

Minimal Six-Dimensional Null Manifold Underlying the Photon

Tingfang Yi

Centiver Ltd, 85 Bolton Street, Cambridge, MA 20140 USA

Abstract

Light's propagation, phase, polarization, and frequency are projections of a minimal six-dimensional null entity unifying spacetime and photon internal degrees of freedom. Observed pairwise and triple couplings emerge naturally, explaining Spin Hall, Berry, Pancharatnam phases, optical activity, and relativistic shifts. Classical fields, quantum detections, and wave-particle duality arise as lower-dimensional projections, while photon discreteness reflects detector intersections. The framework agrees with relativity and QED and predicts testable interference deviations via controlled holonomy.

Introduction- Light occupies a unique and paradoxical position in fundamental physics. While it serves as the universal constant for spacetime measurement, its own intrinsic nature remains fragmented under the standard four-dimensional (4D) Minkowski framework. Propagating at an invariant speed c without a rest frame or proper time, light exhibits properties (such as phase, polarization, and frequency) that appear as external parameters rather than geometric necessities. In the 4D spacetime observer's frame, these properties often manifest as mutually incompatible or gauge-dependent variables. For instance, null propagation precludes the existence of a rest length, yet polarization is strictly transverse; frequency is defined only through an external temporal parameter, while discrete photon detections contrast sharply with continuous field evolution. 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 provide an intrinsic geometric ontology beyond 4D section.

We identify a closed minimal 6D light null manifold with experimental observations and mutual base space-fiber method. The six-dimensional structure of the light entity is not merely a theoretical construction but is grounded in physically observed coupling phenomena among its fundamental degrees of freedom. Together with the six pairwise interactions, they enforce a self-consistent topological structure that is uniquely satisfied by a six-dimensional light entity: any reduction in dimension fails to generate all observed three-way couplings, and additional dimensions are unnecessary for closure. Therefore, the co-occurrence of experimentally observed two- and three-way couplings substantiates the existence of a six-dimensional light entity as the minimal, self-consistent physical structure capable of preserving information with high stability and fidelity.

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, and frequency. These intrinsic dimensions are not extended spatial directions, but as the observable physical attributes of light themselves, thereby bypassing the conceptual hurdles of dimensional compactification or unobservability. Subsequently, longstanding paradoxes of light arise not from intrinsic indeterminacy, but from dimensional reduction under measurement. By transcending the unidirectional governance of the base space over the fiber in classical bundle theory, the framework of mutual base space-fiber introduces a fundamental duality where base and fiber may interchange roles, establishing a mathematical symmetry and connectivity for

reconstructing higher-dimensional entities from their reciprocal geometric projections. Importantly, QED remains fully compatible with the 6D light null entity projections/sectional measurements at the level of all existing 4D predictions. The observations of high-dimensional entity projection demonstrate that, under some conditions, when a continuous higher-dimensional entity is projected onto a space lower by at least two dimensions ($N \rightarrow N-2$), the original topological connectivity is "sheared", resulting in apparent discreteness and point-like behavior. A 4D photonic quantum point is not a stochastic dot, but a compressed cross-section of a 6D light entity with compressed unit of information. The present work formulates the structural framework basis of a minimal 6D light null entity, and detailed dynamical development and quantitative implications will be followed in subsequent studies/reports.

Fundamental Degrees of Freedom of Light and Tetrahedral Coupling Complex-Based on experimental observations in the four-dimensional (4D) spacetime (**Table S1**) and schematic diagram of construction of higher-dimensional light entity (**Fig. S1**), light's intrinsic 4 degrees of freedom (propagation (2D), polarization (2D), phase (1D) and frequency (1D)) with 6 (=2+2+1+1) dimensions in total are identified as minimal light null entity's fundamental degrees of freedom.

The tetrahedral coupling complex provides a minimal closed network that naturally accounts for the observed couplings among the fundamental degrees of freedom of light (**Fig.1**). Specifically:

- 1) Pairwise coupling completeness: Each degree of freedom participates in at least one pairwise coupling, corresponding to the six experimentally observed pairwise interactions (**Table S2**).
- 2) Triple coupling closure: Every combination of three degrees of freedom forms a triple coupling, consistent with the four experimentally observed three-way interactions (**Table S2**).
- 3) Minimal

high-dimensional entity: As the smallest closed network, the tetrahedron demonstrates that the six-dimensional light entity represents the minimal high-dimensional structure capable of self-consistent coupling among all degrees of freedom. 4) Intrinsic self-consistency: No additional degrees of freedom are required, and no reduction is possible without breaking the closed network topology.

