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Investigation into the Photon's Structure

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Abstract

In the present paper we look at the structure of the photon from the point of view of electrodynamics using the generalized Maxwell equations. The reason for our analysis is that today the photon is viewed as a quantum of an electromagnetic field in the form of a harmonic transverse flat wave that travels through vacuum with the speed of light *c*. In this case the wave's front takes the form of an infinite plane. From a physical point of view such a concept, in our opinion, is not very convincing when it comes to representing a photon as a local particle. Indeed, such flat wave representation doesn't agree well with the theory of the photoelectric effect introduced by Einstein back in 1905. The photoelectric effect is the phenomenon of the release of the electron from a material under the influence of electromagnetic radiation. Using the laws of conversation of energy and momentum during the collision between a photon and an electron as two particles, Einstein was able to obtain the experimentally observed photoelectric effect that was not previously explainable using classical physics. In various nuclear reactions, the photon behaves like a particle that conforms to the conservation laws. Considering the above, we will show using the generalized Maxwell equations that the electromagnetic wave associated to the photon is not necessarily a flat one, but rather a cylindrical one.

Subject Areas

Particle Physics

Keywords

Generalized Maxwell Equations, Curvilinear Coordinates, Association of Electromagnetic Waves with Photons, Speed of Wave Propagation

1. Introduction

The concept of the photon was first introduced by Einstein in 1905 when he was explaining the photoelectric effect: the phenomenon of the release of the electron under the influence of electromagnetic radiation. By looking at the photoelectric effect as the collision of two particles: the photon and the electron, and using the laws of the conservation of energy and momentum he was able to explain the experimentally observed photoelectric effect.

On the other hand, today the photon is associated with a transverse flat electromagnetic field. Such a dualism doesn't seem very satisfying to us considering that from a physical point of view it's hard to imagine that the infinite plane (the wave's front) hits a point (the electron's position). That is, at the moment of the collision, it is as if the wave "collapses" into a point. Because of this, we attempt to clarify the situation using the generalized Maxwell equations introduced in [1].

We assume that for the description of the movement of a photon in a vacuum must satisfy Maxwell's equations:

$$\operatorname{rot}\boldsymbol{H} = \frac{1}{c}\cdot\frac{\partial \boldsymbol{E}}{\partial t},$$

$$\operatorname{rot}\boldsymbol{E} = -\frac{1}{c}\cdot\frac{\partial \boldsymbol{H}}{\partial t},$$

$$\operatorname{div}\boldsymbol{E} = 0,$$

$$\operatorname{div}\boldsymbol{H} = 0.$$

From the condition of the stability of a photon [1] it follows that

$$\boldsymbol{E}^2 - \boldsymbol{H}^2 = 0,\ \boldsymbol{EH} = 0\left(\boldsymbol{E}\perp\boldsymbol{H}\right),\ \text{or } \boldsymbol{\Psi}^2 = 0, \tag{1}$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are the vectors of the electric and magnetic fields respectively, and $\boldsymbol{\Psi} = \boldsymbol{E} + i\boldsymbol{H}$ [1]. For the harmonic oscillation $\mathrm{e}^{-i\omega t}$ the Maxwell equations take the form

$$\begin{aligned}\operatorname{rot}\boldsymbol{H} &= -ik\boldsymbol{E},\\ \operatorname{rot}\boldsymbol{E} &= ik\boldsymbol{H},\end{aligned} \tag{2}$$

where $k = \omega/c$ and c is the speed of light. The Maxwell equations in the Cartesian coordinate system have a simple solution in the form of a transverse flat wave traveling with the speed c along the axis z:

$$\begin{aligned}E_x &= A\mathrm{e}^{ikz},\ E_y = B\mathrm{e}^{ikz},\ E_z = 0,\\ H_y &= A\mathrm{e}^{ikz},\ H_x = -B\mathrm{e}^{ikz},\ H_z = 0,\end{aligned} \tag{3}$$

where A and B are constants. It's easy to see that the solution (3) satisfies the condition (1). We note that regarding this solution arise several questions:

1) Is this solution unique? That is, do there exist other electromagnetic waves that can be associated with the photon.

2) Are they always transverse?

