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Quantum Theory and the Nature of Interference

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Abstract

It is shown that many of the difficulties associated with the Copenhagen interpretation of quantum theory are resolved by a new interpretation of interference derived from solutions to Maxwell's equations. An infinite wave model of the photon based on these solutions is described and used to explain the interference of single photons as well as the corpuscular behavior evident in the Compton and photoelectric effects. The wave–particle duality and the uncertainty relations are also discussed. According to the new interpretation of interference in a Young's double-slit experiment, photons which pass through the left-hand slit always arrive in the left-hand part of the screen and no photons pass into this area via the right-hand slit. This conclusion is compared with the viewpoint of the Copenhagen school and an experiment to distinguish between them is suggested.

1. *Introduction*

In the most widely accepted interpretation of the quantum theory, often called the Copenhagen interpretation, the initial and final conditions of a physical experiment are related by a measure of probability derived from the quantum formalism. The abstract nature of this formalism is such that it does not admit the description of any intermediate physical processes connecting the initial and final states, and it is held that questions pertaining to such processes can have no meaning within the context of the theory.

As is well known, the statistical interpretation of the formalism is considered to limit the validity of classical concepts such as momentum and position in accordance with Heisenberg's indeterminacy relations, and the classical notions of particle and wave are regarded as complementary conceptions, neither being in itself an adequate description of the reality represented by the quantum theory. The essential nature of this physical reality which reveals itself both as a particle and as a wave remains obscure and the Copenhagen interpretation implies that no further insight into it is possible.

The corpuscular attributes of matter are naturally self evident and there are several experiments in which the corpuscular nature of light is demonstrated, as, for example, in the Compton and photoelectric effects. But there is only one kind of experiment in which the wave-like nature of matter and light is directly evident, namely in the case of interference and diffraction. These phenomena are usually understood in terms of Huygens' principle in which every point on a wavefront is regarded as a source of secondary wavelets which spread out into the surroundings. On the other hand, the compact and localized structure of a particle is obviously incompatible with Huygens' principle. However, it has been shown in the previous paper (Prosser, 1976) that interference and diffraction can be interpreted without the aid of Huygens' principle in terms of the undulations in a nearly linear trajectory, and this allows a new reconciliation of the wave and particle concepts. It thus becomes possible to account for the wave-particle duality in terms of a single physical model. In this paper these ideas are developed to construct a model of the photon and it is shown that its wave-like and corpuscular attributes are just different aspects of one infinite entity. In so doing we go beyond the Copenhagen interpretation and gain a deeper understanding of the reality which quantum theory describes.

2. *Diffraction and Interference of Single Photons*

Infinite Wave Model of the Photon. A photon may be considered as a superposition of continuous and infinite electromagnetic waves such that these sum to zero except over a small region of space where the photon is localized, in accordance with Fourier's integral theorem. Any one-dimensional function of time or space $H(t)$ can be represented as a sum of infinite periodic waves:

$$H(t) = \int_{-\infty}^{+\infty} f(\nu) \exp(2\pi i\nu t) d\nu \tag{2.1}$$

where the amplitudes $f(\nu)$ are given by

$$f(\nu) = \int_{-\infty}^{+\infty} H(t) \exp(-2\pi i\nu t) dt \tag{2.2}$$

We can consider the photon as a superposition of infinite waves by extending the dimensional basis of the above equations and applying them to a three-dimensional packet of electromagnetic energy. At every point within this packet are associated electric and magnetic vectors which define the magnitude and direction of the electric and magnetic fields. Each point in the packet can be represented in a four-dimensional configuration space (three spatial dimensions plus time) and at each point in this space the associated vectors require representation in a further three dimensions so that the complete representation of the electric or magnetic vector fields requires a seven-dimensional space. Just as a localized function in one dimension can be represented by a suitable sum of functions which are periodic and infinite in one dimension, so also a localized function in seven dimensions can be represented by a suitable sum of functions which are periodic and infinite in seven dimensions. The two forms of representation are mathematically equivalent, but physically they correspond with conceptually different points of view as follows.

Imagine that one is sitting in a darkened room contemplating a beam of light shining towards the ceiling. If one's apprehension is restricted to the perception of resultant energy, then as one's attention moves from the periphery of the beam into the surrounding darkness one imagines that one is entering a region of emptiness. But if one's perception were to extend to the level of the primary waves composing the superposition which results in the localized packet, then one would see that the essential nature of these waves remains unchanged and that they are present as much in the darkness as in the light. The difference between darkness and light is only that there is a change in the relative phases of the waves such that the resultant amplitude is finite in the light whereas in the darkness it is zero.

