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Wave-Particle Properties and Pair Formation of the Photon.

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Abstract. Models of an individual photon having joint wave-particle properties, needle-like geometry, and spin cannot be based on conventional theory, but be deduced in terms of a revised quantum electrodynamic approach. In this paper the latter is applied to two-slit configurations and electron-positron pair formation: (a) Two-slit experiments performed earlier by Tsuchiya et al. and recently by Afshar et al. demonstrate the joint wave-particle properties of the individual photon, and agree with Einstein's argument against Complementarity. The present theory is consistent with these results. (b) The elementary electron-positron pair formation process is considered, with special attention to the involved orbits, conservation of energy, spin, and electric charge. The obtained model appears to be consistent with the process in which the created electron and positron move along two rays and have original directions along the path of the incoming photon. The nonzero electric field divergence of the theory is associated with an intrinsic local electric charge density. This may explain that the photon can decay on account of the impact from an external electric field.

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Ever since the earlier epoch of natural science, the nature of light has appeared as somewhat of an enigma. This also concerns the wave-particle duality and the electron-positron pair formation. In Bohr's principle of Complementarity, the wave-particle duality of the photon has been a cornerstone in the interpretation of quantum mechanics. Thereby the wavelike and particlelike properties are conceived to be complementary, in the sense that they are mutually exclusive, and no experiment can reveal both at once. This formulation is widely accepted by physicists, but it is full of apparent paradoxes which made Einstein deeply uncomfortable [1]. During the latest decades, additional investigations have been made among which the two-slit experiments by Tsuchiya et al. [2] and by Afshar et al. [3] deserve attention. These investigations verify a joint wave-particle duality, in agreement with Einstein's argument against Complementarity.

In the earliest phase of the expanding universe, the latter is imagined to be radiation-dominated. In the course of the expansion the "free" states of highly energetic electromagnetic radiation will at least in a number of cases become "condensed" into "bound" states of matter as determined by Einstein's energy relation.

In this paper the results by Tsuchiya et al. and by Afshar et al. as well as those of electron-positron pair formation will be compared to a revised quantum electrodynamic theory by the author. The latter is based on a vacuum state that includes electromagnetic quantum fluctuations and this supports the introduction of an electric charge density and an associated nonzero electric field divergence which leads to an additional degree of freedom, as compared to the conventional theory. A short description of the theory will be presented, whereas its detailed deductions are given elsewhere [4, 5, 6].

TWO-SLIT EXPERIMENTS

A photon-counting imaging system has earlier been elaborated by Tsuchiya et al. [2]. Two slits of size $50\,\mu\text{m}\times 4$ mm at a spacing of $250\,\mu\text{m}$ were arranged to pass light through an interference filter at a wavelength of 253.7 nm. The full size of the image on the monitor screen was 11.4 mm. Since the purpose was to demonstrate the interference of a single photon, the spacing of individual photons was much longer than their coherence time. For this reason, filters were used to realize a very low light level, with counting rates of 100 per second. As the measurements started, small dots appeared at random positions on the monitor screen. After 10 seconds had elapsed, a photon-counting image was seen containing 10^3 events, but its overall shape was not defined. After 10 minutes, however, the total counts were 6×10^4, and an interference pattern formed by the dots was detected. The diameter of each dot was of the order of 6×10^{-3} of the screen size, and the fringe distance about 5×10^{-2} of it. As concluded by Tsuchiya et al., these results cannot be explained by mutually exclusive wave and particle descriptions, but give clear indication of the wave-particle duality of the individual photon [2].

