

Reconstruction of a Minimal Six-Dimensional Light Entity

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Abstract

We propose a minimal six-dimensional (6D) light null entity in which the six dimensions are intrinsic degrees of freedom of a null physical entity. The six dimensions consist of a two-dimensional null propagation geometry together with four intrinsic one-dimensional degrees of freedom of light: optical phase, polarization, frequency, and orientation along the null momentum generator. In this framework, all four-dimensional (4D) spacetime optical, electromagnetic, and quantum phenomena are understood as lower-dimensional projection or section measurements of a single higher-dimensional null entity.

Introduction-Light occupies a unique position in fundamental physics. It propagates at an invariant speed, carries energy and momentum without rest mass, admits no rest frame or proper time, possesses phase and polarization, and exhibits both continuous field behavior and discrete quantum detections. In four-dimensional (4D) spacetime observations, these properties are individually well detected but collectively incompatible as intrinsic degrees of freedom. In particular, null propagation precludes proper time and rest length, polarization is transverse and gauge-dependent, frequency is defined only relative to an external temporal parameter, and photon detection is discrete despite an underlying continuous electromagnetic field.

These light features are traditionally accommodated within separate theoretical or hypothetical frameworks-classical electrodynamics [1-3], special and general relativity [4,5], and quantum

electrodynamics (QED) [6-8]-whose individual consistency is operational but conceptually fragmented. While QED provides an accurate predictive framework, it does not supply a unified intrinsic ontology for light itself: wave-particle duality, photon identity, nonlocal interference, and measurement collapse remain structurally postulated rather than derived.

Here, using mutual base space-fiber geometric reconstruction method, we reconstruct a minimal 6D light null entity with intrinsic light freedoms: null propagation, optical phase, polarization, frequency, and orientation along the null momentum generator. The 6 dimensions of 6D light null entity are not extensions of spacetime. Subsequently, longstanding paradoxes of light arise not from intrinsic indeterminacy, but from dimensional reduction under measurement. Importantly, QED remains fully compatible with the 6D light null entity projections/sections at the level of all existing 4D predictions.

Minimal Intrinsic Geometry of Light with Six Intrinsic Degrees of Freedom-The intrinsic state of a light entity (**Table S1**) is specified by

$$\mathcal{L} = (\hat{\mathbf{n}}, \phi, \theta_P, \nu, \sigma).$$

Where

$\hat{\mathbf{n}} \in S^2$ is the null propagation direction (2D),

$\phi \in S^1$ is the optical phase (1D),

$\theta_P \in S^1$ parameterizes polarization (1D),

$\nu \in \mathbb{R}^+$ is the frequency (1D),

$\sigma \in \{+, -\}$ labels orientation along the null momentum generator (1D).

These define the minimal intrinsic manifold

$$\mathcal{M}_6 = S^2 \times S_\phi^1 \times S_P^1 \times \mathbb{R}_\nu^+ \times \mathbb{Z}_2$$

which is the smallest closed structure capable of encoding all known native properties of light (**Table S1**). These internal degrees of freedom are not extended spatiotemporal coordinates, but intrinsic attributes of a null physical entity. Their apparent separability in 4D descriptions arises solely upon projection/section. Frequency labels null generator scaling class and cannot be intrinsically reduced to a phase derivative without reintroducing an external time parameter. Orientation along the null momentum generator, to distinguish forward- and backward-directed null propagation while preserving nullity, therefore constitutes an independent intrinsic binary degree of freedom.

The propagation geometry of light is intrinsically two-dimensional, corresponding to the space of null directions. Because a null entity admits no rest frame, no proper time, and no intrinsic transverse localization, its evolution cannot be parameterized internally by a time-like coordinate. Spacetime trajectories emerge only upon projection/section into observer-defined coordinates.

The null condition is identically satisfied,

$$p^\mu p_\mu = 0$$

with

$$E = h\nu, \quad |\mathbf{p}| = \frac{h\nu}{c}$$

Energy and momentum arise from frequency and null orientation, without invoking rest mass or intrinsic temporal evolution. The generator orientation σ enforces the positive-energy condition and distinguishes forward and backward null propagation.