These two ways of perceiving the photon, either as a localized packet or as a composite of infinite waves, correspond with its particle and wave aspects. The vibrations of any particular frequency maintain a real and independent existence over the whole of space. The resultant sum of the electric and magnetic vectors will be zero, however, outside the volume enclosed by the energy packet envelope. It may thus be said that the photon exists over the whole of space but that it is manifest only over a localized region of space.

One may ask what sense it makes to speak of the real existence of component vibrations when it is only their resultant sum which can be measured? The answer is that the component vibrations have individually to satisfy the electromagnetic boundary conditions even when their resultant sum is zero and there is no manifestation. This condition affects the behavior of the region where the resultant is finite, which may itself be far from any boundary.

The infinite waves may be regarded as the field of potential existence of the light. When a photon is created there is a certain shift in the phase relationships of these waves which are forever in existence. When a photon is annihilated a reverse shift occurs, but on the level of the primary vibration there is no essential change and its integrity is maintained whether there is darkness or whether there is light.

Construction of a Photon Wavepacket. We now consider the structure of a wavepacket which embodies features of the photon, namely that it is stable and travels with the velocity of light. For simplicity we consider a packet in two dimensions with field components H_z, E_x and E_y only and which propagates in the y direction. We might consider the superposition of waves modulated sinusoidally in the x direction, since such a superposition can result in a packet localized in the x direction. However, sinusoidal modulation of a plane wave produces a wave which is dispersive, i.e., the wave number k of the resultant is not a linear function of frequency, being given by the relation

$$k^2 = (\omega/c)^2 - (2\pi/\lambda_x)^2 \tag{2.3}$$

where λ_x is the wavelength of the spatial modulation. The phase velocity therefore varies with λ_x and we should not expect that a packet formed from such a superposition would be stable in general. But if we examine the solution for the semi-infinite plane given in the previous paper we see that the constant phase surfaces are all nearly parallel and that the perpendicular distance between two surfaces which differ in phase by 2π is equal to λ on the average. Since this distance corresponds to $2\pi/k$ we have

$$1/k = \lambda/2\pi = c/\omega \tag{2.4}$$

indicating that the wave is not dispersive under these conditions. The same result is obtained in the case of the single slit in an infinite plane. (The solution for a slit 10λ wide closely resembles the half-plane solution from $x = -5\lambda$ to $+\infty$ combined with its mirror image.) The single-slit solution can be represented by a suitable superposition of sinusoidal waves in two dimensions and although each individual wave is dispersive, the resultant sum in this case is not. Evidently there is only a particular class of packet envelopes which exhibit this non-dispersive property. For example, although the envelope resulting from the slit is nondispersive, a rectangular envelope corresponding to a waveguide is known to be dispersive.

There is a further factor which must be taken into account in constructing the photon wavepacket. A spatially modulated wave can progagate freely only if the wave number is real. Equation (2.3) shows that for this to be so

$$\lambda_x > 2\pi c/\omega \tag{2.5}$$

otherwise the wave will be attenuated as it progresses. The theory of wave-packets indicates that if a packet is formed from a superposition of waves having a minimum wavelength of $2\pi c/\omega$ then the minimum dimension of the resulting envelope will be of the same order. Thus the requirement that the packet should progagate freely in the y direction places a limit on the minimum dimension of the packet in the x direction.

We therefore consider the photon wavepacket to be limited in the x direction by a nondispersive envelope to a width of the order of $2\pi c/\omega$. The photon cannot be perfectly monochromatic and we can consider that it is represented by a superposition of waves of slightly different frequencies so that it is limited in the y direction. If the frequencies of the component waves are distributed over the range $\Delta\omega$ then the length Δy of the photon wavepacket will be of the order of $2\pi c/\Delta\omega$, in accordance with Fourier theory. To ensure conformity with the quantum features of the photon, we assume that the integral of the energy density taken over the volume of the packet envelope is equal to $h\nu$.

