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Figure 1*D* is a record of the absorption by a 15 mm. cell of liquid chloroform, $CHCl_3$, included for comparative purposes. The bands at 1.15μ, 1.40μ and 1.69μ have their analogues in the spectrum of methane. Dreisch[8] has shown that the spectrum of chloroform vapor is practically identical with that of the liquid, thus justifying this comparison.

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ON THE NATURE OF LIGHT

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Introduction.—There exists in the quantum theory a most unusual circumstance, for the structure of the very thing concerned in the theory, i.e., radiation remains entirely obscure. Various developments of the theory have largely confined themselves to describing the experimentally known quantum transfers of energy, the physical mechanism of the transfers of energy, the physical mechanism of the transfers and the nature of quanta being only vaguely indicated. An interesting exception is the recent suggestion as to the structure of light put forward by Sir J. J. Thomson.[1] This peculiar theoretical situation has arisen, partly at least, because of the fact that there has been no direct experimental evidence to support a detailed view of the nature of radiation and its interaction with matter. For instance, there is no definite information on the length of time elapsing during the process of absorption of a quantum of energy photo-electrically by an electron, and the so-called length of a light quantum—if such a concept has meaning—is equally unknown experimentally. Clearly, experimental evidence concerning these two quantities would be of great assistance in formulating our ideas of the structure of radiation. This communication deals with an experiment which has established very low upper limits to their possible magnitudes.

The Experiment.—The experiment consisted in producing very short segments of light by passing a light beam through a very rapidly operating shutter and observing the photoelectric currents produced in a potassium photo-cell by these light pulses as a function of their length.

The short light segments were produced by a refinement of a previously described method[2] indicated in figure 1. A sixty cycle transformer, T, charged a condenser, C, to a potential difference of about 10,000 volts at which voltage it discharged across a zinc spark gap, the charging and discharging occurring, of course, 120 times per second. Light from the spark was collimated by a lens, L, and on passing through a Nicol prism, N_1, was plane polarized where with suitable diaphragming it passed between two sets of parallel brass plates, K_1 and K_2, immersed in carbon bisulphide and oriented at right angles to each other and 45° with respect to the electric vector of the polarized light. Emerging from this "double Kerr cell" the light passed to a second Nicol N_2 crossed with respect to the first. Light emerging from N_2 entered a very sensitive potassium photo-cell, PC. Both sets of plates, K_1 and K_2, were connected across the spark gap with wires of variable length (a trolley system, T_1T_2, was arranged so that

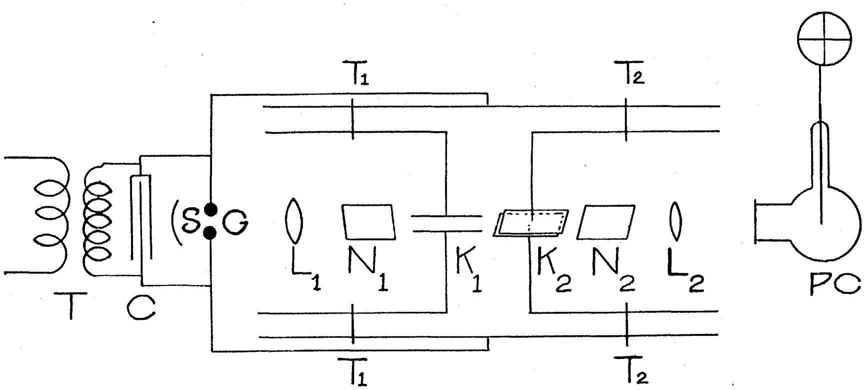

FIGURE 1

the wire paths from the spark gap to either set of plates could be varied conveniently and quickly from 4 meters to 40 meters in steps as small as desired) and, therefore, they assumed potential differences existing across the terminals of the spark gap at a previous time equal to the time required for the propagation of the electrical effects along the wires.

Now during the charging of the condenser the potential differences across both sets of plates are very nearly the same though the wire paths connecting them to the spark gap may be unequal. This is true because the 60 cycle increase of the voltage is very slow in comparison to the rapidity of propagation of the electrical effects along the wires to the Kerr cells. The discharge of the condenser through the spark gap gives rise to a quite different situation, however, because the voltage across the gap drops from a high value to practically zero in an exceedingly short time. The change in voltage is propagated to the Kerr cell plates and they lose their charge at a time subsequent to the spark discharge about equal to the wire path divided by the velocity of light. Thus, it is evident that if the wire paths to the two sets of plates are not the same one pair of plates comes to zero difference of potential before the other pair and there is a short time when an electric field exists between one set and not between the other.