Field Representation and 4D Section-A sectioned/projected single-photon state may be written as

$$\Psi(\hat{\mathbf{n}}, \phi, \theta_P, \nu) = A \mathbf{e}(\theta_P) e^{i\phi}, \quad \mathbf{e} \cdot \hat{\mathbf{n}} = 0$$

Classical electromagnetic fields arise as coherent superposition or ensemble limits of such sectioned/projected states. Maxwell's equations emerge as consistency conditions enforcing transversality, gauge invariance, and null propagation within the section/projection space [1-3].

Quantum phase phenomena, including interference and Berry phases [9], correspond to holonomies in the phase-polarization fiber induced by section/projection along null propagation. Discrete photon detection reflects the intersection of a 4D detector worldvolume with an extended 6D null entity, rather than the existence of a localized particle point. Within this framework, wave-particle duality, photon identity, and measurement collapse are not intrinsic features of light, but structural consequences of dimensional reduction (**Table S2**).

Consistency With Established Physics-Special Relativity: Lorentz invariance is preserved through the intrinsic null structure. No preferred frame or superluminal dynamics is introduced, as all observable propagation occurs along null directions consistent with c . *General Relativity:* In curved spacetime, the null direction follows geodesics, while phase and polarization undergo geometric transport, reproducing gravitational redshift and known polarization holonomies [5]. *Quantum Electrodynamics:* All experimentally accessible QED predictions arise as sections/projections of the 6D null entity. Scattering amplitudes, vacuum polarization, radiative

corrections, and standard optical observables remain unchanged at the level of 4D measurable physics [6-8].

Decisive Experimental Test -In standard quantum optics, interference visibility V and which-path distinguishability D obey the complementarity bound

$$V^2 + D^2 \leq 1$$

which holds even for weak measurements and partial path marking. Any continuous modulation of visibility in the presence of path distinguishability is constrained by this inequality and cannot exceed it within conventional quantum electrodynamics. The six-dimensional null entity framework predicts a controlled and repeatable violation of this bound under specific internal degree-of-freedom manipulations, while preserving single-photon statistics and without invoking post-selection or erasure. Experimental Configuration: A Mach–Zehnder interferometer is configured with the following elements: 1) Single-photon source: heralded single photons via spontaneous parametric down-conversion (SPDC). 2) Path marking: a calibrated birefringent element introducing a fixed, measurable path distinguishability $D > 0$, verified independently by polarization-resolved detection. 3) Internal holonomy module (key element): a closed-loop phase–polarization coupling device inserted in one arm, implementing a nontrivial geometric transformation in the (ϕ, θ_P) internal fiber without altering path distinguishability. 4) Detectors: polarization-insensitive single-photon avalanche photodiodes (SPADs). Crucially, the internal holonomy module is designed such that path information remains available in principle, and no which-path erasure is performed. Predictions: Conventional quantum electrodynamics: Visibility is bounded by the complementarity inequality,

$$V_{\text{QED}} \leq \sqrt{1 - D^2}$$

and internal polarization manipulations cannot increase V once D is fixed. Six-dimensional null entity framework: Interference visibility depends on the internal geometric holonomy accumulated along the null entity's propagation and is given by

$$V_{6D} = \sqrt{1 - D^2} + \kappa \mathcal{H}(\phi, \theta_P)$$

where \mathcal{H} is a closed-loop holonomy functional determined by the phase-polarization fiber geometry, and κ is a coupling constant fixed by the birefringent strength.

For sufficiently small but finite κ , the theory predicts

$$V_{6D}^2 + D^2 > 1$$

representing a direct violation of quantum complementarity without path erasure, post-selection, or detector-induced decoherence. Falsifiability Criterion: Observation of $V^2 + D^2 \leq 1$ under all internal holonomy manipulations falsifies the six-dimensional null entity model. Observation of a reproducible violation $V^2 + D^2 > 1$ under fixed, independently verified D constitutes decisive evidence for intrinsic internal structure beyond four-dimensional projection. This experiment therefore provides a sharp, unambiguous distinction between the proposed framework and standard quantum electrodynamics.

