AN ATTEMPT TO DETECT COLLISIONS OF PHOTONS

By A. L. Hughes and G. E. M. Jauncey
Department of Physics, Washington University

(Received June 16, 1930)

Abstract

Assuming that light is corpuscular and that collisions between light corpuscles (i.e. photons) can occur, it is shown that two photons of identical frequency ν, moving along paths which make an angle 2θ with each other, will on collision give rise to a photon of frequency $\nu(1+\cos\theta)$ travelling forward along the line bisecting the angle. To test this, two beams of sunlight (one suitably deflected by a mirror), filtered through red glass, were passed through lenses 24 cm in diameter and of 33 cm focal length, so that the beams, whose axes made an angle of 120° with each other, intersected at a common focus. The point of intersection of the beams was examined through a green filter with the dark-adapted eye. No light was detected. Calculations show that if the photon has a cross section, its area must be less than 3×10^{-20} cm^2. From a result of Lord Rayleigh, some writers have suggested an area of the order of λ^2 for the photon. Our result shows the area to be of the order of $10^{-10}\lambda^2$.

1 Introduction

Physicists have become accustomed to the idea of the corpuscular nature of molecules, atoms, electrons, protons, alpha-particles and also, in some cases, of light. Collisions of molecules with molecules as in the kinetic theory of gases, of electrons with atoms as in critical potentials, of alpha-particles with the nuclei of atoms as in the Rutherford scattering experiments and of photons with electrons as in the Compton effect are familiar phenomena. It occurred to the writers that, if light has a corpuscular structure, collision phenomena should occur when two light beams cross each other—in other words, that two photons may collide and produce photons with energies different from the energies of the original photons.

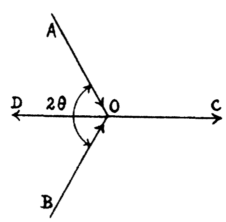

Fig. 1.

2. Theory

Let two photons, each of energy $h\nu$, approach each other and collide as in Fig. 1, and let the angle between AO and BO, the paths of the two photons, be 2θ. The problem is to find the energy of the photon which after the collision proceeds along the bisector OC. If two photons arise out of the collision of two photons and if the principle of conservation of momentum may be applied to photons, the other resulting photon must travel along OD. Let the photon travelling along OC have the energy $h\nu_1$ and the photon along OD an energy $h\nu_2$. The conservation of energy gives

$$h\nu_1 + h\nu_2 = 2h\nu \tag{1}$$

and the conservation of momentum gives

$$h\nu_1/c - h\nu_2/c = 2(h\nu/c)\cos\theta \tag{2}$$

Whence

$$\nu_1 = \nu(1 + \cos\theta) \tag{3}$$

$$\nu_2 = \nu(1 - \cos\theta) \tag{4}$$

or, in terms of wave-length,

$$\lambda_1 = \lambda/(1 + \cos\theta) \tag{5}$$

$$\lambda_2 = \lambda/(1 - \cos\theta) \tag{6}$$

The theory thus leads to the expectation that, if two beams of monochromatic light cross each other, as in Fig. 1, light of a wave-length shorter than that of the two original beams will be observed in the direction OC. In particular, if $2\theta = 120°$ and $\lambda = 6000$A, the wave-length observed in the direction OC will be 4000A. Accordingly an experiment was devised to test this prediction of the theory.

3. Experimental Method

A wide beam of sunlight entered a light-tight box AB through the lens C in Fig. 2 and was brought to a focus at O. A second beam after reflection

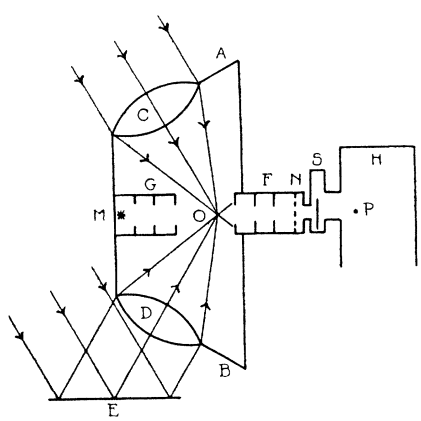

Fig. 2. Diagram of apparatus.