Plane polarized light from the first Nicol N_1 when passing between the first pair of plates K_1 is elliptically polarized if the plates are at a difference of potential. On passing through the second pair K_2 the ellipticity is compensated and light emerges from the combination plane polarized as before and unable to pass through N_2. Only when the electric field between one pair of plates is greater than between the other is there a resultant ellipticity of the light. In this case light passes through the second Nicol N_2 and impinges on the photo-cell PC. Thus, during the charging of the condenser no light passes because the field between K_1 and K_2 are very nearly the same and light emerges from N_2 only during the short interval of time after the discharge of the spark when one pair of plates is charged and the other is not. In other words, light emerges from the system of Nicols and Kerr cells for the very short interval of time equal to the wire path difference from SG to K_1 and K_2, divided by the velocity of propagation of the electrical effects along the wires (approximately the velocity of light). Thereby short segments of light of various lengths were produced by changing the wire path to one pair of plates, keeping the wire path to the other constant. In this way photo-electric effects produced by these short pulses entering the photo-cell were studied as a function of their length.

Results.—The data exhibited in figure 2 typify the results obtained when one of the trolleys was held constant and the other moved from a position of shorter wire path through the position of equality to longer wire path positions. The abscissas thus show the wire path differences in cm. and the ordinates represent the corresponding observed photo-electric currents. It is seen as the trolley is moved from a position of shorter wire path (abscissa $= -100$ cm.) to equality with the other (abscissa $= 0$) the photo-current rapidly decreases to zero and equally rapidly rises again as the trolley is moved to longer wire distances (abscissa $= +100$ cm.). It may be remarked at this point that the curve does not exhibit perfect symmetry about the minimum because the spark is not uniformly intense in time and the coming in or decay of the luminosity produced changes in the slopes of the curve. By taking data over various time intervals after the spark discharge it was shown that sharp changes in slope were due to this cause.

If the light source were uniformly intense and the photo-electric effect per unit light intensity were independent of the length of the light pulses, one would expect that the photo-electric effect would decrease linearly to zero as the wire path difference was diminished and again increase linearly as the path difference were increased. On the other hand, if the length of a light quantum were of the same order of magnitude as the length of the segments, presumably fractional quanta would be produced which would not have enough energy to eject an electron photo-electrically and the photo-current would be abnormally small. Also, in case the time required for an electron to absorb sufficient energy to be ejected were greater than the time it takes for the segment of light to pass over it, i.e., its length divided by the velocity of light, the pulse would not be able to eject the electron and the photo-current for such short segments would be zero. It is clear, therefore, that if either of these quantities were sufficiently large our plot of photo-electric effect versus length of light segment would not show the very sharp minimum of figure 2 but would exhibit a region over which the photo-currents were zero. The sharpness of the minimum of the series of experimental points (circles of figure 2) wherein the smallest light pulses were 10 cm. (similar data have also been obtained with segments as short as 5 cm.), therefore, leads to the conclusion that *if light quanta are of the commonly understood wave nature, they are less than 3 cm. in length and an electron absorbs a light quantum photo-electrically in less than 10^{-10} sec.*

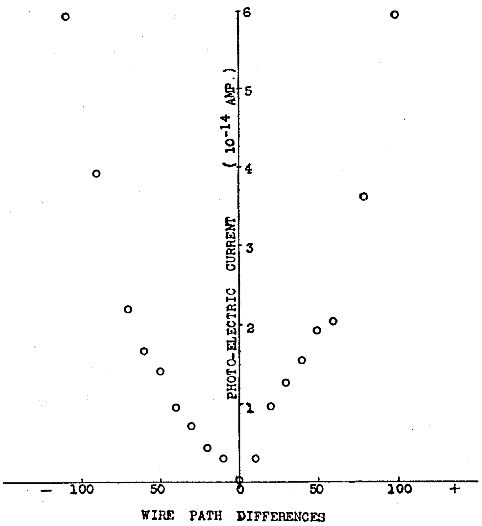

FIGURE 2

Discussion of the Experiment.—One is impressed with the apparent rapidity of action of the combination of Kerr cells and Nicols constituting the light shutter. The production of the short segments is understandable providing that the time of breakdown of the resistance of the spark gap is exceedingly small. Unfortunately, there exists no experimental data on the rapidity of beginning of a spark of this sort—the fastest oscillographs being unable to detect a time of breakdown at all. However, theoretical estimates indicate that the time is very short—less than 10^{-9} sec. It is even more difficult to gain knowledge of the way the voltage decreases during the first stage of the discharge. It seems probable, however, that at the beginning the voltage drops very rapidly. Since the Kerr effect varies as the square of the voltage the ellipticity of the light would change much more rapidly than the voltage. On the basis of these considerations it seems plausible that the Kerr cells were acting with great speed. Perhaps the best experimental evidence that the Kerr effects in the present experiments switched from large to small values in periods of time of the order of magnitude of 10^{-10} sec. is the experiment itself, for it is difficult to account for so sharp a minimum in the observed curves if this were not the case.

