Metanalysis validates comprehensive two part photon

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A compact photon is believed to form sourced electromagnetic fields. Dissatisfaction elicits persistent search for a comprehensive model. Here, I develop and validate a two factor photon function uniting light's relativistic, electromagnetic and thermodynamic properties. A gauge function factor imparts localized behaviors. It carries the electromagnetic field as a vector amplitude to enable confirmed optical behaviors. These factors are shown to be empirically detected. Thermodynamic constraint defines a standard thermal photon. This standardization eases field quantization. The model reveals new photon behaviors.

Keywords: photon, light, relativity

Introduction

In a 1926 letter to Nature [1] , G. N. Lewis proposed the name "photon" for discrete units contributing to radiant energy transport. He postulated six properties accepted as describing an entity that conveys the electromagnetic force. This acceptance is illustrated in [2] where "photon" has over 460 occurrences. Optics [3] provides convincing evidence that photons have an electromagnetic wave nature. Geometric optics, photographic pixel resolution and point-wise diffraction pattern development [4] show that photons are localized in space and time. A recent review [5] describes attempts to unify this dual photon nature. The persistent effort to find a physical photon model reflects a concern that one compact representation is necessary to guide conflict resolution through experiment and theory refinement. To date, the effort has been unsuccessful [6, 7].

Subsequently, Lewis went on to suggest that photons exist as Minkowski world light lines where the indefinite metric has zero length. He proposed a crucial test in which photons were to be shown absent at destructive interference bands. His proposal was immediately refuted [8] so thoroughly that treating light's relativistic character was forsaken ever since. The refutation notes that photon paths connecting constructive interference bands pass through destructive interference bands. The refutation concludes with a heuristic dual action light concept heretofore unconsolidated. Here I develop and validate a photon model for which detector optimization reveals action duality. My photon incorporates light's relativistic, electromagnetic and thermodynamic properties in a compact function expression that facilitates electromagnetic field quantization.

The compact photon function has two electromagnetic factors. One factor is an electromagnetic gauge function. This wave equation function is explicitly localized to the propagation direction. Sec. 1 shows that it embodies the photon's relativistic character, and contributes particle-like behaviors, but no electromagnetic field. The electromagnetic field is borne by the wave equation function as a vector amplitude. Sec. 2.1 shows that with this amplitude factor the photon function can exhibit electromagnetic optical behaviors. Sec. 2.2 shows the photomultiplier and photodiode to be optimized for distinct photon function factor detection. Sec. 2.3 shows that thermodynamic restriction defines Planck Λ photons with standard amplitude peak field and volume. These can be applied to quantize fields and to study photon behaviors.

1 Photons in 4-space

Consider the Lorenz gauge function $\chi(\phi)$ for phase $\phi_\pm = r \pm at$. Fig. 1 shows the ϕ-axes are light lines in the photon 4-space. For rays confined to beams with a finite cross-section the Cartesian coordinates $(r\cos\alpha_1, r\cos\alpha_2, r\cos\alpha_3)$ define a ray direction with fixed direction cosines. With this stipulation $\chi(\phi)$ satisfies the homogeneous wave equation

$$\chi_{rr} - \chi_{tt}/a^2 = 0. \tag{1}$$

In equation (1) the subscripts denote partial differentiation and a is the wave speed. For constant ϕ, $\chi' = \chi_\mu d\mu = 0$ for summation over repeated indices $\mu \in \{r, t\}$ gives

$$\chi_t(\phi_\pm) = -\chi_r(\phi_\pm)\frac{dr}{dt} = \pm\chi_r(\phi_\pm)a. \tag{2}$$

Taking χ_r to be the photon momentum and χ_t to be the photon energy, equation (2) is an energy-momentum relation.