from the mirror E, which is rigidly attached to the box AB, passed through the lens D and was also brought to a focus at O. Thus two cones of light intersected at O. The diameter of each lens was 24 cm. For each lens, the focal length for the central and peripheral rays was 34.3 and 31.7 respectively. The area of cross section of the light passing through each lens was a minimum at 33 cm. The diameter of the sun's image at this point was estimated to be 0.4 cm. This image occurred for each lens at O in Fig. 2. The head of the observer was enclosed in a light-tight helmet H, his eye being at P. The observer looked through the tube F and into the tube G. Both F and G contained diaphragms so as to prevent stray light from entering the eye. At the far end M of the tube G a small lamp was placed. The object of this lamp was to attract the attention of the eye to the direction PM. The line PM passed through O. The directions of the light rays passing through O were such that no direct rays from the lenses could enter the eye. The inside of the box AB was blackened so as to reduce scattering. Dustfree air was blown through the box AB in order to remove dust motes from the air at O and also to keep the inside of the box reasonably cool. The sunlight which entered the box through the lenses previously passed through plates of red glass. A quantitative curve for the transmission of this red glass was very kindly made for us by Professor H. M. Randall, of the University of Michigan, who found that the red glass transmitted wave-lengths between 5500 and 30,000A. At N was placed a green filter, the transmission curve of which was supplied by the Eastman Kodak Company. The green filter transmitted light of wave-length shorter than 5200A. At S was placed a shutter. The observer prepared his eye by sitting with his head in the helmet for 15 minutes. The lamp M was then switched on and the shutter S opened. The lamp was connected in series with a rheostat and increasing resistance was put into the circuit until the light of the lamp was just perceptible. After opening the lamp switch, the observer opened and closed the shutter S in order to determine whether or not green light was coming from O. The result was negative. The observer then rested his eye for a second 15 minutes when more observations were taken, a third set of observations were made at 45 minutes from the time when the helmet was first put on and a fourth set at 60 minutes. The eye is almost completely dark-adapted in 60 minutes, but nevertheless even after this time the result was negative.

As a check on the observations, a sliding shutter was made so that the proportion of sunlight entering the lenses could be suddenly changed from no light entering lens C and 100 percent of light entering lens D, to 50 percent entering each lens, and to no light entering lens D and 100 percent entering lens C. This shutter arrangement was outside the box AB and is not shown in Fig. 2. In whatever position the shutter was the same total amount of light passes through O. In the 50–50 percent position of the shutter the two light beams crossed at O and conditions were such as to allow collisions of photons, while in the 100–0 percent positions of the shutter the two light beams did not cross at O. While one person operated the shutter, another person who was the observer with his head in the helmet called whether or not he noticed a change in the light when a change was made in the position of the shutter. The usual observation was that there was complete darkness and no change. In those cases where the observer judged a change, there was no correlation between the observation and the position of the shutter, and the result was therefore negative. In order that the result might not depend upon a particular observer, five different observers were used. All agreed in giving a negative result.

The apparatus was mounted so that the upper lens could be kept pointing toward the sun. The angle between the central rays passing through each lens was 120°. The peripheral rays of one lens made with the peripheral rays of the other lens angles varying from 80° to 160°. No lenses were used between the eye at P and O in Fig. 2, because of the well-known fact that the brightness of an object as seen by the eye cannot be increased by a lens system.

4. Discussion of Results

The wave-lengths after collision at various angles, as calculated from Eq. (5), are shown in Table I.

Table I. *Change of wave-length on collision.*

Original wave-length	Wave-length after collision Collision angle 80°	120°	160°
5500A	3110A	3670A	4680A
6000	3400	4000	5110
7000	3970	4660	5960
8000	4530	5330	6810
9000	5100	6000	7670