Our reconstruction of 6D light null entity may open avenues of understanding higher dimensional light entity. The intrinsic six dimensions of null propagation, optical phase, polarization, frequency, and orientation along the null momentum generator and their inherent connectivity in 6D light null entity may expand the understandings of nature properties of light.

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Supplementary Materials

Geometric Reconstruction of a 3D Helical Spring Entity-This Supplementary section provides a simple geometric illustration to clarify a general structural point underlying the main text: a single higher-dimensional physical entity may admit multiple lower-dimensional projections that appear mutually incompatible, while remaining fully self-consistent at the intrinsic level.

The illustration is not intended as evidence for the six-dimensional (6D) light entity itself, but as an explicit example demonstrating how base-fiber decomposition and reconstruction operate in an ordinary geometric entity system.

Helical Curve as a Base-Fiber Entity-Consider a three-dimensional helical curve embedded in Euclidean space, parametrized by

$$\mathbf{r}(s) = (R \cos s, R \sin s, Ps)$$

where R is the radius, P is the pitch $s \in \mathbb{R}$ parameter, and s is an intrinsic parameter along the curve. XY-plane: a circle $x^2+y^2 = R^2$; XZ-plane: a sine wave $y = R \sin (z/h)$, and YZ-plane cosine wave $x = R \cos (z/h)$. This curve admits a natural base-fiber decomposition: the axial direction defines a one-dimensional base, the angular coordinate defines a one-dimensional

fiber, the full entity is not reducible to either alone. Importantly, the helix exists as a single, well-defined geometric object independent of any projection.

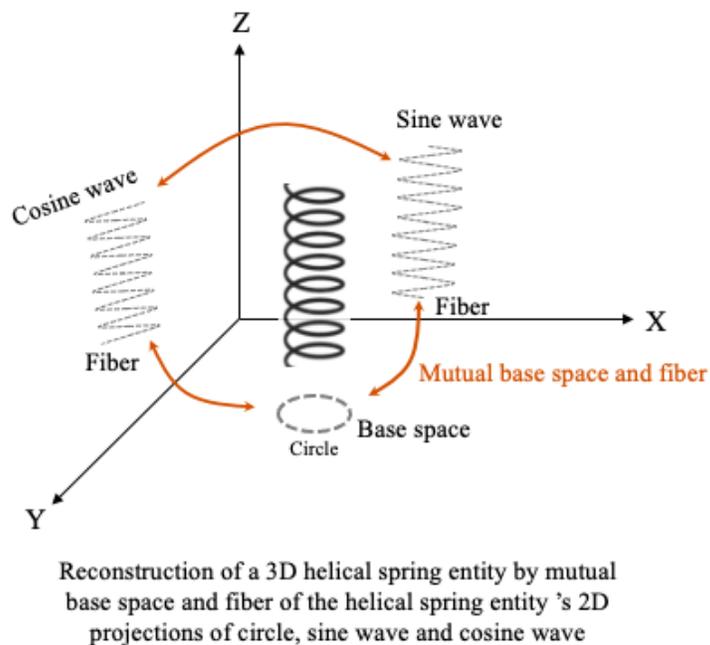


Figure S1. Decomposition and reconstruction of a 3D helical spring entity. Decomposition of a 3D helical spring entity in 2D XY-plane, XZ-plane and YZ-plane with three mutually incompatible projections of a circle, a sine wave, and a cosine wave, respectively. Reconstruction of these three 2D mutually irreducible and incompatible projections by mutual base space-fiber reestablish a sole geometric 3D helical spring entity.

Distinct Two-Dimensional Projections-Different two-dimensional projections (circle, sine wave, cosine wave) of the same helical entity yield qualitatively distinct curves. Each projection is internally consistent, yet the three descriptions are mutually incompatible within two dimensions. Each projection captures a genuine aspect of the helix, yet none alone uniquely specifies the full three-dimensional structure.

