A viewpoint on the momentum of photons propagating in a medium

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A suggestion is proposed to solve the dispute about light momentum in transparent materials: when photons show wave features, the momentum of light conforms to Minkowski's viewpoint; when photons show particle features, the momentum of light accords with Abraham's thought.

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INTRODUCTION.

When considering the momentum of light in a transparent material such as water, there are two kinds of opposing viewpoints. Minkowski[1] stated that it should be $\frac{nh\nu}{c}$. Where n is the refractive index of the medium, h is Planck's constant, ν is the frequency of light, and c is vacuum speed of light. Abraham believed[2] that the light momentum in a medium should be $\frac{mc}{n}$. Where m is the mass of a photon.

Some experiments support Minkowski's momentum, and other experiments show the correctness of Abraham's momentum[3]. So far, a final conclusion on light momentum in a transparent medium has not been reached.

In this work, based on wave-particle duality, a viewpoint for light momentum in mediums is proposed. Analysis showed that, when photons exhibit wave features, Minkowski's momentum works; but when photons exhibit particle behavior, Abraham's momentum works.

DISCUSSION ON PHOTON STATES.

In the single slit experiment for photons, if photons are emitted one by one and diffraction fringes appear on the screen, photons will mainly gather in the fringe positions.

Definition:

(1) a photon is defined as the least part of light with momentum mc and energy mc^2, where m is the mass of a photon.

(2) When photons show a diffraction appearance, they are said to be in a wave state. In this state, photons work like photon clusters. The wave length $\lambda = \frac{h}{p}$ and frequency $\nu = \frac{E}{h}$ hold, where p and E are the average momentum and kinetic energy in one diffraction fringe position, respectively. When in the wave state, photon energy $E = h\nu$ or $E = mc^2$. So, at this frequency, the mass of a photon cluster is $m = \frac{h\nu}{c^2}$. When ν changes, m will increase or decrease.

(3) When photons work like particles, they are said to be in a particle state. If the slit board is removed, the wave appearance will disappear. In this case, photons are in a particle state and a photon's momentum and energy should be mc and mc^2, respectively.

A single photon single slit experiment can show a diffraction appearance, meaning that a light wave is a statistical wave - and can be viewed as a classical wave with wave length $\lambda = \frac{h}{p}$ and frequency $\nu = h\nu$. At this moment, the wave speed in vacuum can be viewed as $\lambda\nu = \frac{h}{p}\frac{E}{\nu} = c$.

In the photoelectric effect experiment, if $h\nu$ is large enough, electrons will be emitted. If $\nu = 5 \times 10^{14}$Hz and the mass of a photon is $m = 10^{-54}kg$, then, when comparing the energy of a photon that is in a particle state with the energy of photons in a wave state, we will get:

$$\frac{h\nu}{mc^2} = \frac{6.63 \times 10^{-34} \times 5 \times 10^{14}}{10^{-54} \times (3 \times 10^8)^2} = 3.68 \times 10^{18}$$

Thus, when photons are in a wave state, their energy is much greater than the energy of a photon in a particle state. So, it can be said that, in a wave state, photons work like photon clusters with quantized energy of $h\nu$ and momentum of h/λ.

The Compton effect experiment also reveals another enlightenment.

When the Compton effect occurs, due to a collision consuming a photon's kinetic energy, the photon wave length $\lambda = \frac{h}{p}$ increases and the frequency $\nu = \frac{E}{h}$ decreases.

For a classical wave, the wave frequency will maintain after colliding with a medium. However, for a particle statistical wave, when particles collide with other material, due to the kinetic energy E decreasing, the wave frequency $\nu = \frac{E}{h}$ will decrease.

Therefore, a light wave should be a particle statistical wave rather than a classical wave.

ANALYSIS OF PHOTON MOMENTUM IN TRANSPARENT MATERIALS.

Referring to the analysis in the above section, when photons go into a medium, four kinds of circumstances will occur:

(1) Before entering the medium, photons are in a particle state. When running in the medium, photons are still in a particle state. In this case, due to the collision consuming photon kinetic energy, photon momentum will decrease and should reflect Abraham's momentum $p = \frac{E}{nc}$, where p is the momentum of a photon.

(2) Before entering the medium, photons are in a particle state. When running in the medium, photons are in a wave state. In this case, photons will change from individual photons to photon clusters. Photon momentum will increase and should be Minkowski's momentum $p = \frac{h}{\lambda} = \frac{nh\nu}{c} = \frac{nE}{c}$, where p is the momentum of a photon cluster.

(3) Before entering the medium, photons are in a wave state. When running in the medium, photons are still in a wave state. In this case, if the mass of a photon cluster increases, the photon momentum will increase; if the mass of a photon cluster decreases, the photon momentum will decrease. -Whether increasing or decreasing, the photon momentum should be Minkowski's momentum $p = \frac{nE}{c}$, where p is the momentum of a photon cluster.

(4) Before entering the medium, photons are in a wave state. When running in the medium, photons are in a particle state. In this case, photons change from particle clusters to discrete particles. The photon momentum will decrease and should correspond to Abraham's momentum $p = \frac{E}{nc}$, where p is the momentum for a single photon.

CONCLUSION.

Photons exhibit wave-particle duality. When photons are in a wave state, they work like photon clusters with momentum $\frac{h}{\lambda}$; when photons are in a particle state, they work like single particles with a momentum of mc. Different from a classical wave, when colliding with a medium, the frequency of the light wave will change. This means that light wave is a statistical wave.

If photons go from vacuum into a medium, the photon momentum will decrease or increase depending on its changing state. In a medium, if photons are in a wave state, the momentum of the light wave should be $p = \frac{nE}{c}$; if photons are in a particle state, the momentum of a photon should be $p = \frac{E}{nc}$.

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[2] Abraham, M. Rend. Circ. Matem. Palermo 28, 1 (1909).
[3] U. Leonhardt, Nature (London) 444, 823 (2006).