3) Are their speeds necessarily the speed of light c?

Below we give, in our point of view, satisfactory answers to these questions which are based on the study of the generalized Maxwell equations [1] in curvilinear system of coordinates.

2. Basic Relations

The more general solutions to the system of Equations (2), other than the flat wave, can be obtained by writing the system (2) in curvilinear orthogonal coordinates ξ,η,ζ. In several cases [2] it's possible to express all 6 functions ($E_\xi, E_\eta, E_\zeta, H_\xi, H_\eta, H_\zeta$) using only two new functions U and V satisfying second order equations (the wave equations or an equation leading up to it). This is possible if Equations (2) allow solutions of the electric type (transverse magnetic wave: $E_\zeta \neq 0$, $H_\zeta = 0$) and magnetic type (transverse electric wave: $E_\zeta = 0$, $H_\zeta \neq 0$). The functions U and V uniquely determine fields of every such types in the case if the Lamé coefficients of the given coordinate systems ξ,η,ζ satisfy the following conditions [2]:

$$\begin{gathered} h_\zeta = 1,\ \frac{\partial}{\partial\zeta}\left(\frac{h_\xi}{h_\eta}\right) = 0, \\ \text{or } h_\xi = g_1(\xi,\eta)g(\zeta),\ h_\eta = g_2(\xi,\eta)g(\zeta),\ h_\zeta = 1. \end{gathered} \tag{4}$$

After performing a few transformations, it's possible to obtain the following equation for the function U:

$$\frac{\partial^2 U}{\partial\zeta^2} + \frac{1}{h_\xi h_\eta}\left[\frac{\partial}{\partial\xi}\left(\frac{h_\eta}{h_\xi}\frac{\partial U}{\partial\xi}\right) + \frac{\partial}{\partial\eta}\left(\frac{h_\xi}{h_\eta}\frac{\partial U}{\partial\eta}\right)\right] + k^2 U = 0, \tag{5}$$

which considering (4) turns into the wave equation:

$$\Delta U + k^2 U = 0, \tag{6}$$

where ΔU is the Laplacian:

$$\Delta U = \frac{1}{h_\xi h_\eta h_\zeta}\left\{\frac{\partial}{\partial\xi}\left(\frac{h_\eta h_\zeta}{h_\xi}\frac{\partial U}{\partial\xi}\right) + \frac{\partial}{\partial\eta}\left(\frac{h_\zeta h_\xi}{h_\eta}\frac{\partial U}{\partial\eta}\right) + \frac{\partial}{\partial\zeta}\left(\frac{h_\xi h_\eta}{h_\zeta}\frac{\partial U}{\partial\zeta}\right)\right\}. \tag{7}$$

After finding a solution to Equation (5), it's possible to construct a solution to Equations (2) of the electric type:

$$\begin{gathered} E_\xi = \frac{1}{h_\xi}\frac{\partial^2 U}{\partial\xi\partial\zeta},\ E_\eta = \frac{1}{h_\eta}\frac{\partial^2 U}{\partial\eta\partial\zeta},\ E_\zeta = \frac{\partial^2 U}{\partial\zeta^2} + k^2 U, \\ H_\xi = -\frac{ik}{h_\eta}\frac{\partial U}{\partial\eta},\ H_\eta = \frac{ik}{h_\xi}\frac{\partial U}{\partial\xi},\ H_\zeta = 0. \end{gathered} \tag{8}$$

The expression for the fields of the magnetic type are easily obtained from (8) considering that Equations (2) are invariant with respect to the transformations

$$H \to E,\ E \to H,\ k \to -k,$$

and therefore we have

$$\begin{gathered} E_\xi = \frac{ik}{h_\eta}\frac{\partial V}{\partial\eta},\ E_\eta = -\frac{ik}{h_\xi}\frac{\partial V}{\partial\xi},\ E_\zeta = 0, \\ H_\xi = \frac{1}{h_\xi}\frac{\partial^2 V}{\partial\xi\partial\zeta},\ H_\eta = \frac{1}{h_\eta}\frac{\partial^2 V}{\partial\eta\partial\zeta},\ H_\zeta = \frac{\partial^2 V}{\partial\zeta^2} + k^2 V, \end{gathered} \tag{9}$$

where V satisfies Equation (5). The general solution gives the superposition of the fields of the electric and magnetic types.