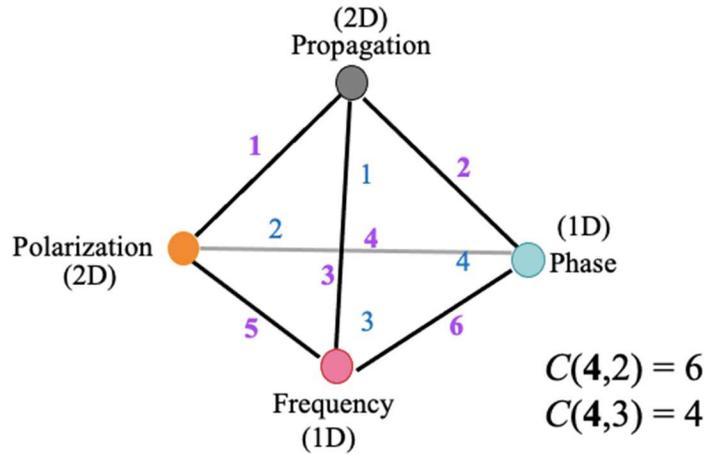
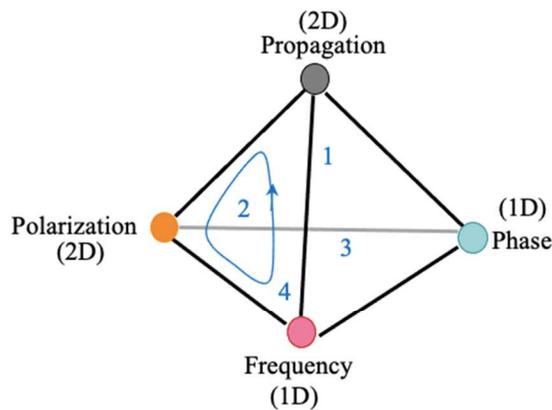


Fig.1. Tetrahedral coupling topology of optical degrees of freedom. The tetrahedral coupling complex represents the minimal closed network underlying the six-dimensional light entity, naturally accounting for the observed six pairwise-couplings and four triple-couplings among its fundamental degrees of freedom. The filled circles in 4 colors represent the four fundamental degrees of freedom (DOF) of light. Each edge/line fragment linking two DOFs represents a pairwise-coupling. The numbers of the 6 pairwise-couplings are in purple color. Each triangle-surface composed of three DOFs represents a triple-coupling with numbers in blue color. Each degree of freedom participates in at least one pairwise coupling, and every combination of three forms a triple coupling, matching the experimentally observed six pairwise and four triple interactions. The topological combinatorial constraints of $C(4, 2) = 6$ and $C(4,3) = 4$ are shown.

The six-dimensional nature of the light entity arises from two complementary constraints. First, its four fundamental degrees of freedom-Propagation (2D), Polarization (2D), Phase (1D), and Frequency (1D)-carry a total of six intrinsic dimensions, establishing a minimal high-

dimensional capacity. Second, the interactions among these degrees of freedom form a tetrahedral coupling complex, the smallest closed network supporting six pairwise and four triple couplings. This network enforces self-consistency: any reduction in dimension or degree of freedom would break the closure, while additional dimensions are unnecessary. Together, these constraints uniquely fix the light entity at six dimensions, making it the minimal, fully self-consistent high-dimensional structure capable of preserving information with maximal stability and fidelity.

Closed tetrahedral information topology- The coupling structure of the four fundamental degrees of freedom forms a tetrahedral network that represents the smallest closed topology capable of supporting complete information circulation (**Table S2** and **Fig.2**). In this topology, every degree of freedom participates in multiple closed interaction loops, ensuring that information propagating through one degree of freedom can return through alternative coupling pathways. Such a fully closed information-flow network naturally explains the robustness and high fidelity of optical degrees of freedom and strongly supports the interpretation of light as a minimal six-dimensional null entity.



- Closed loop 1: Propagation → Polarization → Phase → Propagation
- Closed loop 2: Propagation → Polarization → Frequency → Propagation
- Closed loop 3: Propagation → Frequency → Phase → Propagation
- Closed loop 4: Polarization → Frequency → Phase → Polarization

Fig.2. Minimal closed tetrahedral information topology of the light entity. The four closed information loops are shown. The closed information loop 2 (in triangle in blue with arrow) is shown.

Beyond dimensionality, the tetrahedral network defines a fully closed information-flow topology, in which every degree of freedom participates in multiple interaction loops, explaining the observed robustness, stability, and fidelity of optical properties. Together, these logical, geometric, topological, and empirical considerations converge to establish the six-dimensional light null entity as a physically grounded, minimal, and self-consistent structure underlying the behavior of light.

Minimal Intrinsic Geometry of Light with Six Intrinsic Degrees of Freedom-The intrinsic state of a light entity (**Table S1, Figs. 1, 2 and S1**) is specified by

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

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 (2D),

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

These define the minimal intrinsic manifold, which may be expressed symmetrically as:

$$\mathcal{M}_6 = S_k^2 \times S_P^2 \times S_\phi^1 \times \mathbb{R}_\nu$$

Where

S_k^2 Propagation (null directions) ,

S_P^2 Polarization (Poincaré sphere),

S_ϕ^1

\mathbb{R}_ν Optical phase,

\mathbb{R}_ν : Frequency,

Dimensionality: 2+2+1+1=6. Within this structure, propagation, polarization, phase, and frequency possess equal geometric status.

which is the smallest closed structure capable of encoding irreducible, incompatible and established native properties of light. 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/sectional measurement. Frequency labels null generator scaling class and cannot be intrinsically reduced to a phase derivative without reintroducing an external time parameter.

