

Could Quanta Be Composite? A Heuristic Bounded-Envelope Ontology

Asutosh Kumar,^{1,2,3,*} Vishal Arya,^{3,†} and Sandeep Kumar Singh^{4,‡}

¹Department of Physics, KSS College, Lakhisarai 811311, India

²P. G. Department of Physics, Munger University, Munger 811201, India

³Vaidic and Modern Physics Research Centre, Bhagal Bhim, Bhinmal, Jalore 343029, India

⁴Jindal Global Business School, O. P. Jindal Global University, Sonapat 131001, India

The wave-particle duality of light and matter remains a cornerstone of quantum mechanics, in which the photon and the electron are treated as structureless, point-like elementary particles. In this paper we heuristically explore a composite, ontological picture of quanta in which these particles are modelled as spatially extended wave-packets built from distinct internal vibratory modes – labelled binding, momentum, and action modes – confined within a bounded-envelope. Within the picture, wave-like propagation (envelope expansion and multi-path exploration) and particle-like localization (a resonant lock-and-key collapse upon interaction) appear as two limiting behaviours of a single extended object; on this basis we re-examine the double-slit experiment, the which-path loss of interference, and the delayed-choice quantum eraser. We further give consistency illustrations connecting the framework to the relativistic energy-momentum relation and to Planck's constant, and we discuss candidate empirical signatures of this sub-structure hypothesis.

Keywords: composite quanta; wave-particle duality; double-solution; pilot-wave; objective collapse; bounded-envelope; 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 quanta. Is light a wave, a particle, both or neither? Is a quantum elementary or composite? The research gap we address is the following. The de Broglie double-solution programme and its modern descendants supply mathematically closed dynamics for an extended object that propagates as a wave and localizes on interaction, but they do so at the level of a soliton or a singular field configuration whose internal organization is left unarticulated. The objective-collapse, correspondingly, supplies a quantitative localization dynamics but no account of what, in the object itself, distinguishes an interaction that triggers localization from one that does not. This paper provides an explicit internal decomposition of the extended object heuristically, tied to a stated criterion for when localization occurs.

We begin by recalling the double-slit experiment and its variants and their explanation according to quantum mechanics. We then propose the bounded-envelope framework of wave-packets and, on that basis, re-describe wave-particle duality within a single ontology. We also examine the relativistic energy-momentum relation and the variation of mass with velocity in the light of the proposed framework, and we discuss the 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 shone 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 shone 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 quantum mechanics a particle like a photon or an electron is described by a wavefunction $\psi(x)$, the probability amplitude, whose modulus squared $|\psi(x)|^2$ gives the probability density of finding the particle at a specific location. Throughout we follow the convention of writing $\psi(x)$ for position-space amplitudes and reserving $|\cdot\rangle$ for abstract state vectors. Standard quantum me-

* asutoshk.phys@gmail.com

† vishalarya66@gmail.com

‡ sandeepk.singh@jgu.edu.in

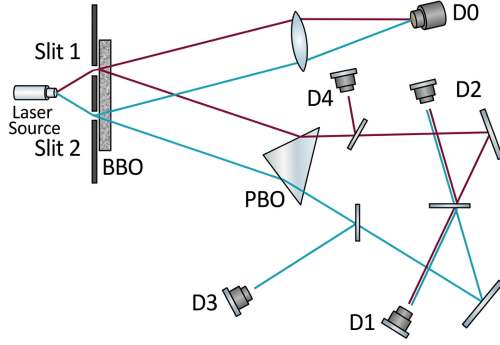


FIG. 1. Schematic diagram of the delayed-choice quantum erasure experiment. For details, see the text.

chanics explains the above phenomena in the following manner.

Single-Photon Double-Slit Interference. When a single photon is incident on a double slit, its amplitude propagates through both slits; on the far side the two emerging components $\psi_1(x)$ and $\psi_2(x)$ overlap and interfere. On detection the amplitude localizes to a single point. While a single photon cannot show a pattern by itself, its landing position is governed by the probability distribution:

$$P(x) = |\psi_1(x) + \psi_2(x)|^2 = |\psi_1|^2 + |\psi_2|^2 + 2\text{Re}(\psi_1^* \psi_2), \quad (1)$$

where the last term is the *interference term*. Accumulating many single-photon events builds up the classic fringe pattern: the photon, in effect, 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:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\psi_1\rangle |D_1\rangle + |\psi_2\rangle |D_2\rangle). \quad (2)$$

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 ($P(x) = |\psi_1|^2 + |\psi_2|^2$).

Delayed-Choice Quantum Eraser. The DCQE uses entangled photon pairs (Fig. 1): a signal photon (to the slits and a primary screen D_0) and an idler photon

(to beam splitters and detectors). Some idler detectors (D_1, D_2) erase the path information; others (D_3, D_4) preserve it; and the choice can occur after the signal photon has hit the screen. The aggregate signal pattern always lacks interference; only coincidence counting against the erasing detectors uncovers fringes hidden in the joint correlations. We stress, with Ref. [7], that there is no retrocausal change of the past: the total screen pattern never shows interference, which is instead recovered only by sorting on the idler data. This statement is the reference point for Appendix B, where the same experiment is treated within our framework.

II. BOUNDED-ENVELOPE COMPOSITE WAVE-PACKET FRAMEWORK

Quantum electrodynamics (QED) and the Standard Model treat the photon (a gauge boson) and the electron (a lepton) as zero-dimensional, structureless point particles, mathematically elementary and incapable of being divided. The assumption of zero-dimensionality introduces mathematical singularities that require renormalization (an effective-field-theory statement about scale-dependence) to yield physical predictions, and the indivisibility of these particles is an extrapolation from current empirical limits; the structure and size of the photon are themselves an active subject of study [28–30]. In this section we develop a heuristic, ontological composite picture of quantum particles (photon, electron, and so on). We derive the motivation for structured, rather than point-like, models of matter from “vibratory” conceptions of matter across many intellectual traditions – e.g. the Vaisesika school, and others. Some Indian texts (e.g. Satyarth Prakash and Vaidic Rashmi Vigyanam [31, 32]) similarly describe matter as built from finer vibrating constituents. 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 quarks and leptons).