The phases are equation (1) characteristic variables for which the curves $\phi_+\phi_- = (r + at)(r - at)$ have invariant form when

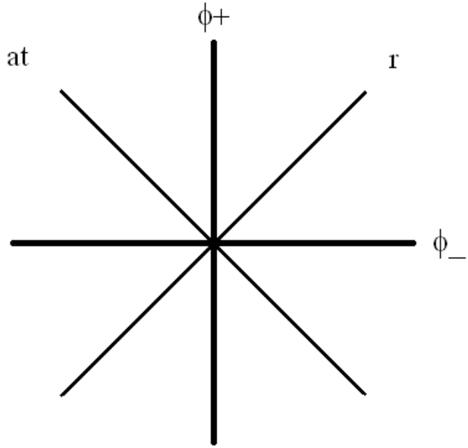

Figure 1. Photon 4-space. The gauge function characteristics $\phi_{\pm} = r \pm at$ are light lines in the generalized 4-space. These characteristics scale reciprocally by the relativistic Doppler factor. So, the $\phi_{+}\phi_{-}$ product is invariant when subjected to a Lorentz transformation.

subjected to the Lorentz transformation

$$\begin{aligned} r &= \gamma(r' - a\beta t'), \\ at &= \gamma(at' - \beta r') \end{aligned} \tag{3}$$

iff $\gamma^2(1 - \beta^2) = 1$. When subjected to the equation (3) transformation, the phases $\phi_{\pm}$ scale by the factor $\gamma(1 \pm \beta)$. If this scale factor is taken to be a Doppler factor, the phase states $\psi_{\pm} = 2\pi\phi_{\pm}/\lambda_{\pm}$ are Lorentz invariant when $\lambda_{\pm} = a/\nu$ is a relative rest wavelength that scales with the Doppler factor for the corresponding $\phi_\pm$. With this Doppler designation, $v = a\beta$ represents a relative speed between two coordinate frames originating on the ray described by r.

These results are illustrated for the representative wave equation function

$$\chi(\psi_\pm) = \pm(\hbar/2\pi)[\sin\psi_\pm + \psi_\pm] \tag{4}$$

where $\hbar$ is the Planck constant h over 2π. Equation (4) has been normalized to have energy $h\nu$ when integrated over the $\psi_\pm$ interval $[-\pi, \pi]$. The equation (4) term linear in $\psi_\pm$ prevents the spatial and temporal dependencies from being assigned to separate factors. It also numerically distinguishes $\chi(\psi_\pm)$ with different $\psi_\pm$ values, but gives

$$\begin{aligned} \chi_t &= \hbar\nu[\cos\psi_\pm + 1], \\ \chi_r &= \pm(\hbar\nu/a)[\cos\psi_\pm + 1]. \end{aligned} \tag{5}$$

Equations (5) satisfy equation (2).

1.1 Quantization Even though the equation (4) energy is $h\nu$ when integrated over one full $\psi_\pm$ phase state period, the energy is not quantized in the sense that only discrete energy values are allowed. When, however, equation (4) photons are cavity confined, only those satisfying specific geometry dependent conditions are self-sustaining. If these must have zero energy at the cavity boundary no energy will be lost there. For a spherical cavity with radius R, the photons are self-sustaining for $\psi_+(L,t) = (2m_+ + 1)\pi$ and $\psi_-(L,t) = (2m_- + 1)\pi$ where m_+ and m_- are integers and L denotes the cavity boundary at R or $-R$. If these conditions are satisfied instantaneously by the incoming wave and its outgoing specular reflection at the boundary the time can be eliminated from the phases. This yields

$\lambda_n = 2R/n$ or $\nu_n = na/2R$ where $n = m_+ + m_- + 1$. Since the phase state periods can be numbered independently, $n \geq 0$ assures $\nu_n \geq 0$. The cavity states for equation (4) photons have an $n = 0$ ground state with zero energy. Like quantum harmonic oscillators, however, the cavity states exhibit a fixed $h\nu_1 = ha/2R$ energy change between successive states. As $R \to \infty$, $h\nu_1 \to 0$ and state spectrum becomes a continuum.

1.2 Spin Fig. 1 shows that in scattering at the coordinate origin an incoming wave with phase ϕ_+ could emerge with unchanged phase or change to a wave with phase ϕ_-. Similarly, an incoming wave with phase ϕ_- could emerge with unchanged phase or change to a wave with phase ϕ_+. Equation (5) gives $2h\nu/a$ as the full wave period momentum change for such scattering. Multiplied by the wave speed a and divided by the angular frequency $2\pi\nu$ this becomes an angular momentum change. In 1931 Raman and Bhagavantam [9] developed selection rules for molecular spin transitions produced by scattered photons with spins having possible 2-state transitions like those just described for the photon phase. The authors used photographically determined intensities for scattered light to validate the selection rules and, thus, a spin for photons.