Within the intrinsic six-dimensional manifold, the metric may be written as a product metric over the independent degrees of freedom,

$$ds^2 = d\Omega_k^2 + d\Omega_P^2 + \alpha^2 d\phi^2 + \beta^2 \frac{d\nu^2}{\nu^2}$$

where $d\Omega_k^2$ denotes the metric on the sphere of propagation $d\Omega_P^2$ directions, $d\Omega_P^2$ denotes the metric on the polarization sphere, and the remaining terms describe the phase and frequency coordinates. The parameters α and β determine the relative geometric scales of the internal dimensions. This structure defines a minimal six-dimensional null manifold in which propagation geometry, polarization, phase, and frequency coexist as intrinsic coordinates.

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.

*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 S3**). A photonic quantum point is not a mere dot or numerical value, but a compressed unit of information. It represents a locally compressed cross-section of a higher-dimensional tensor structure. The observed number, distribution, spacing, and coupling patterns of 4D light/photon quantum dots encode features consistent with the proposed 6D light null entity, providing a quantifiable map of high-dimensional information. This paradigm shift redefines the once-perceived stochastic noise of 4D light quantum dots as a deterministic characteristic spectrum map of 6D light entities, which may serve as solid supporting evidences for the existence of the 6D light entity and a spectrum for decoding intrinsic features of the 6D light null entity (**Fig.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 subtle deviation in specific holonomy-controlled regime. 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.

Discussion-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 their inherent connectivity in 6D light null entity may expand the understandings of nature properties of light. The transition from viewing 4D light/photon quantum dots as stochastic noise to a deterministic characteristic spectrum constitutes a foundational proof of the 6D light entity. The recurring geometric regularities and coupling matrices within these discrete points function as the intrinsic topological signatures of a higher-dimensional entity. A key conceptual advance of this work is the elevation of the internal degrees of freedom of the photon to geometric parity with spacetime coordinates within a unified high-dimensional manifold. Unlike traditional fiber bundle approaches, where spacetime acts as the base and internal structure is relegated to the fiber, here spacetime itself emerges as merely one

projection of the total geometric entity. This reconceptualization dissolves the hierarchical distinction between base and fiber, allowing a truly covariant treatment of light's intrinsic properties, and providing a natural framework to encode polarization, phase, frequency, and orientation on equal footing with null propagation. Such a perspective shifts the paradigm from a spacetime-centric view to a manifold-centric view, wherein the photon's full structure is realized only in the higher-dimensional embedding. The tetrahedral coupling complex and its closed information topology reveal a fundamentally geometric organization of light's intrinsic degrees of freedom, providing a unifying framework for pairwise, triple, and quadruple couplings. This structure suggests that higher-dimensional manifolds can encode observable photonic phenomena, potentially reshaping both theoretical and experimental approaches in quantum optics and photonics. The closed tetrahedral information topology establishes a new geometric paradigm, unifying light's intrinsic couplings and offering a transformative framework for understanding photonic phenomena.

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Supplementary Material

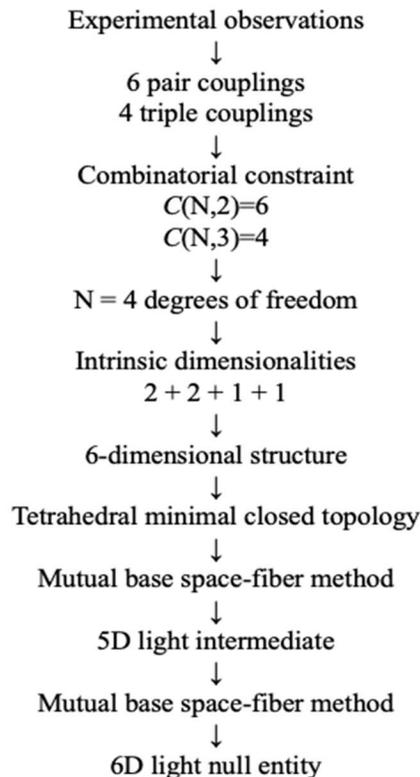
Reconstruction of a Minimal Six-Dimensional Light Null Entity