A. Relation to Prior Work

Our framework is closely related to three research programs. First, the idea of a localized, spatially extended object that propagates as a wave, explores stationary-action paths, and localizes on interaction is, in substance, de Broglie’s double-solution program – a soliton-like particle carried by, or embedded in, a guiding wave – and its Bohmian descendant. This is an active, mathematically developed literature: the modern review by Colin Durt and Wilcox [33]; Holland’s single field equation amalgamating the wavefunction and a singular soliton model of the particle [34]; Drezet’s quantum solitodynamics, in which soli-

tons guided by a base wave reproduce pilot-wave dynamics for the Schrödinger and Klein-Gordon guiding waves [35]; and the mesoscopic tests and convergence results of Durt [36] and Darrow [37]. Our postulate of an internal vibration is, specifically, de Broglie’s internal clock at the Compton frequency, developed in modern form by Darrow and Bush [38] and Dagan and Bush [39].

Second, the electron carries an internal structure at the Compton scale: Hestenes’ zitterbewegung interpretation [40] models the electron as a localized circulatory motion at the Compton frequency and derives spin and the magnetic moment from it; Barut and Zanghi’s classical model of the Dirac electron [41] gives that motion a Lagrangian dynamics. These are the closest existing relatives of the postulate (P1) below. Catillon et al. [42] report an 8% transmission dip in electron channelling through a silicon crystal at 80.874 MeV, the energy at which the atomic-collision frequency matches the electron’s Compton clock – the only claimed experimental contact with the internal clock.

Third, the hydrodynamic pilot-wave analogues initiated by Couder and Fort [43] and reviewed by Bush [44] realize, in a laboratory fluid, an extended object with an internal clock that is guided by its own wave field and localizes on interaction. This is the one place where the ontology we are proposing has been built and measured, and it is the natural intuition-check for (P1)–(P3).

Fourth, our resonant localization mechanism (Postulate P3 below) is a physical collapse model, and there is an explicit literature on exactly this: Ghirardi-Rimini-Weber (GRW) [45], continuous spontaneous localization (CSL) and the reviews of collapse models [46], the Diosi-Penrose proposal, and – conceptually close to our “point of interaction” – Piccione’s collapse model built around fixed spacetime points [47]; see also Laloë [48]. Crucially, those models are experimentally constrained: their collapse rate and localization width are bounded by underground X-ray searches and by matter-wave interferometry (e.g. the Majorana Demonstrator [49]; see also [50]).

Composite-photon and composite-electron models have also been studied previously: Perkins on composite-photon versus elementary-photon theory [51], Rose on massive particles as bound states of massless constituents [52], and Liu on the internal structure of bosons in a composite model [53]. The historical root of the composite-photon line is de Broglie’s neutrino theory of light, of which Ref. [51] is a modern descendant.

Against this background, we are explicit about our contribution and its limits. What we add is a specific, deliberately visual decomposition of the internal structure into three functional modes (binding, momentum, action) and a resonant “lock-and-key” mechanism for localization, offered as an intuitive ontology for wave and particle behaviour. For calibration of the standard of careful, quantitatively grounded, experimentally an-

chored argument, we point to Mairhofer et al. [54], who argue from real large-molecule interference data that a delocalized centre-of-mass wave interacting with a localized structure means objects can show dual features at once – a claim adjacent to ours, but made quantitatively and with explicit experimental grounding.

B. Postulates

The central postulate of the framework is the following. *Quantum particles such as photons and electrons are not elementary, zero-dimensional points; they are structured, spatially extended wave-packets whose constituent vibrating modes explore stationary (optimal) paths non-locally, but localize to a single “point” during an external interaction with a potential barrier while conserving their internal phase information.* An object is “composite” in our sense if its state space carries internal degrees of freedom that (i) can be excited independently of the centre-of-mass motion, and (ii) enter the localization dynamics, so that the object’s response to an interaction depends on the internal state and not on the centre-of-mass variables alone.

The above 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 bounded envelope, consisting of distinct vibrating modes with specialized functions: binding modes (which maintain internal cohesion), momentum modes (which drive translation and rotation), and action modes (which interact with external fields). The propagation speed of the overall envelope differs from the phase velocities $\omega_i/|\mathbf{k}_i|$ of its internal modes. For massless quanta the binding sector is degenerate ($\omega_b = 0$). Assigning quantum numbers, multiplicities, masses, spins, statistics, or equations of motion to these modes is the principal task required to turn the picture into a dynamics (cf. Refs. [33–35, 40, 41]).

(P1a) *Individuation and Persistence of Modes.* The three modes are functional roles (cohesion, translation, external coupling), not a count of substances; we do not claim that the number is fundamental or that the modes are separately countable. A mode is individuated by its coupling – binding modes couple only to the internal kernel K , momentum modes to the envelope’s centre-of-mass variables, action modes to external fields – and is the same mode at two times if that coupling is continuously maintained. Modes do not survive the localization event of (P3) as separately identifiable entities; the envelope after localization is a new envelope whose mode decomposition is again defined by the same functional criteria. We state this because an ontological proposal without individuation criteria makes no determinate claim.

(P2) *Multi-Path Exploration and Non-Local Continuity.* The path of a constituent mode depends on its own nature and on the properties of the medium in which it

propagates; among the multiple available paths it follows the path of stationary action. When travelling from A to B the envelope expands, and the modes remain unbrokenly linked across space by a non-local, elastic field (the binding network), represented by the kernel $K_{ij}(x, y)$ acting on the components of the internal field Ψ .

