On the Speed of the Electromagnetic Wave

D.L. Khokhlov
Sumy State University
R.-Korsakov St. 2
Sumy 40007, Ukraine
e-mail: dlkhokhl@rambler.ru

The quantum mechanical model of electromagnetic waves is considered herein, in which the photon, as a particle, propagates with the speed of light, whilst the wave function of the photon spreads out with an infinite speed. In the stationary state the wave function of the photon spreads out instantaneously over the whole space, whilst in the non-stationary state, within the near zone. Transmission of energy is a non-stationary process, the speed of which is infinite within the near zone and tends to the speed of light in the far zone. This agrees with the results of a recent experiment on the measurement of the speed of propagation of the bound magnetic field. Also, the wave in the stationary state, spreading instantaneously over the whole space, provides an explanation of the null result of the Michelson-Morley experiment whilst assuming Galilean invariance.

Keywords: wave function of photon, transmission of energy, bound magnetic field, Michelson-Morley experiment

The Maxwell-Lorentz equations describe electromagnetic waves propagating with the speed of light c. Within the framework of quantum mechanics, the electromagnetic wave is quantized, with the photon a quantum of the electromagnetic wave. In quantum mechanics the wave function of the photon is an analogue of the classical electromagnetic wave. The spatial wave function is defined instantaneously in the whole space at some instant of time i.e. the spatial wave function spreads out over the whole space with an infinite speed. On the other hand the photon propagates with the speed *c*. Thus, in quantum mechanics, the electromagnetic wave is characterized by two speeds, the infinite speed of the spreading of the spatial wave function and the speed *c* of propagation of the photon.

Consider the classical electromagnetic wave with the vector potential $\vec{A}$. The Maxwell-Lorentz equations for the electromagnetic wave are given by [1]

$$\Delta\vec{A}-\frac{1}{c^2}\frac{\partial^2\vec{A}}{\partial t^2}=0. \quad (1)$$

One can represent the solution of eq. (1) as a plane monochromatic wave

$$\vec{A}=\vec{A}_0 e^{-i\phi} \quad (2)$$

with the phase

$$\phi=\omega t-kr \quad (3)$$

where ω is the frequency, k is the wave vector.

In quantum mechanics [2], one can consider the electromagnetic wave as a bunch of photons with the momentum

$$p=\hbar k \quad (4)$$

where $\hbar$ is the Planck constant. One can conceive of the photon as a particle exhibiting wave behaviour. According to quantum mechanics the wave given by eq. (2) is to be thought of as a wave function associated with a single photon. For photons the Heisenberg uncertainty principle holds:

$$\Delta p \Delta r \geq \hbar / 2. \tag{5}$$

In view of eq. (4), the Heisenberg uncertainty principle restricts the wave function of the photon in space.

Consider the photon as a particle with momentum p at the time t. Introduce the wave function of the photon with the wave vector $k = p / \hbar$. In the stationary state the momentum of the photon is fixed. Then the uncertainty in momentum is $\Delta p = 0$ and the uncertainty in the wave vector is $\Delta k = \Delta p / \hbar = 0$. From Heisenberg's uncertainty principle eq. (5), it follows that the uncertainty in the space coordinate is $\Delta r = \infty$. This means that one cannot specify the space coordinate hence one can consider the wave function of the photon with the wave vector k as being in the whole space at the time t. The wave function of the photon spreads out instantaneously over the whole space with the speed $v_\infty = \infty$. Hence the uncertainty in time is $\Delta t = \Delta r / v_\infty = 0$. This means that one cannot consider the wave function of photon in time. The wave function of photon with the wave vector k defined in the whole space at the time t is spatial in its nature. Since it cannot be defined in time it is non-temporal. This means that one cannot consider the propagation of the wave function of the photon in terms of a classical wave. One can instead consider propagation of the photon as a particle. We shall consider propagation of the photon with the speed c with respect to a privileged reference frame. For this purpose we shall take the cosmic microwave background radiation (CMB) [3] as a privileged reference frame.

Transmission of the momentum (energy) of an electromagnetic wave is associated with the birth (annihilation) of a photon resembling a non-stationary process. For the non-stationary state of the photon the uncertainty in momentum is $\Delta p = p$. The Heisenberg uncertainty principle eq. (5) yields the uncertainty in the space coordinate as $\Delta r = \hbar / 2p = 1/2k$. This means that for the non-stationary state of photon, one can consider the wave within the radius $r \le 1/2k$. One can instantaneously transmit the momentum (energy) of the electromagnetic wave within the radius $r \le 1/2k$. Beyond the radius, $r > 1/2k$, the speed of transmission of the momentum (energy) of the electromagnetic wave tends to *c*.