From the obtained solutions (8) and (9), it's evident that they cannot be associated with the photon because they don't satisfy the stability condition of a particle (1). If one writes a solution in the form of a wave:

$$U(\xi,\eta,\zeta)=\hat{U}(\xi,\eta)\mathrm{e}^{i\beta\zeta},$$

it's possible to satisfy the condition

$$\boldsymbol{EH}=0.$$

In order to satisfy the second condition

$$\boldsymbol{E}^2-\boldsymbol{H}^2=0,$$

it's necessary to set $\beta=k$. In this case, the wave Equation (6) turns into the Laplace's equation:

$$\Delta_{\perp}\hat{U}=0, \tag{6'}$$

where $\Delta_{\perp}$ is the transverse Laplacian. This way, the field relationships (8) and (9) simplify to

$$\begin{aligned} &E_{\xi}=\frac{ik}{h_{\xi}}\frac{\partial\hat{U}}{\partial\xi},\ E_{\eta}=\frac{ik}{h_{\eta}}\frac{\partial\hat{U}}{\partial\eta},\ E_{\zeta}=0,\\ &H_{\xi}=-\frac{ik}{h_{\eta}}\frac{\partial\hat{U}}{\partial\eta},\ H_{\eta}=\frac{ik}{h_{\xi}}\frac{\partial\hat{U}}{\partial\xi},\ H_{\zeta}=0. \end{aligned} \tag{10}$$

The wave of the magnetic type satisfies the following relationships:

$$\begin{aligned} &E_{\xi}=\frac{ik}{h_{\eta}}\frac{\partial\hat{V}}{\partial\eta},\ E_{\eta}=-\frac{ik}{h_{\xi}}\frac{\partial\hat{V}}{\partial\xi},\ E_{\zeta}=0,\\ &H_{\xi}=\frac{ik}{h_{\xi}}\frac{\partial\hat{V}}{\partial\xi},\ H_{\eta}=\frac{ik}{h_{\eta}}\frac{\partial\hat{V}}{\partial\eta},\ H_{\zeta}=0. \end{aligned} \tag{11}$$

From these solutions it follows that with a photon is associated a transverse wave that travels with the speed of light *c*.

The conditions (4) satisfies coordinates systems in which ζ has a Cartesian coordinate *z*, while ξ and η can be any curvilinear orthogonal coordinates: Cartesian ($\xi=x$, $\eta=y$), polar ($\xi=r$, $\eta=\varphi$), etc. From all possiblemathematical options, in our opinion from a physical point of view it makes sense that a photon is associated to a cylindrical wave (and not a flat one as it is believed today) that has a well-defined axis of propagation. Using transverse coordinates r and φ, we obtain $\hat{U}(r,\varphi)$ from Equation (6') for a symmetric wave (i.e. independent of φ) in the following equation

$$\frac{\mathrm{d}^2\hat{U}(r)}{\mathrm{d}r^2}+\frac{1}{r}\frac{\mathrm{d}\hat{U}(r)}{\mathrm{d}r}=0,$$

$$\hat{U}(r)=\hat{A}\ln r,\ \text{where } \hat{A} \text{ constant.}$$

While, for $\hat{V}(r)$, we get the analogous solution

$$\hat{V}(r)=\hat{B}\ln r,\ \text{where } \hat{B} \text{ constant.}$$

Using the formulas in (10) we obtain

$$\xi=r,\ \eta=\varphi,\ \zeta=z,\ h_{\xi}=1,\ h_{\varphi}=r,\ h_{z}=1,$$

and hence for a symmetric cylindrical wave of the electric type we get

$$E_r=\frac{\bar{A}}{r},\ E_{\varphi}=0,\ E_z=0,$$

$$H_r=0,\ H_{\varphi}=\frac{\bar{A}}{r},\ H_z=0,$$

where $\bar{A}=\hat{A}ik$. For the magnetic type we get

$$E_r=0,\ E_{\varphi}=-\frac{\bar{B}}{r},\ E_z=0,$$

$$H_r=\frac{\bar{B}}{r},\ H_{\varphi}=0,\ H_z=0,$$

where $\bar{B}=\hat{B}ik$. Their common solution, as a sum of two types of waves, has the form