(P3) *Resonant Feedback and Stochastic Localization.* On encountering an opposing potential or boundary, the packet establishes a resonant lock-and-key feedback loop set by its internal vibrational frequency. If resonance is achieved, the extended envelope localizes radially inward towards the point of interaction; if not, the packet is reflected, deflected, or transmitted as a whole. We posit that localization is a stochastic process of the continuous-spontaneous-localization type, characterized by a rate λ and a localization width r_C , with the framework's distinctive addition that the rate acquires a resonance contribution depending on the spectral overlap between the packet's action modes and the accessible transitions of the interaction partner:

$$\lambda_{eff}(\omega_a) = \lambda_0 + \lambda_{res} \cdot \Gamma^2 / \left[4(\omega_a - \omega_{target})^2 + \Gamma^2 \right], \quad (3)$$

where λ_0 is a species-independent background rate, λ_{res} the resonant enhancement, Γ the resonance width, and ω_{target} the relevant transition frequency of the target. The localization width r_C replaces the point localization: the envelope contracts not to a mathematical point but to a ball of radius $\sim r_C$. Setting $\lambda_{res} = 0$ recovers mass-proportional CSL exactly; $\lambda_{res} > 0$ is the framework's empirical content.

(P4) *Conservation and Environmental Encoding of Internal Information.* The phase coherence and structural balance of the internal modes are conserved under free propagation. If any part of the binding network interacts with an external system (such as a detector), the path information is encoded into that environment, and the packet's components along the distinguishable paths cease to be mutually coherent. We stress that this encoding is a unitary entanglement with the environment, not a random dephasing of the packet. Entanglement is in principle reversible and its correlations remain recoverable by sorting on the environment, which is exactly what makes the delayed-choice eraser work, whereas irreversible dephasing would make erasure impossible in principle. Irreversibility in this framework enters only through the stochastic localization of (P3), not through (P4).

C. Photons and Degenerate Binding Sector

The framework identifies the rest energy of a quantum with the binding-mode frequency, $m_0 c^2 = \hbar \omega_b$ (Appendix F). For the photon, the postulated rest mass $m_0 = 0$ and therefore $\omega_b = 0$. The postulate (P1) assigns

cohesion to the binding modes, and according to Remark 5 the shared kernel carries entanglement correlations. This leaves the massless photons with no binding modes, no cohesion mechanism and no entanglement kernel. We resolve this contradiction as follows. [This contradiction, and hence the resolution, will not appear if, in future, the photons prove to have a nonzero negligible rest mass.]

First, $\omega_b = 0$ does not mean “no binding sector”; it means a degenerate binding sector. In the dispersion relation $\Omega^2 = \omega_b^2 + c^2 |\vec{k}_m|^2$ the massless case is the null limit $\Omega = c |\mathbf{k}_m|$, in which the internal balance that (P1) attributes to a competition between binding and momentum sectors degenerates into a purely transverse balance among the momentum and action modes. A massless envelope is therefore held together not by an internal restoring frequency but by the transversality condition on its modes – the same structural fact that, in electrodynamics, makes the free photon's polarization transverse. This is a weaker cohesion mechanism than the massive case: the framework predicts no stable rest configuration for a massless envelope, consistent with the fact that a photon has no rest frame.

Second, the entanglement kernel acts on the full internal field, $K_{ij}(x, y) \Psi_i(x) \Psi_j^*(y)$, with i, j ranging over the binding, momentum and action components. The massive case is recovered when the binding-binding component dominates. It makes the kernel a matrix object whose components are unassigned.

Third, Remark 1's lower bound on rest mass is restricted accordingly. It reads as a conditional claim about quanta with $\omega_b > 0$, and the massless case is excluded from its scope by construction.

D. Reconciling Wave-Particle Duality

Using these postulates we can describe the wave and the particle phenomena of light within one ontology (see Appendices A–D). Classically, wave-like phenomena (continuous, extended behaviour) require a wave front to spread across space, while particle-like phenomena (localized, quantized behaviour) require energy to be concentrated in a small region. In our picture the wave-like phenomenon corresponds to the expansion of the envelope and the multi-path exploration of its modes (P1, P2), and the particle-like phenomenon to resonant feedback and stochastic localization (P3): the packet behaves like a particle at the moment of interaction. We therefore describe wave and particle as two limiting responses of one extended object.

(i) *The object is always an extended wave-packet:* a bounded, composite envelope and does not switch between a smooth wave and a solid sphere.

(ii) *Wave behaviour is the propagation stage:* while travelling through space or interacting with macroscopic objects (slits, lenses, polarizers), we observe the continuous propagation of the envelope and the multi-path

distribution of its modes.

(iii) *Particle behaviour is the interaction stage*: on interacting with subatomic potentials (atoms, electrons), a resonant feedback loop drives the extended packet to localize.

(iv) *The criterion separating (ii) from (iii)*: Macroscopic barriers such as slits, mirrors and polarizers are themselves made of atoms. Macroscopic and atomic targets respectively are the far-detuned and near-resonant limits of the single localization rate of Eq. (3): writing $\delta = |\omega_a - \omega_{\text{target}}|$ for the detuning between the packet's action modes and the nearest accessible transition of the interaction partner, the localization rate is resonantly enhanced when $\delta \lesssim \Gamma$ and reduces to the background λ_0 when $\delta \gg \Gamma$. A slit edge is made of atoms, but an optical photon is far detuned from the accessible transitions of a metal aperture, so $\lambda_{\text{eff}} \approx \lambda_0$ and the envelope traverses it as a whole; a photon at an atomic resonance is not, and localizes. Intermediate detunings interpolate continuously between them in which partial localization occurs.

