c^2 k_m^2}{\omega_0^2}\right)^{\beta}, \tag{27}$$

where ω_0 is the primal rest frequency in an uncoupled vacuum, and β is a structural coupling parameter dictated by the medium. Substituting this modulated binding frequency into our invariant equation yields:

$$\Omega^2 = \omega_0^2 \left(1 + \frac{c^2 k_m^2}{\omega_0^2}\right)^{2\beta} + c^2 |k_m|^2. \tag{28}$$

By solving for the group velocity $v_e = \frac{\partial \Omega}{\partial k_m}$ and transforming the total operational frequency into terms of velocity, the effective mass scales according to a generalized framework:

$$\Omega \approx \frac{\omega_0}{\left(1 - \frac{v_e^2}{c^2}\right)^{\frac{1}{2} - \beta}}. \tag{29}$$

We consider some specific values of β for illustration– (i) $\beta = 0$ (Standard Vacuum): The medium exerts no screening. We recover standard relativity: $\Omega \propto (1 - v_e^2/c^2)^{-1/2}$, meaning mass strictly *increases* with velocity. (ii) $\beta = 0.5$ (Invariant Mass Field): The medium perfectly compensates for translational stress. $\Omega = \omega_0$, meaning the operational mass remains completely *invariant* regardless of velocity. (iii) $\beta > 0.5$ (Mass-Decrease Regime): If the medium strongly screens or assists the binding network as momentum rises, the exponent becomes negative. For instance, if $\beta = 1$:

$$\Omega = \omega_0 \sqrt{1 - \frac{v_e^2}{c^2}} \implies m_{eff} = m_0 \sqrt{1 - \frac{v_e^2}{c^2}}. \tag{30}$$

In this regime, as velocity $v_e \to c$, the total internal frequency Ω and effective mass *decrease*, approaching zero.

Structural Mechanism of Mass Decrease. When a heterogeneous wave packet moves through a medium satisfying $\beta > 0.5$, the external environment actively stabilizes the system's topological envelope. As the wave-packet speeds up, the momentum entities draw structural support from the surrounding medium, allowing the internal binding entities to attenuate their vibrational frequency. Because the envelope requires less internal energy to maintain structural balance (P4) at high velocities, the packet dissipates its effective inertia into the surrounding field. Consequently, the system exhibits a monotonic decrease in effective mass as velocity increases, providing a mechanical validation for the coordinate-free transformations derived in Ref. [38].

H. Physical Meaning of Planck's Constant

In standard quantum mechanics, Planck's Constant (h) is simply the constant of proportionality relating a photon's energy to its frequency ($E = h\nu$). We redefine the quantum particle as a spatially extended, topologically bound, heterogeneous network. Within our proposed topological framework, h is not a mere scalar multiplier but becomes a *structural, geometric, and informational invariant* of the wave-packet itself. Planck's constant functions differently under each postulate.

(i) *Minimal Invariant Volume of Action.* In postulate (P1), h is the minimum invariant volume of the topological envelope in phase space. No matter how the internal vibrational frequencies differ from the envelope's translational speed, the total internal action of the combined triad (binding cohesion plus kinetic translation plus external interaction potential) must always sum to exactly h (or a multiple thereof). h is the constant that dictates equilibrium (the absolute balance) between inertial cohesion, kinetic momentum, and interactive action within a stable particle.

(ii) *Limit of Non-Local Stretch.* As the envelope expands and explores multiple trajectories simultaneously, the entities remain connected via a non-local, elastic topological field. Here, h acts as the intrinsic *elasticity modulus* of the binding network. It defines exactly how far the internal entities can spatially dilate across a multiparty spatial distribution before the tension breaks. It ensures that the total action required to stretch the network across multiple paths is strictly conserved. It is the quantifiable tension of the non-local continuous field, preventing the wave-packet from dissipating into the vacuum.

(iii) *Trigger for Critical Collapse.* When the packet meets an opposing potential, it initiates a *lock-and-key* resonant feedback loop. In postulate (P3), h is the absolute *threshold value of action* required to trigger the radial collapse of the topological envelope. The interaction cannot happen gradually; the external field must exchange exactly one quantum of action (h) with the packet's action entities to establish resonance. If the feedback loop achieves an energy-frequency match where $\Delta E/\nu = h$, the network instantly collapses. If the interaction falls short of h, the packet is elastically reflected, maintaining its envelope intact.

(iv) *Minimum Bit of Quantum Entropy.* If the internal phase relations of the entities are permanently fractured by an external detector, the wave-packet loses its structural balance. Before measurement, the topological envelope exists in a state of perfect phase coherence (where the von Neumann entropy of the isolated pure state is zero). Upon interaction, h represents the fundamental unit of topological information that is permanently encoded into the environment. The network cannot fracture arbitrarily. It fractures in integer steps dictated by h. Thus, h becomes the fundamental discrete quantum of structural phase information.