On computation of the time it takes an array of molecules producing a Kerr effect to assume random positions by thermal agitation alone, it is found that it is approximately 10^{-12} sec. One of the writers has shown the existence of a lag in the Kerr effect[2] (which, of course, is compensated out in the two Kerr cells of the present experiments). It is, therefore, not inconceivable that the molecules of the carbon bisulphide persist in the condition producing the Kerr effect for a considerable time after the relaxing of the electric field and then in a very short time (10^{-12} sec.) assume random positions after the breakdown starts. Such a phenomenon would readily account for the quick action of the Kerr cells though the time of discharge of the spark were quite considerable.

In making estimates of the lengths of the light segments in terms of wire path differences it has been assumed that the changes in electrical potential were propagated along the wires with the velocity of light. This assumption has the strongest support of many experiments performed years ago. R. Blondlot[3] observed the propagation of discharges along wires concluding that the surges travel practically with the velocity of light and Saunders[4] and Trowbridge and Duane[5] arrived at similar conclusions using standing waves. It is interesting to point out that in the present experiment photo-electric effects have been observed by light flashes occurring 120 times per second, each flash lasting roughly 10^{-10} sec. In other words, photo-currents produced by light shining only one one-hundred millionth of the time were measured. In order to do this a photo-cell of greatest sensitivity was required. The greatest factor, however, in the success of the experiment was the fact that the light from the spark is enormously intense when shining, as compared to its average intensity over a long interval of time.

Discussion of the Results.—As pointed out in the introduction, it is difficult to estimate on the basis of current theories the magnitude of the two quantities—the length of radiation quanta and the time of photo-electric action. It is often suggested that since it is possible to get interference over path differences of about one meter light quanta must be of even greater length. Such an argument, however, is of little force because such a mode of reasoning would imply also that quanta are "split" at the half-silvered mirror of a Michelson interferometer. A more acceptable estimate is the calculation of the length of light quanta made by G. P. Thomson[6] on the basis of the finite breadth of spectral lines. Thomson concluded that quanta were longer than 8 cm. To test the matter he looked for a decrease in the breadth of a doppler shifted line, observed in a spectroscope in line with two narrow slits placed 45° with a column of rapidly moving atoms emitting light, as the slits were narrowed. Finding no such effect he concluded that quanta were shorter than about 3 cm. in agreement with the results here presented.

There is an even smaller basis for an estimate of the time interval during which an electron absorbs the energy of a quantum. Since the electron acquires a finite amount of energy it is probable that a finite time is involved in the process. In the case of excitation of atoms by radiation it is quite well established now that there is a "dark time" during which an atom remains excited—usually of the order of magnitude of 10^{-8} sec.—but the time interval during which it passes from the normal to the excited state is unknown. There is reason to believe that this latter period is much smaller than the former and one would expect this period of time to be of the same order of magnitude as the time interval associated with photo-electric ejection of an electron. The results here presented clearly support such a view.

This experiment leads to the conclusion that quanta as bundles of energy of considerable dimensions do not exist and suggest that the effects of radiation on atoms are independent of the length of the pulses to the extent that the effects would be independent on the classical theory. This conclusion harmonizes well with a theory advanced by Professor W. F. G. Swann[7] in which he developed the consequences of the postulate that quanta of negligible dimensions follow the Poynting flux of the classical theory. A similar idea is incorporated in the more recent theory of the structure of light put forward by Sir J. J. Thomson.[1] In this theory light has a dual structure consisting of quanta in the form of rings of electric lines of force (dimensions of the order of magnitude of the wave-length) and Maxwellian waves which are the pathfinders determining where the quanta may go—again along the Poynting flux. Both theories are supported by the present experiment.

It is a very pleasant duty to record our indebtedness to Professor W. F. G. Swann for his interest in this work. We wish also to thank Mr. Donald Cooksey for the loan of a pair of very fine Nicol prisms.

* NATIONAL RESEARCH FELLOW.

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