The model still contains a wavefunction – the multi-component field Ψ of Eq. (4) – and a collapse (P3). Wave-particle duality is therefore re-described in terms of envelope expansion versus resonant collapse: the two behaviours are given a common ontological substrate.

E. Non-locality

Remark 4 below describes entanglement by means of a kernel shared between two resonance centres, and states that such a kernel is, in effect, a non-local hidden variable of the Bohmian type. That remark carries certain obligations:

(a) *Bell's theorem*. Bell's theorem [55] and the CHSH inequality [56] exclude local hidden-variable theories, and the loophole-free experiments [57–59] close the detection and locality loopholes simultaneously. Our proposal is explicitly non-local and is therefore not excluded by these results.

(b) *No-signalling*. The existence of a physical connecting medium would permit signalling, unless something independently guarantees that the local marginal statistics at one wing are insensitive to the distant setting. In Bohmian mechanics that guarantee is supplied by the quantum-equilibrium distribution [60], and departures from equilibrium would in fact allow signalling [61]. Our framework inherits the same structure: no-signalling would follow if, and only if, the landing statistics of a localized envelope are Born-distributed.

(c) *Preferred frame and Lorentz covariance*. An “instantaneous radial constraint” on a spatially extended network presupposes a simultaneity slice on which the constraint is imposed. This is the well-known hard problem for collapse and pilot-wave models. Tumulka's relativistic GRW flash model [62] provides an existence proof that a collapse theory can be made fully Lorentz-

covariant, at least for non-interacting particles, by taking the primitive ontology to be a set of spacetime points rather than a field on a slice. That construction is suggestive for us, since (P3)'s “point of interaction” is close in spirit to a flash; making the connection precise is future work.

(d) *Where the multi-particle state lives*. Eq. (4) defines the internal field Ψ on $\mathbb{R}^3$. A generic entangled two-particle state is not a function on $\mathbb{R}^3$, and is not recoverable from a pair of envelopes in three-space plus a two-point kernel: the kernel is a function of two spatial arguments, whereas the state is a function on the six-dimensional configuration space $\mathbb{R}^3 \times \mathbb{R}^3$ and carries relative phase structure the kernel has no room for. This objection applies to every ontology in ordinary space; Bohmian mechanics answers it by putting the guiding wave on configuration space, and the GRW variants answer it by separating the wavefunction from a primitive ontology of flashes or a mass density in $\mathbb{R}^3$. We take the second route. The guiding structure of the framework – the amplitude that determines the modes' stationary-action exploration – lives on configuration space $\mathbb{R}^{3N}$ for N quanta, as in every other formulation of quantum mechanics that reproduces entanglement. The envelopes and their kernels are primitive ontology: the three-dimensional fabric that represents where things are, in the sense of a GRW mass density. The three-dimensional intuitiveness that motivated the picture therefore attaches to the primitive ontology only, not to the full state. The framework offers a three-dimensional image of what an entangled pair looks like, not a reduction of the entangled state to three-dimensional structure.

We further add that the framework is Ψ -ontic in the sense of Pusey, Barrett and Rudolph (PBR) [63]: the envelope and its modes are physical, not representations of an experimenter's knowledge. The PBR theorem is therefore consistent with the picture and, indeed, mildly supportive of the general class to which it belongs.

F. Interpretive Remarks

Our proposed framework provides a visual, mechanical way to picture wave-particle behaviour. By replacing abstract amplitudes with heterogeneous vibrating modes it replicates Feynman paths (modes distributed across stationary trajectories), decoherence (disruption of the modes balance by external potentials) and quantized collisions (interactions as localized envelope impacts). The following remarks are offered as interpretive consequences within the picture.

1. *(Conditional Lower Bound on Rest Mass)* Since mass in this framework corresponds to the energy required by the binding modes to hold the envelope together against the translational expansion of the

momentum modes, it is related to the tension of the non-local network. For quanta with $\omega_b > 0$ this suggests a minimum stable envelope size below which the structure would lose cohesion and dissipate, yielding a lower limit on rest mass. This claim is restricted to massive quanta and does not apply to the photon, for which the binding sector is degenerate.

2. (*Relativistic Energy-Momentum Relation*) Since mass is read as a structural balance between internal binding and translational momentum modes, the framework can be mapped onto the relativistic relation $E^2 = (pc)^2 + (m_0c^2)^2$ (Appendix E). Appendix E establishes only that this relation is obtainable from a re-reading of the standard (Klein-Gordon) relation in terms of binding versus momentum modes.
3. (*Velocity Dependence of Mass*) Tracking the mechanical stresses on the internal modes during translation recovers the standard Lorentzian mass increase (Appendix F). Under the medium-coupling, there is a slower-than-Lorentzian increase of the effective mass with velocity for every $\beta > -1/2$ (Appendix G).
4. (*Entanglement and Non-locality*) Two entangled particles are pictured as two distinct resonance centres sharing a single, continuous, non-local elastic binding network $K_{ij}(\mathbf{x}, \mathbf{y})$ across space. When either particle undergoes a resonant localization (P3), the shared network experiences the radial constraint. We stress that such a shared physical kernel carrying the correlations is, in effect, a non-local hidden variable of the Bohmian type. The remark is a picture of entanglement, not an explanation of it.
5. (*Arrow of Time*) Irreversibility cannot be obtained from a time-symmetric substrate without an additional asymmetric ingredient. With (P3) stated as a stochastic localization process, the framework has such an ingredient, and the arrow follows in the same way and for the same reason that it follows in GRW-type models [64]: the collapse dynamics is fundamentally stochastic and not time-reversal invariant.
6. (*Planck's Constant*) Within the picture, Planck's constant ($\hbar$) is read as an invariant of structural coherence (Appendix H): it sets the equilibrium of the modes, the elastic scale for non-local dilation, the threshold for resonant localization, and the minimum unit of conserved phase information.