These results appear not to have attracted the interest they deserve. However, later Afshar et al. [3] conducted an experiment based on a different methodology but with a similar outcome. In this investigation there was a simultaneous determination of the wave and particle aspects in a "welcher-weg" experiment, beyond the limitations of Complementarity. The experiment included a pair of pinholes with diameters of $40\,\mu\text{m}$ and center-to-center separation of $250\,\mu\text{m}$, with light from a laser of wavelength 638 nm. These values were not too far from those of the experiments by Tsuchiya et al. In addition, six thin wires of $127\,\mu\text{m}$ diameter were placed at a distance of 0.55m from the pinholes, and at the minima of the interference pattern. When this pattern was present, the disturbance to the incoming beam by the wire grid was minimal, but when the interference pattern was absent, the grid obstructed the beam. Also this investigation was conducted in the low photon flux regime. When the flux was 3×10^4 photons per second, the separation between successive photons was about 10 km. The experiments were performed in four ways, i.e. with both pinholes open in absence of the wire grid, with both pinholes open in presence of the wire grid, and with either pinhole open in presence of the wire grid. The which-way information indicates through which pinhole the particlelike photon has passed. At the same time the wavelike photon must have *sampled* both pinholes so that an interference pattern could be formed. Consequently, also these experimental results force us to agree with Einstein's argument against Complimentarity [3].

PAIR FORMATION

The pair formation has for a long time both been studied experimentally [7] and been subject to theoretical analysis [8]. When a high-energy photon passes the field of an atomic nucleus or that of an electron, it becomes converted into an electron and a positron. The orbits of these created particles form two rays which start within a very small volume and have original directions along the path of the incoming photon.

SHORTCOMINGS OF CONVENTIONAL THEORY

In conventional quantum electrodynamics (QED), Maxwell's equations have served as a basis when there is a vacuum state with a vanishing charge density and electric field divergence [9]. According to Schiff [9] and Heitler [8] the Poynting vector defines the momentum of the radiation field. As pointed out by Feynman [10], there are nevertheless unsolved problems which lead to difficulties with Maxwell's equations that are not removed by and not directly associated with quantum mechanics. Consequently, QED will also become subject to shortcomings of the conventional field theory. For a model of the individual photon, we start with the following physical requirements. First, the model should have the form of a wave or wave packet of preserved and limited geometrical shape, propagating with undamped motion in a defined direction. This leads to an analysis in a cylindrical frame (r, φ, z) with z in the direction of propagation. Second, the solutions should extend all over space, and no artificial boundaries have to be introduced. Third, the total field energy should remain finite. Fourth, the solutions should result in an angular momentum (spin). An important concept is the momentum density

$$\mathbf{g} = \varepsilon_0 \mathbf{E} \times \mathbf{B} = \mathbf{S}/c^2 \tag{1}$$

where $\mathbf{S}$ is the Poynting vector. Maxwell's equations yield solutions for any field quantity $\hat{Q}(r)\exp[i(-\omega t + \bar{m}\varphi + kz)]$ where ω is the frequency and k and $\bar{m}$ are the wave numbers with respect to the z- and φ-directions. Here we introduce $K_0^2 = (\omega/c)^2 - k^2$. When $K_0^2 > 0$ the phase velocity becomes larger and the group velocity smaller than the velocity c of light. The general solution has field components in terms of Bessel functions $Z_{\bar{m}}(K_0 r)$, where the r-dependence [11] is of the form $Z_{\bar{m}}/r$ or $Z_{\bar{m}+1}$. Application of these solutions to a photon model leads to the following results:

- Already the purely axisymmetric case $\bar{m} = 0$ results in zero spin.
- The spin vanishes when $K_0 = 0$ and the phase and group velocities are equal to c.
- There is no clearly defined spatial limitation of the solutions.
- With no material boundaries, the total integrated field energy becomes divergent.

At a first glance a needle-like model of the photon may also be based on a spherical wave confined to a narrow cone near the axis $\theta = 0$ of a spherical frame (r, θ, φ). According to Stratton [11] spherical waves propagate in the radial direction at the velocity $c = \omega/k$ with k as a wave number and ω as the frequency. They include radial Bessel functions $z_n(kr)$ and associated Legendre functions $P_n^{\bar{m}}(\cos\theta)$. The dependence on φ is given by the form $\sin\bar{m}\varphi$ or $\cos\bar{m}\varphi$. Such a model suffers from difficulties:

- When propagating in the radial direction, the body of the photon field would increase its cross-section in proportion to r. Its apparition then becomes diffuse at large distances, and this contradicts the observations of propagating light.
- At increasing distances r the propagating wave configuration turns into a distant-field geometry. The latter has only transverse components and no spin.
- Only the near-field geometry can possess a component $g_\varphi \propto \bar{m}(\sin\bar{m}\varphi)(\cos\bar{m}\varphi)$ in the φ-direction. However, there is no such component in an axisymmetric state where $\bar{m} = 0$, and when $\bar{m} \neq 0$ in a screw-shaped state the integral with respect to

φ vanishes. This agrees with conservation of angular momentum, because there would otherwise exist momentum in the near-field which disappears when the configuration propagates into a distant-field state without spin.