2 Photon Behaviors

Since no transverse fields can be obtained from equations (5) as gauge potentials, the equation (4) photon wave equation function must be augmented to exhibit electromagnetic behaviors. For this, we are guided by well established observations.

2.1 Deflection When light is directed at a plane interface between to dielectrics, some is reflected and the balance trans-

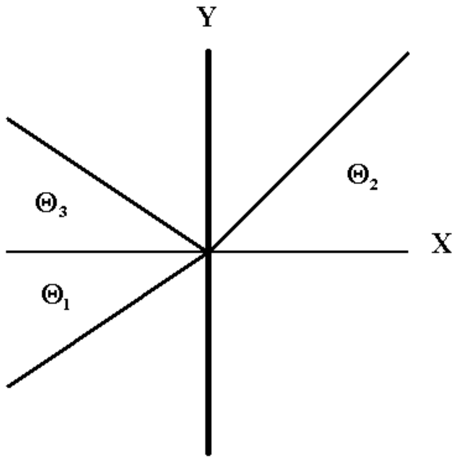

Figure 2. Photon refraction. Photons in a medium with wave speed a_1 reflect from and propagate through an interface with another medium in which the wave speed is a_2.

mitted. For the scheme shown in Fig. 2, the angles specifying the ray directions satisfy the Snell refraction law

$$\frac{\sin\Theta_1}{a_1} = \frac{\sin\Theta_3}{a_1} = \frac{\sin\Theta_2}{a_2}. \tag{6}$$

Multiplying through by $h\nu$ gives an expression that equates photon momentum components in the interface.

Wave amplitudes must satisfy boundary conditions at the interface. In optics the amplitude relations are given by the Fresnel formulas [3]. Attaching these amplitudes to the equa-

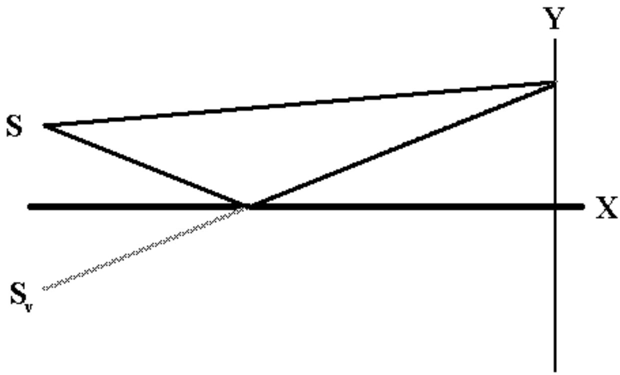

Figure 3. Photon diffraction. Lloyd's mirror configuration in which light from a point source S interferes with light from its virtual image in the x-axis mirror plane. The path length difference for the two rays in the figure is $D = 2dy/L$ when the source distance d and viewing screen intersection y above the mirror are much smaller than the x-axis distance from source to screen L. This contributes $\delta = 2\pi D/\lambda$ to the phase difference at the viewing point.

tion (4) photon wave equation function then attributes all optics behaviors to photons. These include the Brewster law for polarizing angle, expressions for reflecting power, total reflection with π phase change at grazing incidence and interference. The Lloyd's mirror configuration shown in Fig. 3 illustrates these behaviors. Except for the electromagnetic field reversal at grazing incidence, a z-axis line source at S near the mirror plane would be analogous to the Thomas Young double-slit experiment. Intensity at the viewing point can be taken to be that corroborated in [10] for 560 nm synchrotron radiation. The first order fringe has an intensity nearly four times that observed with the mirror removed. Higher order fringes fade to a background intensity twice the no mirror intensity. These suggest two photon interference. High order fade is expected for finite length photons. For these, temporal overlap decreases as the direct and reflected path lengths diverge with increasing fringe order. Also, photons polarized in the plane containing the incident and reflected rays will exhibit enhanced fade attributable to electric field divergence. For the experiment these effects are included in an effective beam cross-section, but the synchrotron results indicate that photon behaviors may be extractable from many photon beams.