G. Candidate Signatures

Candidate signatures, parameterization of (P3), and existing bounds If photons and electrons possess sub-structure, there should be a scale at which it becomes manifest. We list a few candidate signatures and assess each against existing data.

(i) (*Form factors at ultra-high energies*) As Rutherford and deep-inelastic scattering revealed sub-structure in the atom and the proton, collisions near the Planck scale ($\sim 10^{19}$ GeV) might reveal a non-zero electron radius. We note that this scale is some fifteen orders of magnitude beyond any conceivable collider.

(ii) (*Excited states and resonances*) If the electron is composite, sufficient energy might excite internal modes into heavier, unstable states. This runs directly into existing limits, which we now present with their model dependence made explicit. Under the chirality-violating estimate $\delta a \sim m/m^*$, agreement of the electron's $g - 2$ with QED forces any constituent mass scale to $m^* \gtrsim 4 \times 10^5$ TeV, i.e. a size $R \lesssim 5 \times 10^{-25}$ m [65]. Under the chirality-conserving estimate $\delta a \sim m^2/m^{*2}$, which applies when the composite dynamics preserves chiral symmetry so that the anomalous moment is suppressed by a second power of the light mass, the same data give only $m^* \gtrsim$ a few TeV [65, 66]. Which estimate applies depends on the chirality structure of the composite model. Independently, LEP contact-interaction and Bhabha analyses bound the electron radius at $r_e \lesssim 3 \times 10^{-19}$ m [67]; and direct searches exclude an excited electron e^* up to ≈ 3.9 TeV [66]. A composite-electron proposal must confront $g - 2$.

(iii) (*Stability of the electron*) It is sometimes said that truly elementary particles do not decay, but this is not correct as stated: many elementary particles decay (the muon, tau, W, Z, Higgs, and top). The pertinent point is different: the electron is stable because it is the lightest charged lepton, so its decay is forbidden by charge conservation. A composite electron would not automatically be unstable, and any claim of electron decay would have to respect the experimental lower bounds on the electron lifetime.

(iv) (*The internal clock in channelling*) Since (P1)'s internal vibration is de Broglie's Compton-frequency clock, the channelling measurement of Catillon et al. [42] is the one existing experiment that bears directly on it: an 8% dip in the transmission of ~ 80 MeV electrons through a thin silicon crystal at the energy for which the atomic-collision frequency matches the Compton clock frequency. Within our framework this would be read as a resonant enhancement of the localization rate of the kind parameterized in Eq. (3). We list it as a candidate signature because it is, unlike (i)–(iii), an accessible measurement.

(v) (*Collapse-model parameters and a target-species test*) Postulate (P3) or Eq. (3), a collapse model, can be placed on the same exclusion plot as GRW and CSL. Two statements follow. First, the background term. Set-

ting $\lambda_{res} = 0$ reduces Eq. (3) to mass-proportional CSL with parameters (λ_0, r_C) . At the conventional correlation length $r_C = 10^{-7}$ m, the original GRW value is $\lambda_0 \approx 10^{-16} \text{ s}^{-1}$ and Adler's larger estimate is some eight orders of magnitude above it [68]. Underground searches for the spontaneous X-ray emission that such collapse would produce – most stringently the Majorana Demonstrator [49], with related atomic-emission bounds in [50] – exclude rates several orders of magnitude above the GRW value across much of the parameter space and directly challenge the Adler region; the mechanical and interferometric constraints are collected in the review of Carlesso et al. [46]. (P3)'s background sector is an adoption of CSL, and inherits its constraints. Any parameter choice must lie in the region left open in [46, 49]. Second, the resonance term. $\lambda_{res} > 0$ makes the localization rate depend on the spectral relationship between packet and interaction partner, whereas CSL's rate depends on the mass distribution alone. That difference is measurable in principle. Consider a Talbot-Lau or Kapitza-Dirac-Talbot-Lau interferometer of the kind used for large-molecule interference [69], and compare interference contrast for two species chosen to have the same mass and closely matched static polarizability but different internal transition frequencies – structural isomers, or isotopologues in which a vibrational band is shifted. Mass-proportional CSL predicts identical intrinsic collapse contributions for the two; Eq. (3) predicts a difference whenever one species is nearer resonance with the background gas or the grating material than the other. A null result at achievable sensitivity bounds λ_{res} ; a positive result that survives the controls would be evidence for a resonance-dependent localization mechanism of the kind (P3) posits.

Collisional and thermal decoherence already depend on molecular structure through the collision cross-section and the emissivity, and these effects are far larger than any plausible λ_{res} ; separating an intrinsic resonance-dependent collapse from ordinary environmental decoherence would require the standard pro-

gramme of pressure and temperature extrapolation to the isolated limit, and the sensitivity currently reached in that programme is not obviously sufficient. We therefore describe this as a candidate test with a defined falsification target. If the composite hypothesis is false, the claim $\lambda_{res} > 0$ would have to be changed.

In summary, among these candidate signatures, signature (iv) is accessible but unconfirmed and signature (v) is, in principle, both accessible and discriminating, though demanding. We therefore regard the present contribution as primarily an interpretive (ontological) proposal, but no longer as an unfalsifiable one. Finally, we relate the picture to the recent truncated photon result [70]. It concerns the admissible spatial support of single-photon states, and therefore bears directly on whether a bounded envelope with a sharp boundary $\partial\mathcal{E}(t)$ is an available object at all – a question that is prior to, not separate from, our compositeness hypothesis. Our framework concerns an internal mode decomposition of the bounded envelope with $\partial\mathcal{E}(t)$ as an effective, not a sharp, boundary throughout.