In the case of a massive particle, the total (integrated) quantized momentum has been successfully represented by the operator $\mathbf{p} = -i\hbar\nabla$ in the Schrödinger equation. For cylindrical waves, this leads to a relevant photon momentum $p_z = \hbar k$ in the direction of propagation. In other directions, however, the concept $\mathbf{p}$ results in unclear questions as compared to the concept $\mathbf{g}$. First, a configuration of limited transverse cross-section results in a component p_r which would give rise to large transverse losses of momentum. Second, in a axisymmetric case p_φ vanishes, but not necessarily g_φ. Third, conventional theory yields the axial momentum $p_z = h\nu/c$ of a photon having the energy $h\nu$. If the same photon would have an additional momentum in the φ-direction due to its spin, the total local velocity within the configuration would become superluminal.

For spherical waves the concept $\mathbf{p}$ likewise leads to unclear questions. First, for the component p_r there would arise a radial momentum which varies with r and cannot become equal to the constant value $\hbar k$. Second, with $p_\varphi = -i\hbar(1/r\sin\theta)(\partial/\partial\varphi)$ there is a total spin which depends on r and θ, having no counterpart in the result from g_φ. Third, from p_θ there would arise a transverse momentum directed out of a cone defined by a constant θ, and this would cause transverse losses.

REVISED QUANTUM ELECTRODYNAMICS

An extended electromagnetic theory applied to the vacuum state and aiming beyond Maxwell's equations serves as a guiding line and basis of the present theoretical approach [4, 5, 6]. In four-dimensional representation the theory has the form

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) A_\mu = \mu_0 J_\mu \qquad \mu = 1,2,3,4 \tag{2}$$

where A_μ are electromagnetic potentials and the four-current density

$$J_\mu = (\mathbf{j}, \mathrm{i}c\bar{\rho}) = \varepsilon_0(\operatorname{div}\mathbf{E})(\mathbf{C}, \mathrm{i}c) \qquad \mathbf{C}^2 = c^2 \tag{3}$$

with c as the velocity of light, $\mathbf{E}$ denoting the electric field, and $\mathbf{B} = \operatorname{curl}\mathbf{A}$ is the magnetic field derived from the vector potential $\mathbf{A}$. The revised field equations are

$$\operatorname{curl}\mathbf{B}/\mu_0 = \varepsilon_0(\operatorname{div}\mathbf{E})\mathbf{C} + \varepsilon_0\partial\mathbf{E}/\partial t \tag{4}$$

$$\operatorname{curl}\mathbf{E} = -\partial\mathbf{B}/\partial t \tag{5}$$

and $\operatorname{div}\mathbf{E} = \bar{\rho}/\varepsilon_0$ where $\bar{\rho}$ is the charge density. Equations (4) and (5) yield

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right)\mathbf{E} + \left(c^2\nabla + \mathbf{C}\frac{\partial}{\partial t}\right)(\operatorname{div}\mathbf{E}) = 0 \tag{6}$$

for the electric field. The characteristic features of equations (4)–(6) are as follows:

- The theory is based on the radiation field, including an electric charge density.

- The associated electric field divergence introduces an additional degree of freedom, leading to new phenomena, also in situations where it appears to be small.
- The theory is both Lorentz and gauge invariant.
- The velocity of light is no longer a scalar c but a vector **C** with the modulus c.