2.2 Detection Since the photon function's vector amplitude is associated with a phase that designates location on the Poynting vector, it is appropriate to associate the wave equation function phase state with location on a vector for spatially positioning the Poynting vector. Since these spatial vectors are independent, their associated phases will be independent as well. Conceptually, then, the relation between the wave equation function and its electromagnetic field amplitude should be taken as physically associative rather than numerically multiplicative. In the extreme cases where one phase is held constant while the other runs freely, phase independence imparts duality to the photon function. However, photon pairs interact only when they are spatially coincident and have equal phase state values.

The equation (4) wave equation function's electromagnetic field amplitude and its equation (5) particle-like energy and momentum reflect qualitatively distinct physical behaviors for which detectors are optimized. In [4] the simultaneous Mach-Zehnder interferometer output signals from a photodiode and photomultiplier for a green laser pointer source are presented. Signals are detected in parallel planes. With the path length in one interferometer arm altered periodically using a piezotransducer-mounted mirror, both detectors exhibit synchronized, periodic signal modulation above unspecified base values. The photomultiplier signal interference-like modulation corroborates the equation (4) wave equation function wave nature. Its correspondence with the photodiode signal shows factor wavelength equality. Furthermore, the observed synchrony implies some phase locking between photon factors that is most likely light source dependent. An appropriately placed retarder should allow interplane synchrony offset.

Because prior classical photon models fail to describe the photomultiplier particle-like response with a wave-like interference character, attempts have been made to treat photons using quantum mechanics which successfully treats duality for massive particles. The effort does not work well for massless photons. A token interference-like response does result, however, if the photomultiplier detection probability is proportional to the time average energy imparted by photons from the two interferometer paths. For photons with the equation (5) energy function, this average energy is greatest when the photons arrive simultaneously but decreases as arrival delay increases. This result shows that a valid photon model can suggest plausible explanations that would otherwise escape discovery.

2.3 Radiation In applying the equation (4) photon wave equation function to describe photon emergence from sourced fields, we must address two complementary problems:

- What field amplitude is carried by a photon function? and
- What photon spectrum is associated with a field point?

To address the first problem, consider linearly polarized photons with wavelength Λ. The field amplitude E_Λ is found by equating the time average flux $c\epsilon_0 E_\Lambda^2/2$, ϵ_0 being the electric constant, and vacuum light speed c times the energy density. For a photon with effective volume V_Λ at wavelength Λ this gives

$$E_\Lambda^2 = 2(hc/\Lambda)/(\epsilon_0 V_\Lambda) \tag{7}$$

where h is the Planck constant. The Planck law at absolute temperature T has a universal form described by the dimensionless parameter $u = h\nu/kT$ where k is the Boltzmann constant. When divided by u to remove the photon energy, the Planck law spectral flux has a maximum value at

$$u_\Lambda = 1.59 = hc/(kT\Lambda). \tag{8}$$

Although suggestively close to the classical average kinetic energy factor for a noninteractive particle system, the numerical value for u_Λ is illusory. If state occupation were Maxwellian, the value would be 2. The spectral flux, itself, has the value $0.159\sigma T^4$ at u_Λ where σ is the Stefan-Boltzmann constant. If the Planck law is applied to single photons, this spectral flux defines an effective single Planck Λ photon volume given by

$$V_\Lambda = c(hc/\Lambda)/(0.159\sigma T^4) = 0.976\Lambda^3. \tag{9}$$

This implicitly equates the wavelengths for photon amplitude and wave equation function. Values for these properties are presented in Table 1 for Λ values that include the visible range.