Tingfang Yi

Centiver Ltd, 85 Bolton Street, Cambridge, MA 20140 USA

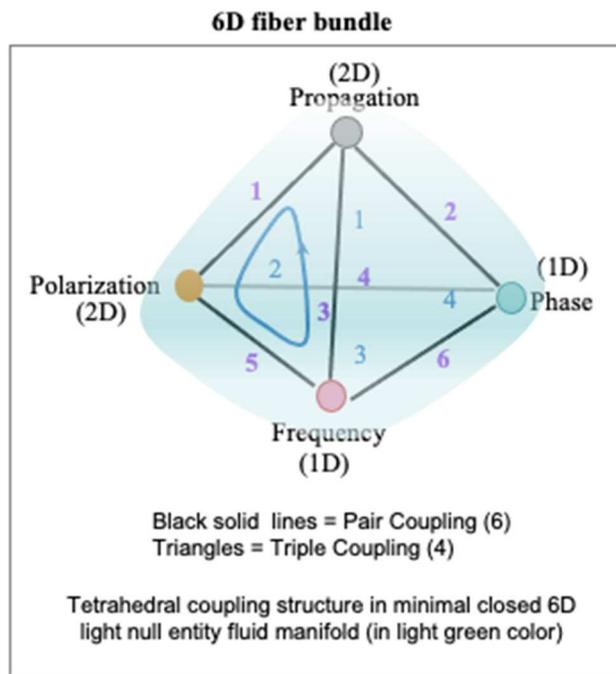
This supplementary section provides a simple geometric illustration to clarify a general structural point underlying the main text: a single higher-dimensional (3D) physical entity may admit multiple lower-dimensional projections/sections that appear mutually incompatible, while remaining fully self-consistent at the intrinsic level. The illustration is not intended as evidence for the six-dimensional (6D) light null entity itself, but as an explicit example demonstrating how mutual base space-fiber reconstruction operates in an ordinary geometric entity system. A 3D helical spring, though embedded in three-dimensional space, is intrinsically a one-dimensional parametric curve whose minimal structural parameters generate multiple physically interpretable properties such as rotation, phase, and chirality. Its lower-dimensional projections, while lossy, preserve structured signatures sufficient for constrained reconstruction. Analogously, the intrinsic degrees of freedom of a 6D light entity may form a minimal irreducible structure within

the six-dimensional
manifestations
that partially encode
logically,
consistent manner.

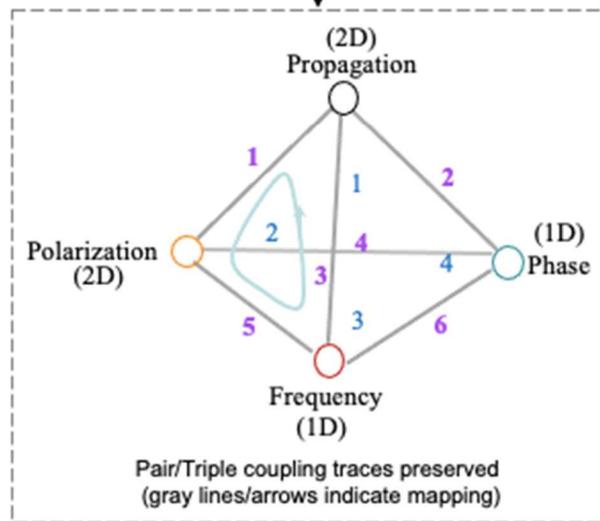


null manifold, whose 4D
represent structured projections
the underlying geometry in a
geometrically, and physically

Figure S1.
construction
null entity.



Projection to 4D



Schematic diagram of
of 6-dimensional light

Fig.S2. Schematic diagram of 6D light null entity projection to 4D, with pair/triple coupling traces preserved and detectable in the 4D spacetime.

Discreteness and dot appearances of at least 2-dimensional (2D) projection reduction of a continuous higher-dimensional entity- The projection of a 3D helical spring entity in vertical direction on 1D straight line space appears two separated dots at the same time (with the projection dot distance equal to the diameter of the spring's circle). The projection of the same 3D spring entity in horizontal direction on 1D straight line space appear multiple separated dots at the same time (with the projection dot number equal to the number of spiral turns, and the neighboring projection dot distance equal to the pitch of the helix).

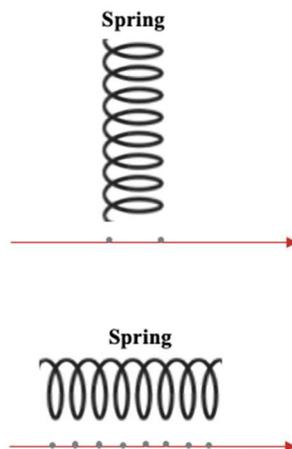


Figure S3. Discreteness and dot appearances with at least 2-dimensional (2D) projection reduction. Discreteness and dot appearances of a single static 3D helical spring entity's one projection on 1D straight line space. One projection of the same 3D spring entity (in vertical or horizontal directions) appears two or multiple separated dots (in gray dot) at the same time on 1D straight line space, respectively.