The presence of the conventional dielectric constant ε_0 and magnetic permeability μ_0 of an empty space may require further explanation. It has earlier been stated that a screening effect of virtual electron-positron pairs reduces a charge such that electrostatic force would vanish at large distances [12, 13]. There are, however, arguments for such a screening not to be important. First, according to Heisenberg's uncertainty relation, the vacuum fluctuations appear spontaneously, shortly, and independently of each other. They can hardly have a systematic screening influence such as that due to the Debye effect in a plasma. Second, static measurements of the dielectric constant and magnetic permeablility result in a product which is equal to the inverted square of the velocity of propagating light. Third, in the vacuum the electron, as well as any charged object, are observed to carry their full external electrostatic fields. Likewise a current-carrying conductor is observed to generate its full external magnetostatic field.

The theory has finally to be quantized. The quantized field equations are generally equivalent to the original equations in which all quantities are replaced by their expectation values [8]. As a first step, the general solutions will be determined, and relevant quantum conditions are imposed afterwards. The present theory may therefore represent the most probable states in a first approximation to a rigorous deduction.

BASIC EQUATIONS OF A PHOTON MODEL

The theory of equations (3)–(6) is now applied to the model of an individual photon in the axisymmetric case where $\partial/\partial\varphi = 0$ in a cylindrical frame (r, φ, z). Screw-shaped modes where $\partial/\partial\varphi \neq 0$ end in several respects up with similar results, but become more involved [5, 6]. The velocity vector of equation (3) is given by $\mathbf{C} = c(0, \cos\alpha, \sin\alpha)$ where α is a constant angle, and $\cos\alpha$ and $\sin\alpha$ could have either sign but are here limited to positive values. This form implies that the energy has one part which propagates in the z-direction, and one part which circulates in the φ-direction and becomes associated with the spin. Normal modes with $\bar{m} = 0$ result in solutions for **E** and **B** in terms of differential expressions of a generating function

$$F = G_0 R(\rho) \exp[\mathrm{i}(-\omega t + kz)] = G_0 \cdot G = E_z + (\cot\alpha) E_\varphi \tag{7}$$

Here G_0 is an amplitude factor, $\rho = r/r_0$, and r_0 represents a characteristic radius of the geometrical configuration. The corresponding dispersion relation becomes $\omega = k\mathrm{v}$ with $\mathrm{v} = c(\sin\alpha)$ thus resulting in phase and group velocities $\mathrm{v} < c$. Not to get into conflict with the experiments by Michelson and Morley, the condition $0 < \cos\alpha \ll 1$ has to be imposed. As an example, $\cos\alpha \leqslant 10^{-4}$ would make the velocity v differ from c by less than the eight decimal in the value of c. Even if the electric field divergence appears to be small, it will still have a profound effect on the physics of a photon model. The obtained normal modes are superimposed to form a wave-packet for which k_0 and $\lambda_0 = 2\pi/k_0 = c/\nu_0$ are the main wave number and wave length, and $2z_0$ represents the length of the packet. According to observations, the packet must have a narrow line width, as expressed by $k_0 z_0 \gg 1$. The spectral averages of the field components in the case $|\cos\alpha| \ll 1$ are then given in terms of $\bar{z} = z - c(\sin\alpha)$. Choosing the real part of the normalized function G which is symmetric with respect to the axial centre $\bar{z} = 0$, the components $(\bar{E}_\varphi, \bar{E}_z, \bar{B}_r)$ become symmetric and the components $(\bar{E}_r, \bar{B}_\varphi, \bar{B}_z)$ antisymmetric with respect to the same centre. Then the integrated electric charge and magnetic moment vanish. The equivalent total mass defined by the electromagnetic energy and the energy relation by Einstein becomes on the other hand

$$m \cong 2\pi(\varepsilon_0/c^2) r_0^2 W_m e_0^2 \int_{-\infty}^{+\infty} f^2 d\bar{z} = h/\lambda_0 c \qquad W_m = \int \rho R_5^2 \, d\rho \tag{8}$$

where

$$f = [\sin(k_0\bar{z})] \exp\left[-(\bar{z}/2z_0)^2\right] \tag{9}$$

$$e_0 = g_0\sqrt{\pi}/k_0^2 r_0 z_0 \qquad G_0 = g_0(\cos\alpha)^2 \tag{10}$$

$$R_5 = \frac{d}{d\rho}\left(R - \rho^2 D_\rho R\right) \qquad R_8 = \left(\frac{d}{d\rho} + \frac{1}{\rho}\right)\rho^2 D_\rho R \tag{11}$$

