

Review Article

Newton's Theory of Light and Wave-Particle Duality

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Abstract: The long history of the dispute among physicists as to whether matter is composed of particles or waves is reviewed. A turning point came at the dawn of the 20th century in the form of the de Broglie momentum-wavelength and Bohr/Planck energy frequency relations. It was on this basis that Schrödinger developed a quantum mechanical differential equation whose solution came to be known as a wave function. The Born Interpretation of these functions holds that their absolute square constitutes a probability distribution which has been used successfully to make predictions of the properties of the system under discussion. It is pointed out that the phenomenon of light refraction played a key role in the development of both Newton's corpuscular theory of light and the competing theory of Huygens which looks upon light as consisting exclusively of waves. It is shown that Newton's failure to predict the decrease in the speed of light as it passes from air into water was *not* because of his belief in the particle composition of light, but rather because he not did anticipate that the mass of a photon changes upon entering a medium of higher index of refraction n . By assuming that the energy E of light is equal pc/n , where p is the momentum of the photons and c is the speed of light in free space, it is shown that the experimental dependence of the speed of light on its wavelength as it passes through a transparent medium is derived successfully through the use of Hamilton's Canonical Equations and Newton's Second Law of Kinetics. It is suggested that the relationship between particles and waves can be understood by noting that the localized properties of matter exhibit themselves in experiments such as the photoelectric effect where attention can be concentrated on the behavior of a single particle. The corresponding wave properties occur when large numbers of particles are observed under exactly similar circumstances, as for example in electron diffraction. The Young double-slit experiment and the Einstein-Podolsky-Rosen paradox are discussed as well.

Keywords: Born interpretation of wavefunctions, Newton's corpuscular theory, Huygens' wave theory, wave-particle duality, light refraction, Einstein-Podolsky-Rosen paradox.

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I. INTRODUCTION

In recent work it has been shown that a Hamiltonian which includes short-range Breit-Pauli interactions such as spin-orbit and spin-spin coupling can be employed successfully for the description of high-energy processes such as positronium decay [1, 2]. It is based on the wave mechanics method commonly employed for molecules and atoms and is therefore denoted as the Exponentially Damped Breit-Pauli Schrödinger (XBPS) model. Its results consist of wavefunctions which are thought to be subject to the Born interpretation [3]. Accordingly, the absolute squares of these functions are associated with

probability distributions which are used to obtain expectation values of measurable properties for the system at hand.

One of the fundamental questions which arise in this context is whether matter is composed of particles or waves. In particular, there has been much speculation about the phenomenon commonly referred to as *wave-particle duality*. This subject leads inevitably to a review of the competition between Newton's corpuscular (localized particle) theory of light and the counter proposal espoused by Huygens which envisions light as consisting of waves which are extended

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throughout space. The following discussion goes into the details of both of these theories, including the various experiments which have been carried out in an attempt to resolve the issues in question.

II. TRANSLATIONAL MOTION AND WAVE-PARTICLE DUALITY

The physical model on which the theoretical arguments of previous work [1, 2] are based operates on the principle that systems such as the neutron and muon are complexes of the electron, proton, neutrino and their respective antiparticles. The questioning of the creation-and-annihilation hypothesis of matter therein is motivated in large part by experience with atoms and molecules. They are observed to decompose into ever smaller components when subjected to external forces and not simply to drop out of existence entirely.

The theoretical framework chosen to provide a quantitative description of such particles is that of the Schrödinger and Dirac equations in which *wavefunctions* are generated. The concept of wave-particle duality will therefore be given careful consideration in what follows.

The wavefunction Ψ which results from solution of quantum mechanical equations was interpreted by Born [3] to have *only statistical significance*. Its absolute square $|\Psi|^2$ serves as a distribution function to be employed in computing the average values of properties of the system under consideration. This identification is not in itself in conflict with the ancient philosopher's idea of an atom or particle, however. It still leaves open the possibility that, at any given time, particles *always have a definite position in space*. It emphasizes instead that observations of identical objects under the influence of the same system of forces over a long period of time *are characterized by a definite statistical pattern*.