The discreteness and dot appearances of a 3D spring entity on 1D (with 2D reduction) straight line space projection demonstrate that the original 3D helical spring topological connectivity is "sheared" in 1D straight line space, resulting in apparent discreteness and point-like behavior (**Fig.S3**). The paradox of discreteness and multiple separated dot appearance of 1D projections of a single 3D spring entity at the same time in 1D line space are compatible and with intrinsic connectivity in the 3D helical spring entity. These observations suggest that, at least under some conditions, when a continuous higher-dimensional entity is projected onto a space lower by at least two dimensions ($N \rightarrow N-2$), the original entity topological connectivity is "sheared", resulting in separated point-like activity and discreteness. Although very limited, loss of connectivity, and very fragmental and incomplete, these discrete dots/projections/sectional measurements at lower ($N-2$) dimension do encode residual fiber data of the parent structure of the higher-dimensional (N) entity, which are not as a consequence of stochastic fragmentation, but as a deterministic reduction of a continuous higher-dimensional geometry. In this formulation, apparent quantum discreteness reflects a geometrically constrained projection with information preserved in compressed form. In an inverse view, the discreteness and multiple or many separated dot appearance/detections/ descriptions at the same time of a single known

object/entity in an N-dimensional space may indicate that these appearance/detections/descriptions maybe a projection of an at least N+2 dimension-object/entity in N-dimension space. It is difficult to reconstruct a 3D spring entity only with the separated dot projections in 1D due to the too much topological connectivity loss during the 2-dimensional reduction.

Decomposition and Reconstruction of a 3D Helical Spring Entity with Mutual Base Space - Fiber-Consider a three-dimensional helical spring 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/section. Different projections in the orthogonal 2D planes (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 2D planes. Each projection captures a genuine aspect of the helical spring, yet none alone uniquely specifies the full 3D structure.

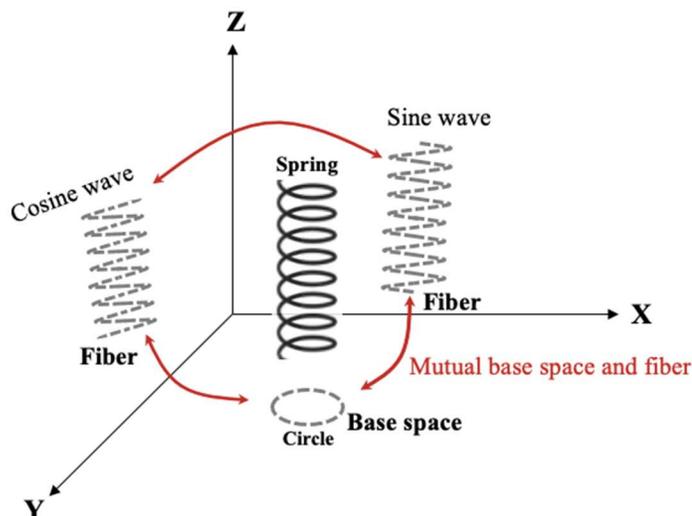


Figure S4. Decomposition and reconstruction of a 3D helical spring entity. Decomposition of a 3D helical spring entity in 2D XY-plane, XZ-plane and YZ-plane with three mutually incompatible projections of a circle, a sine wave, and a cosine wave, respectively. Reconstruction of these three 2D mutually irreducible and incompatible projections by mutual base space-fiber reestablish a sole geometric 3D helical spring entity.

While individual projections are incomplete, the combination of mutual base and fiber parameters of the three 3D projections of circle, sine wave, cosine wave uniquely reconstructs the original helix spring entity. The apparent incompatibility among the projected curves arises solely from dimensional reduction, not from any ambiguity or inconsistency in the underlying object. This (**Fig.S4**) illustrates a general principle: projection multiplicity does not imply ontological multiplicity. Three principles of the mutual base space-fiber 3D entity geometry reconstruction are: 1) irreducible and mutually incompatible 2D descriptions of the 3D entity, 2) no single lower-dimension description is ontologically privileged, 3) intrinsic connectivity of all mutual base space-fibers. The number of three of the mutually irreducible and incompatible 2D descriptions in the three orthogonal planes is equal to the minimal dimension number of three of a helical spring entity. This 3D entity geometric reconstruction method with mutual base space-fiber reconstructions of irreducible and mutually incompatible 2D descriptions and their intrinsic

connectivity may extend to other high dimensional (N+1) geometric entity reconstruction from mutually incompatible lower-dimensional (N) descriptions with 1D difference. It may be inefficient to use the mutual base space-fiber reconstruction method for higher-dimensional reconstruction with 2D difference due to the loss of too much connectivity information during 2D reduction. The number of mutually irreducible and incompatible lower-dimensional descriptions (projections/sections) of a higher-dimensional entity are related to the minimal dimension number of the higher-dimensional entity.

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.