III. CONCLUSION

The classification of photons and electrons as indivisible point particles has served as a robust and predictive framework for over a century. In this paper we have explored an alternative ontology in which these particles are pictured as extended, composite wave-packets, and we have shown heuristically how wave-like propagation and particle-like localization can be described as two limiting behaviours of one such object. This picture retains both a wavefunction and a collapse; wave-particle duality is thereby re-described. We offer this work as a conceptual and interpretive contribution rather than as a competing empirical theory. The essential next steps are the construction of a genuine dynamics for the modes and the sharpening of the resonance signature into an experiment with a quantified sensitivity target. Exploring this sub-structural frontier might resolve the persistent problems of modern physics.

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Appendices

Based on postulates (P1)–(P4) we set out a formal framework and use it to illustrate wave and particle phenomena and the relativity of mass and energy. We emphasize that the expressions below are consistency illustrations attached to the postulates rather than a closed predictive dynamics. The appendices are presented as a checklist – a record of which standard results a candidate ontology must eventually recover, and of the form each takes in this language.

$$S = \int_A^B \mathcal{L}_{int}(\Psi, \partial_\mu \Psi, \mu(\mathbf{x})) d^4x + \int dt \iint_{\mathcal{E}} K_{ij}(\mathbf{x}, \mathbf{y}) \Psi_i(\mathbf{x}) \Psi_j^*(\mathbf{y}) d^3x d^3y, \quad (5)$$

where the time integration in the second term is required for the two terms to have the same dimensions; with K_{ij} non-local elastic kernel on the full internal field so that S is an action throughout. Minimizing the action across a boundary where $\mu(\mathbf{x})$ shifts discontinuously yields Snell's law,

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

where the refractive index is $n = c|\mathbf{k}_m|/\omega_m$. We stress that this is the standard result of Fermat/Snell shown to be compatible with the picture; not an outcome of a derivation, and the intermediate variational steps are not supplied because the Lagrangian density $\mathcal{L}_{int}$ is unspecified. If the boundary potential $V(\mathbf{x})$ fails the reso-

Let a quantum particle be a localized, bounded envelope $\mathcal{E}(t) \subset \mathbb{R}^3$ with effective boundary $\partial\mathcal{E}(t)$. We map its internal state to a composite field vector:

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

Each mode has a characteristic vibrational frequency $\omega_b, \omega_m, \omega_a$, while the envelope centre-of-mass velocity is $\mathbf{v}_e = \dot{\mathbf{x}}_c$. By (P1), $\mathbf{v}_e \neq \omega_i|\mathbf{k}_i|$ (a speed distinct from the internal frequencies).

The wave and particle phenomena of light considered below include: (a) reflection; (b) refraction; (c) diffraction; (d) double-slit interference without a detector; (e) double-slit interference with a which-path detector; (f) the delayed-choice quantum eraser; (g) the photoelectric effect; (h) the Compton effect; and (i) pair production.

A. Reflection and Refraction

When the expanded envelope meets a denser medium, its action modes interact with the boundary field (P3). Because a uniform boundary provides no unique resonance point – in the language of Eq. (3), because the packet is far detuned from the accessible transitions of the medium – no localization is triggered; the boundary shifts the phase and direction of the momentum modes, and the packet is deflected (reflection) or transmitted with altered internal velocity (refraction), preserving the binding network. With a localized medium parameter $\mu(\mathbf{x})$, the total action of the modes from A to B is

nance condition

$$\mathcal{R} = \left| \int_{\partial\mathcal{E}} \psi_a(\mathbf{x}, t) \cdot V(\mathbf{x}) d^2x \right| < \mathcal{R}_{crit}, \quad (7)$$

the envelope reflects specularly, reversing the momentum mode to conserve structural balance (P4). The measure is a surface element d^2x ; $\mathcal{R}$ and $\mathcal{R}_{crit}$ are action-valued. We note that $\mathcal{R}_{crit}$ is not determined by the postulates, so Eq. (7) is a schematic criterion rather than a computable condition.

B. Diffraction and Interference

At a barrier with narrow openings the envelope is constrained; its different modes explore the open paths

simultaneously (P2) while remaining elastically linked. Differing internal speeds create a spatial grid of constructive and destructive phase relations behind the barrier. For a single-photon double slit, the envelope expands across both slits, the modes traverse both (P2), and – because the modes travel at different speeds than the envelope (P1) – they arrive with spatial phase differences. When the leading edge establishes resonance with a screen atom (P3), the extended network localizes to that point. The structural profile at the screen follows from the global stationary action of the unified network,

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

where $S/\hbar$ is the phase. Placing a which-path detector projects an active potential; by (P4) the interaction encodes path information and drains the phase balance of the binding modes, so the components through the two slits are no longer phase-coherent and cannot form a unified grid, yielding a non-interfering pattern. Formally, an environmental coupling encodes the path,

$$\Psi \otimes |0\rangle_{env} \longrightarrow (1/\sqrt{2})[\Psi_1 \otimes |D_1\rangle_{env} + \Psi_2 \otimes |D_2\rangle_{env}], \quad (9)$$

where Ψ_1 and Ψ_2 denote the three-component internal fields associated with the two slit paths and $|D_1\rangle, |D_2\rangle$ are orthogonal detector states.

Which-path loss and the eraser. Irreversible random dephasing destroys the phase with no record left to sort on, under which no erasure is possible even in principle; unitary entanglement with an environment leaves the correlations intact and recoverable by sorting on the environment, which is what makes the eraser work. The eraser is described here as coincidence sorting and not as restoration. The aggregate distribution at the screen, obtained by tracing over the idler, never shows fringes – in agreement with Sec. I and with Ref. [7] – because the reduced state of the signal is an incoherent mixture regardless of what is later done to the idler. A downstream erasing measurement provides a partition of the recorded events into subensembles, within each of which the conditional distribution exhibits complementary fringe patterns that cancel in the sum. Nothing is restored, and nothing propagates backwards.