$$E_r=\frac{\bar{A}}{r}\mathrm{e}^{ikz},\ E_{\varphi}=-\frac{\bar{B}}{r}\mathrm{e}^{ikz},\ E_z=0,$$

$$H_{\varphi}=\frac{\bar{A}}{r}\mathrm{e}^{ikz},\ H_r=\frac{\bar{B}}{r}\mathrm{e}^{ikz},\ H_z=0.$$

This solution to the cylindrical wave resembles the solution to the plane Equation (3) that can be obtained the same way using the above formulas in the Cartesian coordinate systems *x*, *y*, *z*. This way

$$h_{\xi}=h_{\eta}=h_{\zeta}=1,\ \hat{U}=Mx+Ny,\ \hat{V}=\bar{M}x+\bar{N}y,$$

where $M, N, \bar{M}$, and $\bar{N}$ are constants.

3. Note

The conclusions obtained above are based on the fact that the photon is a stable particle and its electromagnetic field satisfies the relations (1). For nonstable particles, the spectrum of the solution in β is not restricted by the condition $\beta=k$, but rather can be arbitrary. This seems to indicate that there can exist nonstable particles of various frequencies and velocities. If a fluctuation in a vacuum creates a particle is active for a time Δt and is large compared to the period of oscillation, that is $\Delta t\omega \gg 1$, then within a particular interval of time the above formulas hold.

The more interesting case, from our point of view, is when $\beta=0$ ($\beta=\omega/v$) or when with a fixed frequency ω the wave's speed $v\to\infty$. In this case, all derivatives with respect to ζ are equal to zero and the relations (6), (8), and (9) take the form

$$\Delta_{\perp}\hat{U}+k^2\hat{U}=0, \tag{6''}$$

$$\left.\begin{aligned} &E_\xi = 0,\ E_\eta = 0,\ E_\zeta = k^2\hat{U}, \\ &H_\xi = -\frac{ik}{h_\eta}\frac{\partial \hat{U}}{\partial \eta},\ H_\eta = \frac{ik}{h_\xi}\frac{\partial \hat{U}}{\partial \xi},\ H_\zeta = 0 \end{aligned}\right\} \text{Electric type} \tag{8'}$$

$$\left.\begin{aligned} &E_\xi = \frac{ik}{h_\eta}\frac{\partial \hat{V}}{\partial \eta},\ E_\eta = -\frac{ik}{h_\xi}\frac{\partial \hat{V}}{\partial \xi},\ E_\zeta = 0, \\ &H_\xi = 0,\ H_\eta = 0,\ H_\zeta = k^2\hat{V} \end{aligned}\right\} \text{Magnetic type} \tag{9'}$$

where $\hat{V}$ satisfies (6"). We see that in this case, unlike the photon, the wave has a longitudinal component and is not a transverse one.

Using, as for the photon above, the coordinates r and φ, the solution to Equations (6") for a symmetric wave is expressed using the Bessel functions $J_0(x)$ and $N_0(x)$ ($x = kr$) [2],

$$J_0(x) \to 1 \text{ when } x \to 0,\quad J_0(x) \sim \sqrt{\frac{2}{\pi x}}\cos\left(x - \frac{\pi}{4}\right) \text{ when } x \gg 1,$$

$$N_0(x) \to -\frac{2}{\pi}\ln\left(\frac{2}{\gamma x}\right) \text{ when } x \to 0,\quad N_0(x) \sim \sqrt{\frac{2}{\pi x}}\sin\left(x - \frac{\pi}{4}\right) \text{ when } x \gg 1,$$

where $\gamma = 1.78\cdots$ is Euler's constant.

Imagining, we can propose that using such particles, which we give the name "fluctons", we can facilitate instant communication on arbitrary distances (*i.e.* $v \to \infty$) and in their application to jet engines achieve arbitrary velocities. This may pave the path for reaching the farthest corners of the Universe.

Conflicts of Interest

The author declares no conflicts of interest.

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