While standard 4D physics describes light as a gauge field quantum, it treats the phenomenon as a foundational limit, yet it remains ontologically silent-much like a 2D projection of a 3D spring entity that appears irreducible within a 2D plane. However, if the 4D light we observe is merely a low-dimensional shadow/section measurement, its true substance remains invisible in our 4D geometry. This raises a profound possibility: can the ontological essence of light only be answered by stepping into the higher dimensions from which it originates?

Relation to the Six-Dimensional Light Null 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 of light in 4D-including 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 discrete quanta versus continuous fields, and independent polarization, phase, and propagation orientation-may be interpreted as projections of a higher-dimensional 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 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 space 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 space-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.

Minimality and Dimensional Necessity of the Six-Dimensional Null Structure-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,

Next, we examine the consequences of attempting to eliminate any one of the four internal degrees of freedom (ϕ, ν, θ_p) , which are irreducible and mutually incompatible descriptions in 4D observations.

(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.

The above analyses suggest the minimal dimension number of a higher-dimensional light entity can be the number of irreducible and mutually incompatible descriptions/freedoms of null propagation (2D), polarization (2D), optical phase (1D), and frequency (1D): $2+2+1+1=6$. Any Lorentz-invariant intrinsic description of a massless spin-1 null entity encoding phase interference, polarization helicity, frequency-defined energy, and orientation along null generator

requires dimension ≥ 6 . The minimal 6D light null entity is uniquely determined by the six mutually incompatible degrees of freedom observed in 4D; it is compelled by logical, geometric, topological, informational closure, and physical experimental consistency, realizing a triple consistency of structure, projection, and intrinsic physical properties.

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.

Connection Structure and Berry-Phase Geometry- Couplings among the internal degrees of freedom arise through geometric connections defined on the internal fiber.

Let

$$A = A_i dx^i$$

denote a connection one-form defined over the polarization–phase submanifold. The associated curvature two-form is

$$F = dA$$

This curvature represents the geometric Berry curvature associated with cyclic evolution of polarization and phase. Observable geometric phase phenomena, including the Berry phase and Pancharatnam phase, arise as holonomies of this connection.

For a closed loop γ in the internal space, the accumulated geometric phase is

$$\Gamma = \oint_{\gamma} A$$

This geometric structure naturally generates experimentally observed effects such as spin-orbit coupling of light, optical activity, and polarization-dependent phase shifts.

Geometric Interpretation of Tetrahedral Coupling-The four fundamental degrees of freedom

$$(\hat{k}, P, \phi, \nu)$$

form a relational structure whose coupling topology corresponds to a complete graph K_4 . In this graph, each pair of degrees of freedom is connected by an interaction channel, producing six pairwise couplings.

Geometrically, these pairwise interactions correspond to components of the connection

$$A_{ij}$$

Higher-order interactions arise through the curvature structure. Triple couplings correspond to curvature components of the form

$$F_{ijk} = \partial_i A_{jk} + \partial_j A_{ki} + \partial_k A_{ij}$$

The resulting relational structure is equivalent to the 3-simplex (tetrahedron). Its six edges correspond to pairwise couplings, while its four triangular faces represent triple couplings among three degrees of freedom. The tetrahedral topology therefore provides the minimal closed

network capable of supporting the observed coupling relations among propagation, polarization, phase, and frequency.

Photon Trajectories in the Six-Dimensional Manifold-Within the intrinsic six-dimensional manifold, the evolution of a light entity follows a generalized geodesic trajectory.

Let the six-dimensional coordinates be

$$x^A = (\hat{k}, P, \phi, \nu)$$

The dynamical trajectory is then governed by the geodesic equation

$$\frac{d^2 x^A}{d\lambda^2} + \Gamma_{BC}^A \frac{dx^B}{d\lambda} \frac{dx^C}{d\lambda} = 0$$

where λ parameterizes the null propagation generator. Observable spacetime trajectories correspond to projections of this higher-dimensional path onto the four-dimensional measurement space.

Geometric Interpretation of Photon Detection- In this framework, a photon is not a localized particle point but an \mathcal{M}_6 extended trajectory within the six-dimensional manifold .A detector is described by a four-dimensional spacetime worldvolume D_4 . Detection events correspond to intersections between the detector worldvolume and the six-dimensional photon manifold,

$$\mathcal{M}_6 \cap D_4$$

These intersections appear in four-dimensional observations as discrete photon detection events. Thus, apparent particle-like discreteness emerges as a geometric consequence of dimensional projection rather than an intrinsic fragmentation of the light entity.

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, which

may provide an alternative intrinsic geometric description consistent with existing data. In both 3D spring and 6D light entities, 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.

Intrinsic degrees of freedom as high-dimensional manifolds: The four intrinsic 1D degrees of freedom detected in 4D-optical phase, polarization, frequency, and orientation, are actually projections of 3D topological structures within the 6D entity. What we measure as linear parameters are the "shadows" of complex rotational and helical behaviors in the hidden 2D subspace. Invariance of light speed: The invariant light speed c is redefined as the intrinsic propagation velocity of the 6D fluid medium. Because 4D observations are merely cross-sections of this global 6D state, the perceived speed remains constant regardless of the observer's relative 4D velocity. Single photon interference: The "interference" may be the self-interaction of the 6D manifold's geometry, which only appears as "divided" when viewed through restricted 4D window.