Representation of the Photon and its Path. The motion of the photon wave-packet represents a flow of energy and can be represented by the motion of a group of flow lines. We adopt the convention that at any point the spacing of the flow lines is proportional to the intensity of the field. Thus the spacing of the flow lines depends upon the form of the envelope, but generally we can assume that the flow lines are more densely gathered at the center and more widely spaced at the periphery of the photon. The length of the lines represents the length of the photon Δy. For an optical photon the packet will be of the order of 10^{-7} m in width and up to several meters in length, depending upon the coherence properties of the source.

In free space the flow lines representing the photon will remain parallel, but as the packet approaches a diffracting edge the flow lines will begin to undulate in the same manner as for the plane wave. The packet of lines representing the photon must trace out exactly the same lines as those of the plane wave as it moves in order that the boundary conditions for all the infinite component waves may remain satisfied. If the center of the photon passes thorugh the point x_0 on the x axis it will continue to move along the line of flow which passes through that point. (See Figure 1b of the previous paper.) The edges of the photon—defined as the points of, say, 5% of maximum intensity—follow similar, usually almost parallel, lines.

The general form of a flow line is that as it approaches the diffraction screen the angular deviations from the normal increase, reaching a maximum of about 3° in the plane of the screen. These undulations, which are responsible for the maxima and minima of the diffraction pattern, continue beyond the screen with reducing angular deviation and increasing wavelength, unless the flow line enters the region of shadow cast by the screen. This region is defined by the area enclosed by the dark side of the screen and the nearest line of unit amplitude. Outside this area the flow lines weave alternately to the left and right and their displacement from a line running at right angles to the screen is slight even at a great distance from the screen. For this reason a wavepacket which does not enter the shadow region is not significantly dispersed.

If the flow lines enter the shadow region the undulation ceases, the trajectory becomes linear and the lines begin to diverge, so that the packet will begin to disperse. A general discussion of the stability of the packets lies beyond the scope of this paper, but as a rought approximation for the two-dimensional packet considered here one may define the dispersion at any point as the distance between the lines of 5% intensity at that point divided by the corresponding distance in the plane of the diffraction screen. Because the density of the flow lines is proportional to the field intensity it follows that the disperson of the packet is inversely proportional to the field intensity.

If a source emits photons in random directions and these photons are subsequently made to form a parallel beam by a collimating lens placed before a diffraction screen, then since no direction of emission is preferred the whole pattern of flow lines for a plane wave will eventually be traced out by the flow lines representing the photon. Because the density of flow lines is greatest at diffraction maxima the probability that a photon will be detected there is greatest and correspondingly least at the minima. Thus a diffraction pattern will be built up when a sufficient number of photons have been emitted, even if the intensity is so low that on average only one photon is present between the source and the detector at any time. This phenomenon of the interference of single photons is very difficult to understand on the basis of Huygens' principle.

3. *Corpuscular Phenomena*

Having shown how an infinite wave model of the photon accounts for its wave-like aspects as evident in diffraction we shall now show, in an essentially qualitative way, how the same model accounts also for its particle-like aspects. For this purpose we consider the Compton and photoelectric effects which played an important part in the conceptual development of quantum theory.

Compton Effect. The Compton scattering of light by electrons is usually explained in terms of the collisions of particles in which the photon is assumed to possess an energy $h\nu$ and a momentum $h\nu/c$. The situation is depicted in Figure 1. By writing down the equations representing the conservation of energy and momentum, Compton (1923) derived a relation between the wavelength, λ', of the scattered photon and that of the incident photon λ, namely

$$\lambda' - \lambda = (h/mc)(1 - \cos\phi) \tag{3.1}$$

This relation arises from the wave picture on account of the requirement that Maxwell's equations must be satisfied at the electron boundary, and this boundary is moving. We can make an approximation to this case by considering the reflection of a plane electromagnetic wave at a plane boundary. A plane conductor can be considered as a plane of free electrons and so the boundary conditions appropriate to a moving electron will be similar to those for a moving plane. It is well known that if the plane is stationary an electromagnetic wave incident at an angle θ_i will give rise to a reflected wave of the same frequency such that the angle of reflection θ_r is equal to θ_i. The case for a moving plane has been treated by Fujita and Muramatsu (1968) and here both the frequency and angle of the reflected wave are modified as follows. A simple analysis is possible if we restrict attention to the case where the change of frequency is small.