For example, consider the case in which the motion of a planet in the gravitational field of a star is charted over the course of centuries. From this information a distribution function can be defined which gives the percentage probability of finding its center of mass in a certain volume element. However, just because this distribution function has a continuous form does not at all mean that one must ascribe delocalized characteristics to the planet.

Yet, the concept of wave-particle duality is generally taken to mean that sub-atomic systems such as electrons and photons cannot be regarded in this way. Experiments can be carried out whose interpretation is argued to be impossible without giving up a strictly localized description of such systems [4]. Because of the fact that our view of physical reality is profoundly affected by the degree to which the particle model of subatomic systems succeeds in explaining experimental observations, it is important to give careful scrutiny to

the wave-particle duality interpretation. In particular, one should focus on the question: *does a single particle ever exist in more than one location at any one time?* It is probably safe to conclude that Newton would have vigorously opposed such a suggestion. He would have attempted to settle the matter exclusively on the basis of indisputable observations [5], being careful in his argumentation to avoid the slightest dependence on the assumptions of some theoretical model.

To begin such a discussion, it is well to return to the treatment of translational motion in dynamical theory. Schrödinger was led to his operator substitution hypothesis [6] by studying the motion of a free particle, i.e. in pure translation. He employed de Broglie's ideas [7] regarding the equivalence of certain properties of particles and waves to define a prototype differential equation which could be generalized to deal with more complicated phenomena requiring the use of a potential. Einstein also used a free particle's motion to guide his development of the theory of special relativity [8]. These observations suggest that the essence of the wave-particle duality concept can also be found in the study of translational motion.

The free-particle wavefunction is $\exp[\pm i(kr - \omega t)]$, where $|k| = |p|/\hbar = 2\pi/\lambda$ and $\omega = E/\hbar = 2\pi\nu$ (\hbar is Planck's constant 6.625×10^{-34} Js and $\hbar = h/2\pi$; p is the momentum and E is the energy of the free particle). It should be clearly understood that such a wavefunction is a characteristic of a *single* particle in this picture [3, 4]. A term such as "stream of like particles" in this connection merely implies that *each* such particle is described *by the same statistical distribution*. Experimentally one could determine the latter by subjecting *one* such particle to exactly the same experimental conditions a large number of times. The same distribution function is also relevant to the description of the motion of *many* such particles at one time, however, in which case the wave properties of the aggregate system can be observed directly, but this relationship can only hold if the particles in the aggregate system do not interact with one another. Otherwise, each of their wave functions would necessarily be different than for their corresponding isolated state. There are limits to which it is feasible to consider a stream of electrons as free particles, entirely unaffected by each other, but this condition is fulfilled to a very good approximation in the classical electron diffraction experiment [9]. One can easily distinguish between an experiment carried out for a single particle and one for a collection of them, but as long as the above condition of non-interaction is fulfilled, it is permissible to use the same statistical distribution function in both cases.

Since any free particle can be treated in the same way, it is also readily understandable why a statistical distribution based on the above wavefunction appears to be a *universal* property of pure translation.

Even at relativistic speeds, the eigenfunctions of the total Hamiltonian for any isolated system, independent of its composition, are also eigenfunctions of the translational energy operator. Thus such a relationship between the momentum and kinetic energy of the center of mass and the wavelength and frequency of the relevant statistical distribution would always be guaranteed.

In this connection, it is worth recalling that $\Sigma \mathbf{p}_i$ commutes with each \mathbf{p}_i and \mathbf{r}_{ij} (inter-particle separation) quantity, so that the translational energy operator itself must have a common (complete) set of eigenfunctions [10] with any Hamiltonian containing exclusively these kinds of variables. Hence, any exact solution of a corresponding Schrödinger equation must always be characterized by a definite value of the translational energy. This observation underscores another assumption in the usual separation-of-variables argument for internal and center-of-mass coordinates, however. The Breit-Pauli terms mentioned in a relativistic treatment [11] contain momentum factors as well as particle separations. Consequently, even when the non-relativistic kinetic energy is employed, the desired separation is not complete for a Hamiltonian containing these types of interactions. This presents no real problem for calculations of one-electron atoms, in which the masses of the constituent particles differ greatly, but for a system consisting of only e^+ and e^- [1, 2], there is need for more careful consideration.