In 4D spacetime, the 6D light entity manifests in a state that is neither truly wave nor truly particle. Its observed interference patterns and discrete detection events are projections/sections

of its higher-dimensional fluid manifold. Conventional terms like "wave" and "particle" are only approximate descriptors, but do not capture the true 6D nature of light. This duality of "wave-like, particle-like" state is not a physical paradox but a geometric necessity, arising from the information compression and topological constraints imposed when a continuous 6D entity is mapped onto the restricted dimensions of observable reality. Consequently, quantization is interpreted not as an intrinsic fragmentation of the entity, but as a topological consequence of 6D-to-4D dimensional reduction.

The 6D light null entity differs fundamentally from Kaluza-Klein, Twistor, and conventional multi-dimensional light field approaches. In this framework, the additional dimensions correspond directly to intrinsic photon degrees of freedom-optical phase, polarization, frequency, and orientation along the null momentum generator-rather than to abstract spatial or complex coordinates. This construction defines a minimal, closed manifold that unifies all empirically established photon properties within a single coherent geometric structure.

By expanding the dimensionality of light to a minimal 6D manifold, we may bridge the gap between continuous field theory and discrete quantum mechanics in a geometric reinterpretation. The "quantum" is revealed not as a fundamental graininess of nature, but as a topological 2D reduction consequence of observing a 6D null entity from a 4D perspective. This reconstruction suggests that the four fundamental properties of light are intrinsically coupled within a higher-dimensional geometry, awaiting a unified mathematical description. Projecting a 6D light entity onto 4D spacetime is analogous to projecting a 3D helical spring onto a 1D line space with 2D reduction: most internal couplings/connectivity are sheared or averaged out, leaving only

residual information that manifests as tiny phase shifts or visibility perturbations, which become observable only under specific conditions such as path marking or weak measurement, making the experimental detection of 6D corrections in 4D a highly constrained task. A critical inquiry arises as to whether the two dimensions 'lost' of 6D light null entity in the 4D projection correspond to the non-commutativity of quantum operators, potentially revealing a direct geometric mapping between the intrinsic manifold's extra-degrees of freedom and the complex structure of Hilbert Space.

Experimental observations of mixed topologies in light, such as spin-orbit coupling, vector beams with spatially structured polarization, and knotted optical vortices (Hopfions) exhibiting nonzero Hopf invariants, strongly suggest that the photon's internal degrees of freedom are interwoven in a higher-dimensional manifold, providing compelling indirect evidences for the existence of a 6D light entity beyond conventional 4D spacetime. Hopfions are known topological solutions of the 4D Maxwell equations, yet the 6D light entity framework naturally explains why photons can carry such topological invariants during free propagation. As indirect evidence, the existence and stability of Hopfion topology indicate that the photon's internal degrees of freedom are far richer than predicted by standard Maxwell theory, and this stability is naturally accounted for within the 6D model. Fragmentary experimental evidence suggests the possible existence of a phase-polarization-frequency Hopf-type coupling in light. Observations such as frequency-dependent spin-orbit effects, wideband vector beams with subtle polarization-phase correlations, and structured optical frequency combs hint that these internal degrees of freedom may be interwoven in a topologically nontrivial way. While a direct measurement of the full Hopf linking across all three degrees of freedom has not yet been realized, these indications

point toward the potential presence of a higher-dimensional internal geometry consistent with the proposed 6D light entity.

What was previously dismissed as random, chaotic light/photon quantum dots is now revealed to be a highly structured information map of the 6D light entity. The distribution, spacing, and coupling of these dots encode reproducible features of the underlying higher-dimensional structure. This recognition constitutes a conceptual leap, transforming formerly overlooked fragments into a valuable spectral blueprint for probing the internal architecture of light. Much like discrete points on a 1D line can reveal the precise pitch and diameter of a 3D helix, the spatial intervals and coupling variances of these 4D fragments provide a structured mapping of high-dimensional dynamics. By decoding the distribution matrices of these formerly dismissed residues, we transition from observing random probability to reconstructing the 6D geometric reality, unlocking the precise cryptographic key to the internal architecture of light.

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 couplings (pairwise/triple) with other degree of freedom (DOF) have been experimentally observed in 4D, 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	DOF coupling experimentally observed ?
1 Null propagation speed c	Yes	Yes	No	Proper time, rest frame	Null base geometry (2D)	Yes
2 Absence of rest mass	Yes	Yes	No	Proper length, localization	Null constraint	-
3 Optical phase ϕ	Yes	No (requires time)	No	Discrete detection	Phase fiber (1D)	Yes

Light property	Empirically established	Defined intrinsically in 4D? (parameter)	Reducible from other properties?	Mutually incompatible with	Candidate intrinsic dimension	DOF coupling experimentally observed ?
4 Frequency ν	Yes	No (observer-dependent)	No	Null proper time	Frequency fiber (1D)	Yes
5 Polarization	Yes	Gauge-dependent	No	Scalar wave description	Polarization fiber (2D)	Yes
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	-
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	-

(Note: “-” mean not available or not detected.)