Reconstruction from Mutual Base–Fiber Information-While individual projections are incomplete, the combination of mutual base and fiber parameters uniquely reconstructs the original helix. The apparent incompatibility among the projected curves arises solely from dimensional reduction, not from any ambiguity or inconsistency in the underlying object. This (**Fig.S1**) illustrates a general principle: projection multiplicity does not imply ontological multiplicity.

Three principles of the mutual base-fiber 3D entity geometry reconstruction are: 1) mutually irreducible and incompatible 2D descriptions of the 3D entity, 2) no single lower-dimension description is ontologically privileged, 3) intrinsic connectivity of all mutual base-fibers. This 3D entity geometric reconstruction method with mutual base-fiber reconstructions of irreducible and mutually incompatible 2D descriptions and their intrinsic connectivity may extend to other high dimensional geometric entity reconstruction from mutually incompatible lower-dimensional descriptions.

In standard fiber-bundle geometry, the base space and the associated projection are fixed a priori, which implicitly assumes the existence of a preferred decomposition of the system. This assumption is appropriate when the physical object itself distinguishes external coordinates from internal degrees of freedom. However, it already encodes a choice of projection and therefore cannot be regarded as an intrinsic property of a genuinely higher-dimensional object.

Relation to the Six-Dimensional Light Entity- The mutually incompatible observations in 2D projections or cross-sections of a 3D helical spring-such as top-view circular projections versus side-view sinusoidal profiles-cannot be reconciled within any single 2D theoretical framework, yet they are naturally unified in the full 3D structure, indicating that the 2D observations are projections of a higher-dimensional entity. Analogously, the paradoxical phenomena observed for light in 4D-including wave-particle duality, the coexistence of discrete quanta and continuous fields, and the independent behavior of polarization, phase, and propagation orientation-cannot be fully explained within conventional 4D theories. These 4D contradictions similarly suggest that the observed phenomena are projections/sections of a higher-dimensional light entity, whose intrinsic structure can reconcile these apparent paradoxes in a self-consistent manner.

Even when low-dimensional theories provide self-consistent explanations for observed phenomena, the existence of higher-dimensional structures can remain necessary to resolve apparent paradoxes. For example, in condensed-matter physics, the quantized Hall conductance in the integer quantum Hall effect cannot be fully explained by semiclassical 2D electron models; only by invoking the underlying topological invariants does one obtain a unified, self-consistent description. Similarly, in high-energy physics, the Kaluza-Klein framework demonstrates that the electromagnetic field can be interpreted as a manifestation of 5D spacetime geometry, a higher-dimensional structure that naturally unifies interactions otherwise treated independently in 4D. By analogy, the mutually incompatible observations of light in 4D-wave-particle duality, discrete quanta versus continuous fields, and independent polarization, phase, and propagation orientation-may be interpreted as projections of a higher-dimensional (6D) light entity, whose intrinsic

structure reconciles these low-dimensional paradoxes in a self-consistent manner beyond the explanatory reach of conventional 4D theories.

The six-dimensional null light entity proposed in the main text follows an analogous structural logic. Observable four-dimensional electromagnetic and quantum phenomena correspond to different projections/sections of a single intrinsic entity whose degrees of freedom naturally decompose into base and fiber components. Wave-like, particle-like, and field-like behaviors arise as incomplete projections imposed by measurement, rather than as independent or contradictory intrinsic properties. This geometric illustration demonstrates that such projection/section-induced plurality is a standard and well-controlled feature of higher-dimensional physical descriptions.

The six-dimensional structure of the light null entity arises naturally from the intrinsic geometry of null propagation geometry, optical phase, polarization, frequency, and orientation along the null momentum generator. By allowing base and fiber roles to exchange among these five components, each acquires full geometric status, rather than being treated as an auxiliary or dependent degree of freedom. This mutual base–fiber relation ensures that all projections are mutually consistent and fully capture the underlying higher-dimensional object. Any attempt to reduce the dimensionality would collapse this internal consistency, while any additional dimensions would lack intrinsic constraints or observable necessity. Therefore, six dimensions represent the minimal and complete geometric description of the light null entity, uniquely determined by its projection/section-consistent structure.