with $D_\rho = \frac{d^2}{d\rho^2} + \frac{1}{\rho}\frac{d}{d\rho}$. Finally the integrated angular momentum is given by

$$s \cong 2\pi(\varepsilon_0/c)(\cos\alpha) r_0^3 W_s e_0^2 \int_{-\infty}^{+\infty} f^2 d\bar{z} = h/2\pi \qquad W_s = -\int \rho^2 R_5 R_8 \, d\rho\,. \tag{12}$$

Even if the total electric charge of the photon vanishes, there is on account of the nonzero electric field divergence a local nonzero electric charge density

$$\bar{\rho} = e_0 f(\varepsilon_0/r_0)(1/\rho)\frac{d}{d\rho}(\rho R_5)\,. \tag{13}$$

Due to the factor $\sin(k_0\bar{z})$ this density oscillates rapidly in the axial direction. Thus the charge distribution consists of two equally large positive and negative contributions.

To proceed further the form $R(\rho)$ has to be specified. There are two options, namely where this function is convergent or divergent at the origin $\rho = 0$. In the convergent case $R(\rho) = \rho^\gamma e^{-\rho}$ and $\gamma \gg 1$ is adopted and motivated elsewhere [4, 5, 6]. The forthcoming results turn out not to depend explicitly on γ, and the exponential factor does not appear in the end result but secures the convergence of any integrated moment with R. In the evaluation of expressions (8) and (12) for W_m and W_s the Euler integral appears. The dominant terms at large γ give the result $W_m = W_s/\gamma$. The function R further has a maximum at the effective radius $\hat{r} = \gamma r_0$ being sharply defined at large γ. Combination of equations (8) and (12) with the quantum conditions $mc^2 = h\nu_0$ and $s = h/2\pi$ for a photon having the spin of a boson then leads to an effective transverse diameter

$$2\hat{r} = \frac{\lambda_0}{\pi(\cos\alpha)}\,. \tag{14}$$

In the divergent case the form $R(\rho) = \rho^{-\gamma}e^{-\rho}$ and $\gamma \gg 1$ is adopted and motivated in a similar way. The dominant terms in the integrals (8) and (12) then result in

$$W_m = \int_{\rho_m}^{\infty} \rho R_5^2 \, d\rho = \frac{1}{2}\gamma^5 \rho_m^{-2\gamma} \tag{15}$$

$$W_s = \int_{\rho_s}^{\infty} \rho^2 R_5^2 \, d\rho = \frac{1}{2}\gamma^5 \rho_s^{-2\gamma+1} \tag{16}$$

where $\rho_m \ll 1$ and $\rho_s \ll 1$ are small radii at $\rho = 0$. To compensate for the divergence of W_m and W_s when ρ_m and ρ_s approach zero, we introduce the parameters $r_0 = c_r \cdot \varepsilon$ and $g_0 = c_g \cdot \varepsilon^\beta$ where c_r and c_g are positive constants and the dimensionless smallness parameter ε is defined by $0 < \varepsilon \ll 1$. Then expressions (8) and (12) result in

$$m = \pi^2(\varepsilon_0/c^2)\gamma^5(1/k_0^2 z_0)^2 c_g^2(\varepsilon^{2\beta}/\rho_m^{2\gamma})J_m = h/\lambda_0 c \tag{17}$$

$$s = \pi^2(\varepsilon_0/c)\gamma^5(1/k_0^2 z_0)^2 c_g^2 c_r(\cos\alpha)(\varepsilon^{2\beta+1}/\rho_s^{2\gamma-1})J_m = h/2\pi \tag{18}$$