The values for E_Λ and V_Λ defined by equations (7) and (9) are value standards for thermal photons from a blackbody at

Table 1. Linearly polarized Planck Λ photon properties.
(ν_Λ- frequency; Λ - wavelength; E_Λ - peak electric field; V_Λ - volume)

hν_Λ	Λ	E_Λ	V_Λ
eV	nm	V/μm	μm^3
8.	155	8.91	0.004
4.	310	2.23	0.029
2.	620	0.56	0.233
1.	1240	0.14	1.87
0.5	2480	0.03	14.9

temperature T given by equation (8). With such standards it is now possible to study how photons with other wavelengths at T compare with the standard or how photons at other T values compare with the standard. The model allows such questions to be considered for empirical evaluation based on the properties presented in the table. These are consistent with field strength and effective volume required for photon-like behavior for visible wavelengths. In particular the field at 2 eV produces a potential insufficient to ionize a 1 Å diameter atom and yet the effective volume allows observed spatial resolution. Recent measurements [11] using copropagating laser beams have allowed the transverse electric fields to be determined for a few cycle, linearly polarized laser light pulse. The field was reconstructed from measured kinetic energy spectra for electrons detached from neon atoms ($E_I = 21.6$ eV) by a copropagating XUV (93 eV) burst. Together, the above equations predict that $\sim 2 \times 10^4$ photons would be required for the $\sim 7 \times 10^7$ V/cm field found at 750 nm. These equations also predict that the XUV photons do not carry an electric field sufficiently large to produce the observed photoionization. These results clearly demonstrate that photons exhibit two qualitatively different interaction modes with matter. The amplitude interacts electromagnetically; the wave equation function interacts energetically. Importantly, as wavelength increases the energy density decreases and the photon becomes more purely electromagnetic.

The measured frequency spectrum for which the transverse electric field was measured suggests field quantization may be a possible solution to our second problem. For this the coefficient at each frequency in the electric field spectral function at a particular space point is replaced with sufficient photons to provide that frequency's electric field. When two photons have the same equation (4) wave equation function, each will transport an $h\nu$ energy quanta in a full wave period and the composite will behave as a photon pair with twice the energy. But the composite may be a subtle recombination. For example the photons $\mathbf{E}_x \mid \psi_+ >$ and $\mathbf{E}_y \mid \psi_+ >$ could combine to give

$$\mathbf{E}_x \mid \psi_+ > + \mathbf{E}_y \mid \psi_+ > \stackrel{?}{\Longleftrightarrow} = 2\mathbf{E}_{xy} \mid \psi_+ > \tag{10}$$

where $\mathbf{E}_x$, $\mathbf{E}_y$ and $\mathbf{E}_{xy}$ have the equation (7) magnitude in the $\mathbf{x}$, $\mathbf{y}$ and $\mathbf{x} + \mathbf{y}$ coordinate directions. The photons in this equation conserve number and energy. But, because equation (7) amplitude quantization invalidates the distributive law, the two forms give different light intensity contributions. Since light intensity is proportional to the time average squared electric field, the left-hand side light intensity contribution is proportional to the photon number while the right-hand contribution is proportional to the photon number squared. Another important example describes conversion between two paired linearly polarized photons and two circularly polarized photons. If either polarization is not primitive, it could only be observed to react with the energy borne by a pair. Such behavior reality can only be verified by experiment. If these effects are real, however, they will add stocasticity to quantized fields.

Conclusion

Sourced electromagnetic fields can be quantized by a two factor photon function with the 1926 Lewis properties. Relativistic properties are determined by a gauge function factor dependent on a 2-state phase. Electromagnetic fields are conveyed by the amplitude factor. Laboratory condition thermodynamics allows Planck Λ photon volume and peak electric field to be defined for field quantization. This quantitative unification localized in energy, momentum, space and time is behaviorally valid. Furthermore, the compound function provides for photon duality: when the wave equation phase state is constant photon behavior is characterized by the electromagnetic field amplitude; when the electromagnetic amplitude is constant photon behavior is characterized by the wave equation function phase state. Our detectors are optimized to separate these photon behaviors. This duality allows photon intensity to vanish without photon destruction and allows electromagnetic fields to be formed from photons with quantized amplitudes.

The model can guide future study. The presentation suggests that linear polarization primitivity, photon polarization state interconversion and association with phase state, transition to intensities where the Malus cosine-squared law applies, phase state dependence on relative speed and Planck law dependence on pressure be examined experimentally. High priority should be given to determining whether linear and circular polarizations are single photon states or only higher energy paired photon states. The model is open to spherical coordinate extension for cosmic distances.

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