It is seen that wave-lengths between 5500 and 9000A in the original beams produce wave-lengths after collision which can penetrate the green filter N in Fig. 2. Since the sensitivity of the eye rapidly decreases as the wave-length decreases below 4500A we shall consider only those wave-lengths between 4500 and 5000A which pass through the green filter. Let us assume that these are produced by the central rays passing through the lenses, then we are interested only in the wave-lengths 6750 to 7500A in the original beams. From data which were very kindly supplied to us by Dr. C. G. Abbot of the Smithsonian Institution, we estimate that the rate at which the energy of sunlight in a range 6750 to 7500A is incident on a surface perpendicular to the beam is about 0.12 cal/min. cm^2 at midday in the springtime in St. Louis. The area of each lens is 453 cm^2 and the rate at which energy passes through each lens is therefore 54.4 cal/min. The coefficient of transmission for the red glass in the range 6750 to 7500A is 0.45 and the average wave-length is 7125A so that there are 3.7×10^{20} photons per minute passing through each lens. When the sliding shutter is used in the experiment in the 50–50 percent position, the number of photons in each beam passing through O in Fig. 2 is 1.85×10^{20} per minute. For simplicity we shall treat the beams which intersect at O as two square cylinders of side 4 mm, with 1.85×10^{20} photons passing through each cylinder per minute. Within a volume $(4\times 4\times 4)/\sin 120°$ mm^3 of one cylinder there will be at any instant of time 4.6×10^7 photons. Bombarding them from the second beam there will be 3.1×10^{18} photons/sec. If the effective collision area of each photon is A cm,^{2} the total area of the photons in the first beam presented to the photons in the second beam is $4.6 \times 10^7 \times A$. The chance of a photon in the second beam colliding with any photon in the first beam is $4.6 \times 10^7 \times A/(0.4 \times 0.4) = 2.9 \times 10^8 \times A$. The total number of collisions per second will then be $9 \times 10^{23} \times A$. Ives[1] estimates that the pupil of the dark-adapted eye has a diameter of about 6 mm. The distance of the eye of the observer from O in Fig. 2 is 25 cm, so that the solid angle subtended by the pupil at O is 0.00044. Let us suppose that after collision the resulting photons are equally likely to travel in any direction. The number of photons entering the eye per second will then be $0.00044 \times 9 \times 10^{23} \times A/4\pi = 3.3 \times 10^{22} \times A$.

There is some variation amongst different writers as to the energy of the smallest light stimulus which can be detected by the eye. Reeves[2] gives 19.5×10^{-10} erg/sec, Russell[3] gives 7.7×10^{-10} erg/sec and Buisson[4] 12.5×10^{-10} erg/sec. If we take the average of these values we shall at least have the correct order of magnitude. Assuming a wave-length of 5000A, we find that the minimal light stimulus is given by 336 photons entering the eye per second. Ives[1] gives the minimal light stimulus as 1000 photons per second. Using this value of Ives so as to be on the safe side, we obtain

$$3.3 \times 10^{22} \times A = 10^3$$

whence

$$A = 3 \times 10^{-20} \text{ cm}^2$$

If the photons are thought of as having a circular cross section, this corresponds to a diameter of 2×10^{-10} cm. The result of our experiment is therefore that the collision area of a photon, if such a thing exists, is less than 3×10^{-20} cm^2.

Photons are supposed to obey the laws of the Bose-Einstein statistics and no two photons can occupy the same cell. A physical interpretation of this may be that no two photons can be at the same place at the same time, and hence there can be no collisions of photons. Our result is compatible with this view. Lord Rayleigh[5] has considered the case of a resonator being actuated by a plane wave and has calculated the area of the primary wave front which propagates the same energy as is dispersed by the resonator. This area is $\lambda^2\pi$ where λ is the wave-length. This result has been said by some writers to indicate that the area of the cross section of a photon is of the order of λ^2. According to this idea then we might have expected an area of cross section of 2.5×10^{-9} cm^2. Our experiment, however, gives an area less than 3×10^{-20} cm^2, which is of the order of 10^{-10} times the expected area.

We are indebted for information concerning the dark-adapted eye to Professor Allen of the University of Manitoba, to Dr. Jones of the Eastman Kodak Company, and to Dr. Priest of the Bureau of Standards. From this information, we have learned that the dark-adapted eye is the best instrument for making the observations in this experiment.

[1] H. E. Ives, Astrophys. J. **44,** 124 (1916).
[2] P. Reeves, Astrophys. J. **46,** 167 (1917).
[3] H. N. Russell, Astrophys. J. **45,** 60 (1917).
[4] H. Buisson, Astrophys. J. **46,** 296 (1917).
[5] Lord Raleigh, Phil. Mag. **29,** 209 (1915).