A single 6D light null entity can manifest through many mutually incompatible 4D projections, sections, or experimental observations, which may individually appear paradoxical or contradictory. These 4D observations point to the existence of a higher-dimensional entity, in which many apparent paradoxes are naturally resolved. In both cases, the lower-dimensional projections or measurements do not by themselves determine the existence, correctness, or complete structure of the higher-dimensional entity, but all projections must be consistent with the underlying geometry.

Minimality and Dimensional Necessity of the Six-Dimensional Null Structure-We now show that the six-dimensional structure proposed here is forced by internal consistency requirements. Any intrinsic description of light with fewer than six independent degrees of freedom fails to reproduce at least one empirically established native property of light without introducing observer-dependent or non-geometric postulates.

Consider a general intrinsic description of light as a null entity characterized by a propagation geometry and a set of internal degrees of freedom $\{\chi_i\}$. Empirically, a physical realization of light simultaneously exhibits:

1. null propagation with invariant speed c ,
2. well-defined optical phase supporting interference,
3. frequency determining energy and momentum,
4. polarization with helicity structure,
5. a definite orientation along the null momentum generator.

We examine the consequences of attempting to eliminate any one of the four internal degrees of freedom (ϕ , ν , θ_P , σ).

(i) Absence of intrinsic phase (ϕ).

Without an intrinsic phase variable, interference phenomena must be defined entirely through external time parameters. This renders phase observer-dependent and incompatible with the existence of geometric (Berry-type) phases observed under cyclic polarization transport. A null entity admitting no proper time cannot generate phase evolution intrinsically unless phase is an independent internal coordinate.

(ii) Absence of intrinsic frequency (ν).

If frequency is not an independent intrinsic degree of freedom, energy must be introduced externally via observer-defined temporal slicing. This violates Lorentz invariance at the intrinsic level and obstructs the invariant null energy-momentum relation $E=h\nu$. Frequency therefore cannot be derived from phase alone without reintroducing an external time parameter, which a null entity lacks.

(iii) Absence of intrinsic polarization (θ_P).

Polarization cannot be reconstructed from phase, frequency, or propagation geometry. Attempts to treat polarization as a derived gauge artifact fail to reproduce helicity conservation and polarization-dependent geometric transport in curved spacetime. The empirical independence of polarization thus requires a distinct intrinsic dimension.

(iv) Absence of generator orientation (σ).

Eliminating orientation along the null generator removes the ability to distinguish forward- and backward-directed null propagation while preserving nullity. This leads to an ambiguity in the sign of energy and obstructs the enforcement of the physical positive-energy condition.

Orientation therefore constitutes an independent intrinsic binary degree of freedom.

These four internal degrees of freedom are mutually irreducible and cannot be generated from one another without violating Lorentz invariance, null structure, or empirical polarization and phase phenomena. Together with the intrinsically two-dimensional null propagation geometry, they form a six-dimensional minimal closed manifold.

Any intrinsic description with fewer than six dimensions necessarily fails to encode at least one empirically observed property of light without introducing external observer-dependent structures. Conversely, any extension beyond six dimensions introduces unconstrained degrees of freedom lacking empirical necessity. The six-dimensional null entity is therefore both minimal and complete, uniquely determined by consistency rather than choice.

Table S1: Mutually irreducible and incompatible properties of light and structural relations

This table analyzes light properties which are mutually irreducible and cannot be generated from one another within a 4D intrinsic framework, and reach the minimal set (in bold) of independent intrinsic degrees of freedom required to encode known optical and quantum phenomena of light.