C. Polarization

The modes possess directional axes of vibration relative to the envelope. At a polarizing filter, modes vibrating perpendicular to the filter axis are blocked and only parallel modes pass (P3); the emerging packet is pruned to a single plane. Modelling polarization by the orientation vector $\hat{\mathbf{n}}$ of the action modes and a filter axis $\hat{\mathbf{p}}$, the resonance condition is

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

A deterministic threshold applied to a definite orientation predicts a step function – every photon passes for θ below a critical angle and none above it – not a $\cos^2 \theta$ transmission probability. Malus's law $\mathcal{T}(\theta) = \cos^2 \theta$ is imposed at the level of the threshold distribution and is not a consequence of (P1)–(P4).

D. Photoelectric Effect, Compton Effect and Pair Production

Photoelectric Effect. Electron ejection depends on the resonant feedback loop (P3) rather than on intensity: the action-mode frequency must match or exceed the bound electron's resonance. Below threshold the packet cannot lock and is not absorbed; above threshold a single packet locks, localizes (P3), and ejects the electron with negligible delay. For an incident packet on a bound system, the resonance condition is

$$\mathcal{R}(\omega_a) = \mathcal{R}_0 \cdot \Gamma^2 / [4(\omega_a - \omega_{atomic})^2 + \Gamma^2] \\ \text{lock} \Leftrightarrow \mathcal{R}(\omega_a) \geq \mathcal{R}_{crit} \text{ and } \hbar\omega_a \geq \Phi, \quad (11)$$

with Γ the resonance width of the bound state – physically, its natural linewidth broadened by the local environment – so that the lock condition is satisfied across a continuum above threshold. The occurrence of the lock is all-or-nothing: either a resonant localization event happens or it does not, and this is what makes the effect intensity-independent and prompt. The partition of the delivered energy is not: the full packet energy $\hbar\omega_a$ is transferred, of which Φ is expended in severing the target's binding network and the remainder is deposited in the momentum modes of the liberated electron,

$$K_{max} = \hbar\omega_a - \Phi, \quad (12)$$

which is Einstein's relation, recovered here as a consistency illustration and not derived: the framework supplies no independent determination of Φ or of the transfer efficiency. Formally, if the lock condition of Eq. (11) is met, the extended envelope localizes,

$$\text{supp } \Psi(\cdot, t) \longrightarrow B(x_0, r_C), \quad (13)$$

that is, the effective support of the internal field contracts to a ball of radius $\sim r_C$ centred on the interaction point, at the rate λ_{eff} of Eq. (3).

Compton Effect. A high-energy packet incident on a weakly bound electron cannot satisfy the full-absorption lock condition, so a partial scattering loop transfers a fraction of the momentum modes to the electron; to conserve structural balance (P4) the packet sheds energy and its internal frequency drops ($\omega_a \rightarrow \omega'_a$), lengthening the wavelength. The resulting shift is the standard Compton relation,

$$\Delta\lambda = \frac{h}{m_e c} (1 - \cos \theta), \quad (14)$$

which we reproduce as a known result compatible with the picture; the framework does not independently predict the coefficient $\frac{\hbar}{m_e c}$.

Pair Production. A sufficiently energetic action packet ($\hbar\omega_a \geq 2m_e c^2$) in the strong gradient of a nuclear field ∇V_{nuc} strains the binding network beyond its elastic limit, and structural balance (P4) forces a bifurcation of the envelope,

$$\mathcal{E}_{photon} \longrightarrow \mathcal{E}_{electron} \cup \mathcal{E}_{positron}, \quad (15)$$

the modes reorganizing into two stable envelopes with localized internal binding rotations (rest mass). Note that particle number is not conserved in quantum field theory and “the photon” that bifurcates here is not the QFT photon. The above equation is a picture of pair production in a first-quantized language, and the framework has no account of the process as a field-theoretic amplitude.

E. Relativistic Energy-Momentum Relation

The key relation we invoke here is the Klein-Gordon dispersion relation, so positing it is equivalent to positing the relativistic structure. We map the interplay of the binding modes (internal cohesion, rest mass) and the momentum modes (spatial translation). The binding mode oscillates at ω_b even at rest ($v_e = 0$), while the momentum mode carries a wavevector k_m ; these modes are taken to be structurally orthogonal within the network, so their frequencies combine in quadrature to give the total packet frequency,

$$\Omega^2 = \omega_b^2 + \omega_{trans}^2, \quad (16)$$

with, in a vacuum where field perturbations propagate at c , $\omega_{trans} = c|\mathbf{k}_m|$. Hence

$$\Omega^2 = \omega_b^2 + c^2|\mathbf{k}_m|^2. \quad (17)$$

This is precisely the Klein-Gordon dispersion relation. The assumption that *orthogonal modes combine in quadrature* is therefore the assumption of the Pythagorean (relativistic) structure itself – the argument recovers the standard relation. The envelope velocity is the group velocity, $\mathbf{v}_e = \nabla_{\mathbf{k}_m} \Omega$, giving

$$\mathbf{v}_e = c^2 \mathbf{k}_m / \Omega \implies \Omega \mathbf{v}_e = c^2 \mathbf{k}_m. \quad (18)$$

The action modes scale frequencies into mechanical quantities via $\hbar$: total energy $E = \hbar\Omega$, momentum $\mathbf{p} = \hbar\mathbf{k}_m$ (imposed here rather than derived), and rest mass $m_0 c^2 = \hbar\omega_b$ (at $\mathbf{v}_e = 0, \mathbf{k}_m = 0$). Multiplying Eq. (16) by $\hbar^2$ gives

$$(\hbar\Omega)^2 = (\hbar\omega_b)^2 + \hbar^2 c^2 |\mathbf{k}_m|^2, \quad (19)$$

i.e.

$$E^2 = (m_0 c^2)^2 + c^2 |\mathbf{p}|^2 \implies E^2 = (pc)^2 + (m_0 c^2)^2, \quad (20)$$

which is the standard relativistic relation, re-read in terms of internal versus translational modes.