The Authors of [4] estimated the speed of propagation of the bound magnetic field in the near zone. The magnetic field is supposed to be the sum of a bound field and radiation. The idea behind the experiment is as follows. The magnetic field generated in the emitting antenna induces an electromotive force in the receiving antenna. A procedure to estimate the speed of propagation of the bound magnetic field is applied. The speed of the radiation is supposed to be equal to *c*. The speed of propagation of the bound magnetic field is reported to be $v > 10c$ in the near zone $r < 1/2k$. In the far zone, $r >> 1/2k$, the speed of propagation of the bound magnetic field tends to zero with the radiation being responsible for propagation of the magnetic field with the speed *c*. Propagation of both bound field and radiation occurs through the transmission of energy. Hence the experiment favours an infinite speed of transmission of energy in the near zone $r < 1/2k$, and the speed *c* in the far zone $r >> 1/2k$.

Instantaneous spreading of the wave function of the photon throughout the whole space yields the phase of the electromagnetic wave between the source and the receiver at the time of reception [5]

$$\Delta\phi = \phi_r(t_r) - \phi_s(t_r) = k[r_r(t_r) - r_s(t_r)]. \qquad (6)$$

Unlike the classical case in which the phase of the wave is defined in terms of the space coordinate of the source at the time of emission,

$r_s(t_e)$, here the phase is defined in terms of the space coordinate of the source at the time of reception $r_s(t_r)$. Since the wave is defined instantaneously, this admits of Galilean invariance of the phase eq. (6) and hence Galilean invariance of space and time.

Consider an electromagnetic wave (photon) in the Euclidean space and absolute time of the CMB frame. Consider the Michelson-Morley experiment in a frame moving with the velocity *v* with respect to the CMB frame. Suppose that the electromagnetic wave (photon) moves with the velocity *c* with respect to the CMB frame, independently of the velocity of the source. Assuming Galilean invariance of space and time, the travel time is a function of the velocity of the frame, with the maximum difference of travel time between two legs for two-way travel being $\Delta t = (l/c)(v^2/c^2)$, where l is the length of the leg. According to quantum mechanics [2], a single photon interferes with itself. The wave function of the photon is a superposition of the waves specified along two different legs, with the photon as a particle moving along one of the legs. When determining the distance between the source and receiver at one and the same instant of time it does not depend on the velocity of the frame. Hence, the phase difference between the source and receiver, eq. (6), does not depend on the velocity of the frame. Thus, there is no phase shift due to the velocity of the frame, between two waves specified along two different legs, and this explains the null result of the Michelson-Morley experiment. The Special Theory of Relativity [6] interprets the null result of the Michelson-Morley experiment as evidence for Lorentz invariance. In view of the foregoing explanation, admitting Galilean invariance of the phase of an electromagnetic wave, one cannot consider the null result of the Michelson-Morley experiment as evidence for Lorentz invariance.

In conclusion, the wave function of a photon, being a quantum analogue of the classical electromagnetic wave, accompanies a single photon propagating as a particle with the speed *c*. One can define the wave function of a photon instantaneously in the whole space for the stationary state of the photon and in the near zone for the non-stationary state of the photon. That is, the wave function of the photon spreads instantaneously throughout the whole space for the stationary state of the photon and in the near zone for the non-stationary state of the photon. Whilst considering the photon in the stationary state one can define the phase of an electromagnetic wave instantaneously in the whole space at the time of reception. This admits of Galilean invariance of the phase of electromagnetic wave, which explains the null result of the Michelson-Morley experiment, without invoking Lorentz invariance. Transmission of energy is associated with the non-stationary state of the photon and hence it can propagate with infinite speed in the near zone. In the far zone the speed of transmission of energy is limited by the speed of propagation of the photon. This is in agreement with the results of a recent experiment concerning measurement of the speed of propagation of the bound magnetic field.

Acknowledgements

I wish to thank Stephen J. Crothers for the help with the English of the paper.

References

[1] L.D. Landau and E.M. Lifshitz, *The classical theory of fields*, 4th Ed., Pergamon, Oxford. (1976).

[2] P.A.M. Dirac, *The Principles of Quantum Mechanics*, Oxford University Press, London. (1958).

[3] C.H. Lineweaver et al., “The dipole observed in the *COBE* DMR 4 year data”, *Astrophys. J*. **470** (1996) 38-42.

[4] A.L. Kholmetskii et al., “Experimental test on the applicability of the standard retardation condition to bound magnetic fields”, *J. Appl. Phys.* **101** (2007) 023532.

[5] D.L. Khokhlov, “ Michelson-Morley experiment within the quantum mechanics framework”, *Concepts of Physics* **5(1)** (2008) 159-163.

[6] W. Pauli, *Theory of Relativity*, Pergamon, New York. (1958).