Light property	Empirically established	Defined intrinsically in 4D?	Reducible from other properties?	Mutually incompatible with	Candidate intrinsic dimension
1 Null propagation speed c	Yes	Yes	No	Proper time, rest frame	Null base geometry (2D)
2 Absence of rest mass	Yes	Yes	No	Proper length, localization	Null constraint
3 Optical phase ϕ	Yes	No (requires time parameter)	No	Discrete detection	Phase fiber (1D)
4 Frequency ν	Yes	No (observer-dependent)	No	Null proper time	Frequency fiber (1D)
5 Polarization	Yes	Gauge-dependent	No	Scalar wave description	Polarization fiber (1D)
6 Transversality	Yes	Constraint-based	Derived	Longitudinal modes	Projection constraint
7 Discrete detection events	Yes	No	No	Continuous fields	Projection effect
8 Wave-particle duality	Yes	No	No	Classical ontology	Projection effect
9 Photon identity indistinguishability	Yes	No	No	Particle localization	Intrinsic nonlocality
10 Zero proper time	Yes	Yes	No	Internal clock	Null geometry

	Light property	Empirically established	Defined intrinsically in 4D?	Reducible from other properties?	Mutually incompatible with	Candidate intrinsic dimension
11	Energy–momentum relation $E = pc$	Yes	Yes	Derived	Rest mass	Frequency + null orientation
12	Handedness / helicity (spin-1)	Yes	Yes	No	Scalar waves	Generator orientation (1D)

Experimentally established properties of light most notably optical phase, frequency, polarization, and helicity-cannot be derived from one another, nor from null propagation alone, within a 4D intrinsic description. At the same time, these properties are observed to coexist in every physical realization of light. The table highlights that these properties are: empirically independent, structurally incompatible as intrinsic 4D variables, and yet simultaneously realized.

The six-dimensional null light entity proposed in the main text introduces the minimal number of intrinsic degrees of freedom required to encode all entries in Table S1 without redundancy. Observable 4D electromagnetic and quantum phenomena arise as sections/projections that selectively access subsets of these intrinsic variables. The table therefore provides a compact structural summary of the physical motivation for the intrinsic dimensionality adopted in the theory.

Table S2. Selected 4D observations and paradoxes that may be naturally interpreted through a six-dimensional (6D) light null entity.

	4D Observation / Theory	Paradox / Incompatibility	6D Light Null Entity Interpretation
1	Quantum Electrodynamics (QED)	Vacuum fluctuations, wave-particle duality, photon self-energy divergences	Separation of 2D null propagation and 4D internal DOFs (phase, polarization, frequency, orientation) provides a geometric basis for quantization and avoids singularities.
2	Quantum Mechanics	Discrete quanta vs continuous wavefunction	Discrete observables arise from intrinsic 4D fiber, preserving continuity in propagation without ad hoc collapse.

4D Observation / Theory	Paradox / Incompatibility	6D Light Null Entity Interpretation
3 Maxwell Electromagnetism	Polarization, phase, and orientation treated independently; cannot capture discrete-continuous duality	Internal DOFs along 6D null path unify field and particle descriptions, allowing simultaneous discrete-continuous behavior.
4 Gravitational lensing of light	Classical EM predicts deflection but ignores internal quantum DOFs	6D propagation along null geodesic with evolving internal DOFs predicts subtle polarization- or frequency-dependent lensing effects.
5 Photon entanglement	Nonlocal correlations appear “spooky” in 4D	Correlated internal DOFs (phase/polarization/frequency) are naturally linked in 6D, offering a local geometric interpretation.
6 Casimir effect / zero-point energy	Divergent energy density in vacuum	Internal fiber structure constrains allowed modes, providing a geometric cutoff and reinterpretation of vacuum energy.
7 Coherence / decoherence phenomena	Loss of phase information in standard 4D treatment	Phase and orientation as intrinsic 6D dimensions enable natural tracking of coherence in complex systems.

Observers restricted to low-dimensional subspaces perceive only fragments of higher-dimensional entity structures, giving rise to observable contradictory phenomena. By reconstructing light’s behavior from its low-dimensional projections/sections, we show that wave-particle duality, spin-1 characteristics, and polarization naturally emerge from a six-dimensional geometric framework of a minimal 6D light null entity. This approach predicts specific correlations between polarization, helicity, and momentum that are directly testable in controlled optical experiments. Our results suggest that many “intrinsic” properties of light are in fact observer-dependent projections/sections of a higher-dimensional structure, providing a pathway to experimentally probe the underlying six-dimensional ontology and revealing new high-dimensional signatures in light-matter interactions.