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.

Experimental manifestations of optical couplings- In conventional 4D theoretical frameworks, pairwise couplings among light’s degrees of freedom are naturally accounted for, such as

Experimental manifestations of optical couplings		
	Coupling	Experimental manifestation
Pairwise	Propagation – Polarization	Spin–orbit interaction of light/Spin Hall Effect of Light
	Propagation – Phase	Optical vortex / orbital angular momentum
	Propagation – Frequency	Spatiotemporal wave packets; Doppler/Gravitational Redshift
	Polarization – Phase	Pancharatnam–Berry phase
	Polarization – Frequency	Optical Activity Dispersion
	Phase – Frequency	Ultrafast pulse shaping/spectral phase; Chirped Pulses
Triple	Propagation – Polarization – Phase	Vector vortex beams; Geometric Phase Transport
	Propagation – Phase – Frequency	Spatiotemporal optical vortices; Chirped pulse propagation/ dispersion
	Propagation – Polarization – Frequency	Spatiospectral vector beams; Spin-dependent dispersion
	Polarization – Phase – Frequency	Ultrafast vector pulses/Ultrafast polarization dynamics

interactions between polarization, phase, propagation, and frequency. However, the observed four triple couplings present a challenge: within 4D space-time, three-way closed interactions cannot be generated self-consistently, and are often treated as high-order interference effects or phenomenological observations without an underlying geometric or topological justification. Consequently, traditional theories can describe pairwise interactions but lack an explanation for the origin and closure of triple couplings, nor can they account for the global self-consistency of the degrees of freedom. In contrast, the six-dimensional light entity, structured as a tetrahedral minimal closed network, naturally embeds both pairwise and triple couplings. Triple couplings emerge as unavoidable consequences of the higher-dimensional topology (**Table S1**), providing **Table S2. Experimental manifestations of optical couplings.** The experimental manifestations and observations in previous reports of the 6 pairwise couplings and 4 triple couplings are shown.

direct physical evidence for the six-dimensional structure. This framework not only explains why pairwise couplings manifest in 4D and triple couplings appear as their high-dimensional projections, but also establishes the six-dimensional entity as the minimal, self-consistent structure capable of preserving information with maximal stability and fidelity.

The six-dimensional light null entity is supported by six mutually consistent foundations:

- 1) logical dimensional necessity;
- 2) geometric minimality;
- 3) coupling self-consistency;
- 4) empirical consistency with experimentally observed multi-degree-of-freedom interactions;
- 5) Topological combinatorial constraint: the experimentally observed six pair couplings and four triple couplings uniquely determine the number of fundamental degrees of freedom through combinatorial topology: the relations $C(N,2)=6$ and $C(N,3)=4$ independently yield $N=4$ (the 4DOFs with 6 dimensions). This over-constrained agreement between topology, coupling structure, and experimental observations strongly supports the existence of a six-dimensional light null entity;
- 6) complete graph K_4 , the coupling structure of the four fundamental degrees of freedom forms a complete graph K_4 , equivalent to a tetrahedral 3-simplex. This structure naturally contains six pair relations and four triple relations, matching the experimentally observed coupling patterns. In geometric terms, the relational configuration of four objects is coordinatized by six independent parameters, consistent with the six-dimensional structure of the light entity. This correspondence suggests that the six-dimensional light null entity reflects an underlying relational geometric structure rather than an arbitrary extension of dimensionality.

Table S3. 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
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	4D Observation / Theory	Paradox / Incompatibility	6D Light Null Entity Interpretation
1	Quantum Electrodynamics (QED)	Vacuum fluctuations, wave-particle duality, photon self-energy divergences	2D reduction projection results in discreteness, dot-like behavior and quantum observations. 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.
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 degree of freedoms (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	Coherence / decoherence phenomena	Loss of phase information in standard 4D treatment	Phase and orientation as intrinsic 6D dimensions may 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 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.

The four intrinsic degrees of freedom of light form a tetrahedral K_4 coupling, establishing the minimal closed network for all pairwise and triple interactions. This 3-simplex naturally embeds in the six-dimensional manifold and maps onto CP^3 , where the symplectic structure governs their coupled dynamics. The tetrahedron thus provides a clear geometric representation of the internal 6D connectivity, while projections to 4D spacetime preserve key relational and topological features. In this way, the minimal 6D light null entity can be understood as a higher-dimensional geometric backbone whose structural and informational integrity is faithfully reflected in experimentally accessible 4D phenomena.