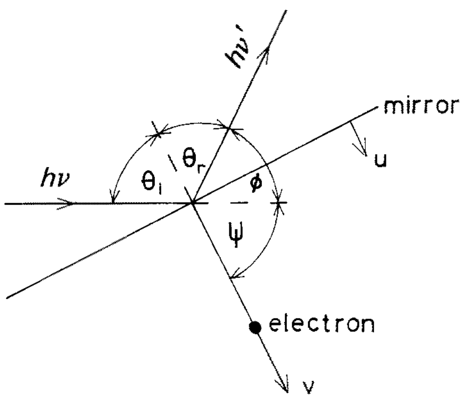

Figure 1 – Compton scattering.

If the reflector moves in a direction perpendicular to its plane with a velocity u and the frequencies of the incident and reflected waves are ν and ν' respectively then

$$\frac{\nu'}{\nu} = 1 - \frac{2u \cos \theta_i}{c} \qquad (u^2 \ll c^2) \tag{3.2}$$

$$\cos^2 \theta_r = 1 - [(\nu/\nu') \sin \theta_i]^2$$

In cases where the change of frequency is small we can assume $\theta_i = \theta_r = \psi$, as represented in Figure 1. The electron is initially at rest and after interaction with the photon has a velocity v. Its average velocity during the interaction is therefore $v/2$, which we can identify with u to obtain

$$\nu'/\nu = 1 - (v/c) \cos \psi \tag{3.3}$$

The photon is emitted by an atom for which the stable states differ in energy by $h\nu$, and neglecting relativistic effects we can write

$$h(\nu - \nu') = \tfrac{1}{2} m v^2 \tag{3.4}$$

Eliminating v from the last two equations gives

$$(\nu'/\nu) = 1 - (2h\nu/mc^2) \cos^2 \psi \tag{3.5}$$

i.e.

$$\Delta\nu = \nu - \nu' = (2h\nu^2/mc^2) \cos^2 \psi \tag{3.6}$$

The corresponding change in wavelength is given by

$$\Delta\lambda = (c/\nu^2)\, \Delta\nu = (2h/mc) \cos^2 \psi \tag{3.7}$$

but since $\phi + 2\psi = 180°$

$$\Delta\lambda = (h/mc)(1 - \cos \phi) \tag{3.8}$$

which is the same as equation (3.1). This analysis is not intended to be rigorous; it merely allows the use of some published results for a plane boundary to indicate the feasibility of an explanation of the Compton effect in terms of waves. The interaction of a wavepacket with an electron also results in momentum being imparted to the latter as in the particle description. This is because the normal pressure of radiation exerts a force (F) on the electron for a time (t) during which the electron remains within the packet envelope. The momentum imparted to the electron will be $\int_0^t F\, dt$. The force which is thus exerted on the electron is responsible for the emission of electrons in the photoelectric effect.

The Photoelectric Effect. The corpuscular aspect of photon behavior is perhaps most clearly evident in the photoelectric effect. The explanation just given of the manner in which force is exerted on an electron by a wavepacket is not sufficient in itself to account for this effect, because one would expect many of the atoms of the photo-emitting material to be encompassed by the photon envelope, yet it is to only one of the constituent electrons that the energy of the photon is transferred. We shall now give a qualitative account of a possible mechanism for this effect in terms of the wave theory.

We consider first the manner in which a photon is created. An electromagnetic disturbance is caused when an excited atom reverts to its ground state. This atom has dimensions of the order of 10^{-8} cm and we suppose that it emits visible radiation with a wavelength of about 10^{-5} cm. Now we have seen that a wavepacket cannot propagate freely unless its dimensions are greater than the wavelength of the radiation composing it. Therefore the radiation initially emitted by the atom is not freely propagated. However, attenuated waves can still be emitted and initially these will produce a localized field of energy surrounding the atom. After about 10^{-15} sec this "bubble" of energy will have grown to a size where unattenuated propagation can occur and the bubble becomes a wavepacket expanding in the direction of propagation and having a cross sectional diameter of about 10^{-5} cm. Radiation continues to flow out from the atom until it has delivered sufficient energy, i.e., $h\nu$, to enable it to remain stable in the ground state. The integral of the energy density taken over the volume of the photon envelope must be equal to $h\nu$. The length of the photon will be dependent on the mode of the original atomic oscillations. If these are such that the resulting E and H vectors are large in magnitude the photon will be short, but if they are weak the photon will be long and coherent.