F. Relativistic Mass Increase as Structural Loading

According to postulate (P2), the envelope’s center-of-mass moves at the group velocity v_e of the unified binding network. Using Eq. (17) and $v_e = \frac{\partial \Omega}{\partial k_m} = \frac{c^2 k_m}{\Omega}$, so that $k_m = \frac{\Omega v_e}{c^2}$, substitution gives

$$\Omega^2 = \omega_b^2 + \Omega^2 \frac{v_e^2}{c^2} \implies \Omega = \frac{\omega_b}{\sqrt{1 - \frac{v_e^2}{c^2}}}, \quad (21)$$

and with $E = \hbar\Omega$, $m_0 c^2 = \hbar\omega_b$, the effective mass $m_{eff} = E/c^2$ transforms as

$$m_{eff} = \frac{m_0}{\sqrt{1 - \frac{v_e^2}{c^2}}}. \quad (22)$$

Physically, as $v_e \rightarrow c$ the momentum modes exert extreme phase shear; to keep the network from fracturing (P4) the total frequency Ω must escalate. Within the picture the Lorentzian increase of m_{eff} is a load-bearing response rather than an accumulation of substance – recovering the standard result.

G. Background Medium Coupling

This appendix is an extension of Appendix F. We remark that one must distinguish between an emergent, medium-dependent effective response of a bound envelope and the rest mass of a fundamental particle; conflating the two is a category error.

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. We, however, believe that space is not truly empty, that is, there is a substantial background medium. Suppose a background medium couples to the binding modes so that their frequency depends on momentum as

$$\omega_b(k_m) = \omega_0 f^\beta(k_m/k_0), \quad (23)$$

where ω_0 is the primal rest frequency in an uncoupled vacuum, β is a dimensionless structural coupling parameter, and $x = k_m/k_0$ is dimensionless. One may consider $f(x) = \sum_{n=0}^{\infty} a_n x^n$ (a power series) in general. Substituting this into Eq. (17),

$$\Omega^2 = \omega_0^2 f^{2\beta} + c^2 k_0^2 x^2. \quad (24)$$

Differentiating both sides of Eq. (24) implicitly with respect to k_m and re-arranging to find the group velocity $v_e = \frac{\partial \Omega}{\partial k_m}$ yields

$$\Omega v_e = \frac{\omega_0^2 \beta}{k_0} f^{2\beta-1} \frac{\partial f}{\partial x} + c^2 k_0 x. \quad (25)$$

Now assuming $a_0 = 1$ (standard normalization) and symmetric dispersion ($a_{\text{odd}} = 0$) for long wavelengths

or small wave numbers ($x^2 \ll 1$), we have $f(x) \approx 1 + a_2 x^2$. Using $(1 + x^2)^p \approx 1 + p x^2$, Eq. (24) becomes $\Omega^2 \approx \omega_0^2 \left[1 + \left(\frac{c^2 k_0^2}{\omega_0^2} + 2\beta a_2 \right) x^2 \right]$. Taking the square root (with $a_2 = 1$ and $k_0 = \omega_0/c$):

$$\Omega \approx \omega_0 \left[1 + \frac{1}{2} (1 + 2\beta) x^2 \right]. \quad (26)$$

Expanding Eq. (25) to the lowest order in x yields

$$\Omega v_e \approx \omega_0 c (1 + 2\beta) x. \quad (27)$$

Eliminating x from the above equations, we obtain Ω as a function of v_e . For $\beta = 0$ (no medium coupling) one recovers standard relativity and for $\beta = 1/2$ the velocity-dependence of the total operational frequency is $\Omega(v_e) = \omega_0 / \sqrt{1 - \frac{v_e^2}{2c^2}}$. For $\beta = 1$, using Eqs. (26 & 27), we have $\Omega(v_e) \approx \omega_0 / \sqrt{1 - \frac{v_e^2}{3c^2}}$. Similarly, for arbitrary $\beta \neq 0$, one can obtain

$$\Omega(v_e) \approx \frac{\omega_0}{\sqrt{1 - \frac{1}{1+2\beta} \frac{v_e^2}{c^2}}}. \quad (28)$$

Hence, for $\beta > 0$ (coupling with the medium) in the low-momentum or long-wavelength regime ($c^2 k_m^2 \ll \omega_0^2$), the effective mass increases with velocity more slowly than the standard Lorentz factor:

$$m_{eff} \approx \frac{m_0}{\sqrt{1 - \frac{1}{1+2\beta} \frac{v_e^2}{c^2}}}. \quad (29)$$

In another approximation, since $\Omega \approx \omega_0$ to the zeroth order, $x = \frac{1}{1+2\beta} \frac{v_e}{c}$ from Eq. (27). Substituting this into Eq. (26) and re-expressing the total operational frequency in terms of velocity gives

$$\Omega(v_e) \approx \omega_0 \left(1 + \frac{1}{2(1+2\beta)} \frac{v_e^2}{c^2} \right). \quad (30)$$

Eq. (30) can be seen as an approximation of Eq. (28) for small velocities.

H. Planck's Constant

In standard quantum mechanics Planck's constant is the proportionality between a photon's energy and frequency ($E = h\nu$). Within the extended-envelope picture h can be read under each postulate as: (i) a minimal invariant volume of action in phase space (P1); (ii) an elasticity scale limiting the non-local stretch of the modes (P2); (iii) the threshold of action for resonant collapse, $\Delta E/\nu = h$ (P3); and (iv) the minimum unit of conserved phase information encoded on interaction (P4). We remark that much of this restates the conventional role of h as the quantum of action and the elementary phase-space cell; it is offered as an interpretation consistent with the picture, not as a result.