with

$$J_m = \int_{-\infty}^{+\infty} f^2 d\bar{z} \cong z_0\sqrt{2\pi}\,. \tag{19}$$

Here we are free to choose $\beta = \gamma \gg 1$ which leads to $\rho_s \cong \rho_m = \varepsilon$. The lower limits ρ_m and ρ_s of the integrals (15) and (16) then decrease linearly with ε and the radius r_0. This forms a "similar" set of geometrical configurations, having a common shape independent of ρ_m, ρ_s, and ε in the range of small ε. Taking $\hat{r} = r_0$ as an effective radius, combination of relations (17) and (18) finally yields a photon diameter

$$2\hat{r} = \frac{\varepsilon\lambda_0}{\pi|\cos\alpha|}\,. \tag{20}$$

The individual photon model becomes strongly needle-shaped when $\varepsilon \leqslant |\cos\alpha|$.

APPLICATION ON TWO-SLIT EXPERIMENTS

The ranges in the two cases (14) and (20) can be estimated by assuming an upper limit of $2\hat{r}$ when equation (14) applies and $\cos\alpha = 10^{-4}$, and a lower limit of $2\hat{r}$ when $\varepsilon = \cos\alpha$ in equation (20). Then the effective diameter would be in the range $\lambda_0/\pi \leqslant 2\hat{r} \leqslant 10^4\lambda_0/\pi$, but the lower limit could even be lower when $\varepsilon < \cos\alpha$:

- The diameter of the dot-shaped marks by Tsuchiya et al. is of the order of 6×10^{-3} of the screen size, i.e. about 10^{-4} m. With the wave length $\lambda_0 = 253.7$ nm, the effective photon diameter would then be in the range of $7 \times 10^{-4} \geqslant 2\hat{r} \geqslant 7 \times 10^{-8}$ m. This covers the observed size of the dots.
- The width of the slits by Tsuchiya et al. is 5×10^{-5} m and their separation distance is 25×10^{-5} m. The pinhole diameters and center-to-center separation by Afshar et al. are 4×10^{-5} m and 25×10^{-5} m, respectively, and the wavelength is $\lambda = 638$

nm. In the latter experiments the diameter is estimated to $2 \times 10^{-7} \leqslant 2\hat{r} \leqslant 2 \times 10^{-3}$ m. In both experiments the ranges of $2\hat{r}$ thus cover the slit widths and separation distances.

- A large variation of a small $\cos\alpha$ has only a limited effect on the phase and group velocities. Also a variation of ε does not influence the deductions of the theory, even if it ends up with a change of the diameter. This leads to the somewhat speculative question whether the compound parameter $\varepsilon/\cos\alpha$ could adopt different values during propagation. This could be related to “photon oscillations” as proposed for a model with a nonzero rest mass, in analogy with neutrino oscillations [4, 5, 6].
- As compared to the slit widths and the separation distances, the obtained ranges of $2\hat{r}$ become consistent with the statement by Afshar et al. that the same wave-like photon can *sample* both pinholes to form an interference pattern.
- Interference between cylindrical waves should take place in a similar way as between plane waves. In particular, this becomes obvious at the minima of the interference pattern where full cancellation takes place.
- Due to the requirement of a narrow line width, the wave packet forms a very long and narrow wave train.
- Causality raises the question how the photon can “know” to form the interference pattern already when it passes the slits. An answer may be provided by the front part of the packet which may serve as a “precursor”, or by a counterpart to the precursor phenomenon earlier discussed by Stratton [11].

APPLICATION ON PAIR FORMATION

We now turn to the intrinsic electric charge distribution, representing an important but somewhat speculative part of the analysis. It concerns the process by which the configuration is broken up to form a pair of particles of opposite polarity. Thus it may be justified to investigate whether the total intrinsic charge of one polarity can become sufficient as compared to the charges of the created electron and positron. With the present strongly oscillating charge density in space, the total intrinsic charge of either polarity can be estimated from equations (9) and (13). This charge appears only within half of the axial extension, and its average value differs by the factor $2/\pi$ from the peak value of its sinusoidal variation. From equation (13) the intrinsic charge becomes

$$q = (z_0/\pi)\int_{\rho_q}^{\infty} 2\pi r(\bar{\rho}/f)dr = 2\sqrt{\pi} z_0 \varepsilon_0 \gamma^3 (1/k_0^2 z_0) c_g (\varepsilon^\beta/\rho_q^\gamma) \qquad (21)$$