When the wavepacket interacts with an electron in the photoemitter a reverse process occurs. The electron begins to oscillate in sympathy with the electromagnetic field. The self-field of the electron is in opposition to the field in the photon envelope so that the result is that energy is transferred to the electron and the wavepacket is diminished. But as soon as the packet is reduced below the critical diameter it can no longer propagate freely and an energy bubble is formed around the electron. More energy is given to the electron and its self-field increases. The wavepacket thus begins to collapse onto the electron and the final result is that the energy of the photon is given to the electron and the photon is annihilated by the self-field of the electron.

4. *The Infinite Wave Concept and the Copenhagen Interpretation*

Comparison of Interpretations of Interference. The explanation of wave- and particle-like phenomena in terms of the infinite wave concept is of an essentially classical nature supplemented by the idea that energy is exchanged only in units of $h\nu$, which thus remains as the essential quantum feature. However, the adherents of the Copenhagen interpretation assert that such a classical description of quantum phenomena is not admissible. It will be interesting therefore to consider a physical phenomenon in terms of both interpretations with a view to establishing some point of difference between the two which might be made the subject of an experimental test. We shall consider the interference pattern built up by a succession of single photons passing through a Young's double-slit arrangement as shown in Figure 2. The source is assumed to be at a great distance from the slits so that the incident light may be considered parallel.

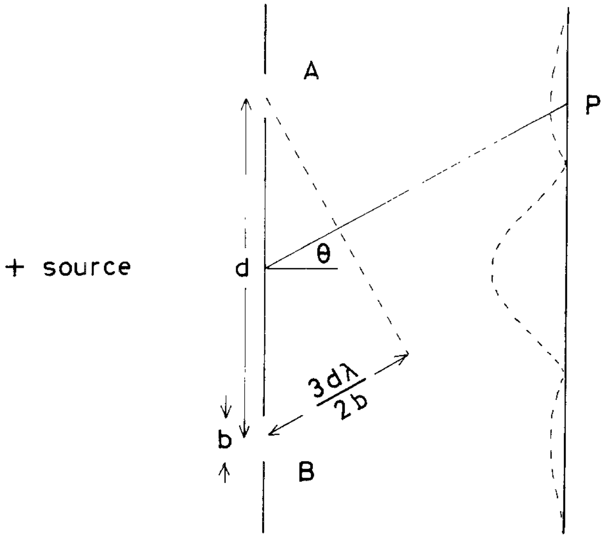

Figure 2—Interference experiment.

According to the infinite wave interpretation, a photon emitted from the source will follow a certain trajectory and can be represented by a selection of flow lines taken from the pattern corresponding to a plane wave. The precise trajectory which will be followed depends on the initial direction of emission of the photon and this in turn depends on complex influences in the emitter which are not fully known. Whatever these processes may be, we may say that for a uniform source there is an equal probability of emission in every direction. In the absence of the slits the lines of energy flow are parallel and there is an equal probability that the center of the photon will arrive at any point on the screen. However, the introduction of the slits causes undulations to occur in the photon trajectory and there is then an increased probability that the photon will arrive on the screen at the places where the flow lines are most dense. After a sufficiently large number of photons have been emitted most of the possible trajectories will have been traced out and hence an interference pattern corresponding to that for a plane wave will have been built up. The *a priori* probability that a photon will arrive at a given point on the screen is proportional to the density of flow lines and this is proportional to the intensity of a plane wave at that point i.e., $H_zH_z^*$.

On the other hand, from the standpoint of the Copenhagen interpretation there is no meaning in ascribing a trajectory to the photon. It exists potentially in the whole of space until it is detected. The probability that it will be detected at a given point is determined by the magnitude of the wave function or state vector at that point. If the wave function is ψ, then the probability of detection is $\psi\psi^*$, and it can be shown that this varies in the same way as $H_zH_z^*$, in conformity with the correspondence principle.

Both interpretations thus lead to the same physical result, the appearance of an interference pattern. The difference is that in the wave theory the introduction of probability arises only because of ignorance concerning the complex influences in the emitting atom, whereas in the Copenhagen interpretation probability is considered to be a primary element. According to the wave theory, changes in the probability of detection are caused by changes in the photon trajectories, whereas in the Copenhagen interpretation this is due to changes in the amplitude of the wave function and the existence of a trajectory is denied. From the standpoint of the wave theory the interpretation of $\psi\psi^*$ as a probability of detection is correct, but ψ can have meaning only in relation to an *ensemble* of photons; it cannot be considered capable of a complete description of all that happens between the emission and detection of individual photons. For this, a detailed knowledge of the emission and absorbtion processes is required.

Although the wave theory does not provide the detailed knowledge of these processes, it does make a specific prediction which cannot be derived from the Copenhagen ideas. Referring to the energy flow line diagram for the double slit (Figure 3c of the previous paper) shows that no lines cross the axis of symmetry between the slits. This is related to the fact that the lines of constant phase always cross the axis at right angles and hence the flow lines, which are orthogonal to the phase lines, cannot cross it. It follows that there is no photon trajectory which can cross this axis and we must conclude that photons which illuminate the right-hand part of the screen always pass through the right-hand slit and that no photons pass into this region via the left-hand slit.

This conclusion is in conflict with the Copenhagen interpretation which asserts that since it is not possible to determine through which slit the photon passes without destroying the interference pattern, it is not meaningful to ask through which slit the photon passes while the pattern exists. Nevertheless it should be possible to investigate this difference between the wave theory and the Copenhagen interpretation by means of the following experiment and so to determine which viewpoint is the correct one.

Experiment to Determine the Nature of Interference. Consider two parallel slits of width b in a conducting plane, the centers of the slits being separated by a distance d (Figure 2). If a screen is separated from the plane of the slits by a distance much greater than d, the intensity I on the screen will be given by the formula for Fraunhofer interference

$$I = (A \sin^2 \beta \cos^2 \gamma)/\beta^2 \tag{4.1}$$

where $\beta = \pi b \sin \theta/\lambda$, $\gamma = \pi d \sin \theta/\lambda$, λ is the wavelength of the radiation and A is a constant. The source is a microwave generator with a sharply pulsed output. A time-sensitive detector placed at P could distinguish radiation which has passed through slit A from that which has passed through slit B on account of the difference of $d \sin \theta$ is the respective path lengths. Suppose for example that the detector is placed at the first intensity maximum of the diffraction pattern, where $\sin \theta \simeq 3\lambda/2b$, and if $d = 100$ cm, $b = 3$ cm, $\lambda = 1$ cm, then the difference in the path length is 50 cm, corresponding to a time difference of 1.7 nsec. Time intervals of this magnitude should be detectable with modern apparatus. A similar experiment could also be performed at optical wavelengths using a sharply pulsed laser as a source and a suitably fast photodetector.

If some of the photons arriving at P had in fact traveled through one slit, and some through the other, one would expect the detector to register two pulses separated by an interval corresponding to the different times of transit via the respective slits. On the other hand, if the photons travel through one slit only, then only one pulse would be observed. One should therefore be able to distinguish between these two cases by observing the form of response of the detector.

In this experiment we are concerned with a transient pulse. Such a pulse can be considered as a superposition of plane waves of different frequencies. The flow lines corresponding to the pulse can be obtained by summation of the energy components at each frequency. Although the flow-line pattern will be different for each frequency, the feature that no lines cross the axis of symmetry will be retained in every case, as discussed in the previous paper. It follows that in the summation representing the flow pattern for the pulse the same feature will remain and that therefore energy will not flow across the axis. Thus even though we are dealing with a transient situation, the essential physical basis of the experiment remains unchanged.

It has generally been believed that whenever a successful attempt is made to determine through which slit a photon passes the interference pattern is destroyed. In the present case the argument from the Copenhagen point of view would be that the switching of the source modulates the radiation so that it is not sufficiently monochromatic for interference to be observed. If the pulse is sufficiently sharp to allow determination of the transit times via the respective slits. then the modulation of the frequency would be such as to ensure that the interference pattern was not produced. It is important to stress, therefore, that in the present experiment we are not primarily concerned with whether the interference pattern exists. We wish to confirm that in the configuration of source, slits and screen shown in Figure 2, photons arriving in the right-hand part of the screen *always* travel through the right-hand slit. If this can be successfully demonstrated it will support the interpretation of interference which we have given earlier and it would follow that discussions of the double-slit problem in terms which imply that photons pass sometimes through one slit and sometimes through the other are not relevant. On the other hand, failure to demonstrate this point would call Maxwell's equations into question.