where the last factor is equal to unity when $\beta = \gamma$, and the limit $\rho_q = \varepsilon$ for a similar set of configurations. Relations (21) and (8) then yield

$$q^2 = (8/\pi^3)\varepsilon_0 c^2 \gamma z_0 m = (8/\pi^3)\varepsilon_0 ch\gamma(z_0/\lambda_0) \cong 45 \times 10^{-38} \gamma(z_0/\lambda_0) \qquad (21)$$

and $q/e \cong 4.2(\gamma z_0/\lambda_0)^{1/2}$. With a large γ and a small line width the intrinsic charge substantially exceeds that of the particle pair. However, the question remains how much of the intrinsic charge becomes available during the disintegration.

There are three conservation laws in the pair formation process. The first concerns the total energy. Here we limit ourselves to the case where the kinetic energy of the particles can be neglected as compared to the energy of their rest masses. Conservation of total energy is expressed by $mc^2 = hc/\lambda_0 = 2m_e c^2$. Equation (12) yields a photon diameter

$$2\hat{r} = \frac{\varepsilon h}{2\pi m_e c|\cos\alpha|} \,. \tag{23}$$

With $\varepsilon \leqslant |\cos\alpha|$ we have $2\hat{r} \leqslant 3.9 \times 10^{-13}$ m being equal to the Compton wavelength and representing a clearly developed form of needle radiation. The second conservation law concerns the preservation of angular momentum. It is satisfied by the spin $h/2\pi$ of the photon as given by expression (18). This momentum becomes equal to the sum of the spin $h/4\pi$ of the created electron and positron. The third law deals with the preservation of charge. This condition is satisfied by the vanishing integrated photon charge, and by the opposite polarities of the created particles. In a more detailed picture where the photon disintegrates into charged particles, it could also be conceived as a splitting process of the electric charge distribution. Magnetic moment conservation is satisfied by having parallel angular momenta and opposite charges of the electron and positron, and by a vanishing magnetic moment of the photon [4, 5, 6].

The basis of the conservation laws is rather obvious, but it becomes nontrivial when comparing conventional quantum electrodynamics with the revised theory:

- The needle-like radiation of the present photon model is necessary for understanding the creation of an electron-positron pair which forms two rays that start within a small region, and which have original directions along the path of the incoming photon. Such needle radiation does not come out of conventional theory.
- The present revised theory leads to a nonzero spin, and is thus consistent with a photon as a boson which decays into two fermions.
- The nonzero divergence of the electric field allows for a local electric charge density. This may indicate how the intrinsic electric charges can form two charged particles of opposite polarity when the photon structure becomes disintegrated. Such a process is supported by the fact that the photon decays through the impact of the electric field from an atomic nucleus or an electron. This is unlikely to occur if the photon body remains electrically neutral at any point of its volume.
- The present approach has some similarity with the breaking of the stability of vacuum by a strong external electric field, as investigated by Fradkin et al. [14].

CONCLUSIONS

Conventional theory including Maxwell's equations in the vacuum is shown not to form a relevant basis for photon models in terms of plane, cylindrical or spherical electromagnetic modes. This also concerns twisted light beams reviewed by Battersby [15] and corkscrew-shaped radio waves investigated by Thidé et al. [16] which on the other hand are likely to start new important trends in communication and radio astronomy. For a photon model with spin, an extended theoretical basis is required, such as that of the present revised theory. Two applications have been discussed:

- The two-slit experiments by Tsuchiya et al. and Afshar et al. demonstrate the joint wave-particle properties of the photon, and agree with Einstein's argument against Complementarity. These experiments are not explainable by conventional theory, but the present theory appears to be reconcilable with their outcome.
- The same theory further leads to a wave-packet photon model with needle-radiation properties due to which the created electron-positron pair is expected to form two rays that start within a very small region and have original directions along the path of the incoming photon. The nonzero electric field divergence is associated with an intrinsic electric photon charge density which may account for the fact that the photon can decay under the impact of an external electric field.

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