The Uncertainty Relations. This account of quantum phenomena in terms of infinite waves is essentially deterministic and it might be thought that such a description would be incompatible with the Uncertainty Principle, according to which it is not possible to determine all the characteristics of a physical situation with arbitrary precision. The view which emerges from the infinite wave concept, however, is that the physical situation can be exactly described in principle, but that the canonically conjugate pairs of variables which appear in the uncertainty relations are not suitable measures for such an exact description.

If the electromagnetic wavepacket which constitutes the manifest aspect of the photon is to have a frequency defined within the limits of $\Delta\omega$, the arguments of Section 2 show that it must be of a certain length, Δy, in accordance with the relation $\Delta\omega\, \Delta y \sim 2\pi c$. It will therefore take a time $\Delta t = \Delta y/c$ for the envelope to traverse a particular point and it must take this time to give up its energy in any interaction. Using Planck's formula $E = h\omega/2\pi$ gives the uncertainty relation $\Delta E \cdot \Delta t \sim h$. This relation can thus be simply understood as stating that if the energy of the photon can be defined within the limits of ΔE, then by reason of the finite photon length a time Δt will be required for its energy to be given up in any interaction. It does not imply that there is anything implicitly uncertain abut the nature of the interaction or the photon. It is not possible to define a wavepacket in terms of a single point and a single frequency. In general the packet will be distributed in space in a definite way depending upon the spectrum of frequencies which are associated with it. We can infer from this that single values of energy and position are not appropriate measures for description of a photon. However, the photon can be exactly defined by an average value of position and a distribution of energy or frequency components. This distribution, while not single valued, can be perfectly definite. The so-called "uncertainty relations" can thus be seen to arise from the necessary relationship between the distribution of frequency components in a wavepacket and the spatial extension of the resultant envelope.

5. *Discussion*

It is interesting to recall that the Copenhagen interpretation was criticized at the time of its inception by several of the scientists upon whose work the whole foundation of the theory rests. Einstein, Schrödinger, and De Broglie were prominent among those who were reluctant to accept a fundamental indeterminacy at the basis of physical reality. For many years after publishing his famous equation Schrödinger sought to interpret it in terms of waves, very much in the manner described in this paper. He did not succeed in this, however, because he restricted his attention to the ψ waves or wave functions themselves and it turns out that wavepackets constructed from these waves are unstable. Criticism of the Copenhagen interpretation has continued for more than forty years. A review of the present situation has been given by Ballentine (1970), who concludes that there are serious logical problems inherent in the notion that the statistical interpretation of quantum theory is also complete.

In this paper we present a new approach. We have shown that the problem of interpretation has its roots in the conceptual understanding of interference in terms of Huygens' principle, and once this obstacle is removed it becomes possible to account for both corpuscular and wave-like properties of the photon in terms of a single physical model. We have shown how this model reproduces the results of the Copenhagen interpretation with respect to the position probability density in an interference experiment yet gives additional information which may be made the subject of an experimental test.

It should be emphasized that the infinite wave concept does not lead to rejection of the idea that the ψ function in quantum mechanics is a measure of the probability of detection of a particle. This remains true and all conclusions of quantum theory based on this tenet remain valid. But from the point of view of the wave theory the ψ function can refer only to an ensemble of particles; it cannot provide a complete description of the behavior of individual particles. In cases where quantum theory makes quantitative predictions, these will stand, but where the current interpretation asserts that experimental results are indeterminate or not meaningful then we may hope to gain some further insight, as we have shown by identifying the slit through which a photon has passed in an interference experiment. Furthermore, once it is recognized that a particle follows a trajectory which is not uniquely described by quantum theory, then it is possible to resolve all the well-known paradoxes associated with the theory such as those of Einstein, Podolsky, and Rosen, Schrödinger's cat, and the negative result experiments suggested by Renninger and others. All these paradoxes arise because the wave function is considered to be a complete description of the physical situation.

Thus far we have been concerned only with photons, and the question arises as to how other particles with mass and charge are to be accounted for. But bearing in mind that interference effects can be obtained with all particles, even when the intensity of the incident beam is very low, it would seem that this must have the same cause as in the case of the photon, namely that it is due to undulations in the particle path resulting from the conditions imposed on the infinite components of the particle by the boundaries of the interference apparatus. If this is so, then it would appear that the infinite substructure of the particle is a general principle of nature.

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