With the above line of argumentation one can summarize the situation, at least tentatively, as follows: the wave properties of a given system only arise when *large numbers of such particles are observed under the same conditions over the entire duration of an experiment*. By contrast, the characteristic properties of a localized system exhibit themselves even if attention is restricted to the behavior of a single particle. The photoelectric effect [12] is a prime example of the latter type, and this experiment led Einstein to re-examine the long-held position that light is strictly a wave-like phenomenon [13]. The opposite side of the coin is the diffraction experiment, in which interference patterns are observed. It seems unavoidable to conclude that such spectral images do not result from a single photon (or other particle), in agreement with the above principle. Yet, it is exactly experiments of the latter type which have led to the conclusion that a single particle can also exhibit wave characteristics.

This is the crucial contention which needs to be carefully examined. For if the wave properties commonly associated with particles only arise because of the collective motion of large numbers of them, as suggested by the above statistical argument, *there is really no need to speak of a wave-particle duality* to describe the relevant experimental findings. Instead, the de Broglie wavelength [7] and the Bohr/Planck frequency [14] can simply be characterized as statistical

parameters needed to specify an appropriate distribution function for a large sample of indistinguishable particles, each of which possesses the same momentum and energy. Similarly one can also understand the Heisenberg uncertainty relation [15] as a purely statistical law, whereby the quantities Δp and Δq in this inequality are taken as rms deviations from mean values of complementary dynamic variables. They are determined by carrying out *a series* of equivalent measurements on large *representative samples* of a given type of particle.

In short, if waves are nothing but streams of individual particles, then Newton was right when he argued in favor of his corpuscular theory of light [5]. Before taking a closer look at the key interference phenomena which are always cited in favor of the principle of wave-particle duality and against his position, however, it is well to examine another experiment which gave a decided impetus to the wave theory of light during Newton's lifetime.

III. THE REFRACTION OF LIGHT

The bending of light rays at an interface of two media of different density was one of the earliest phenomena to be characterized by a mathematical equation [16, 17]. The sine law of refraction was discovered by Snell several thousand years after the other two laws governing this process had been discovered. Newton [5] attempted to explain such observations in terms of the particle model of light, while Huygens [18] argued that they could only be understood in terms of wavelike properties.

Newton lost the argument, but it is interesting to see why. Since the angles of incidence and refraction (see Fig. 7 of Ref. [19]) were not changed in multiple passes of light rays through the same media, it could safely be assumed that the energy of the hypothesized particles of light remains constant. The fact that the light is bent downward upon entering a medium of higher density indicates that the potential V acting on the particles must be attractive, i.e. it decreases after crossing such an interface. Combining these two facts led unmistakably to the conclusion that the kinetic energy T of the light particles must be *greater* in the denser medium. Assuming that T was proportional to the square of the velocity, in accordance with the then accepted dynamical theory, thus led to the prediction that the speed of light must be greater in water than in air, which is incorrect [19]. *Proceeding on the principle that an assumption which is contradicted by observation is false, it was thereupon concluded that this result refuted the particle theory of light once and for all.*

Examination of the above argument shows that another error of a different kind was made, however, which ultimately invalidates the latter conclusion. In the first place the kinetic energy of the photon does not

satisfy the non-relativistic relation employed therein. When the correct formula is used, one is still led to conclude that the momentum of the photon increases in going to the denser medium, but since the mass of such particles cannot safely be assumed to be constant in a proper relativistic treatment, *it no longer follows that the velocity of light must increase as well*. The conclusion that light rays cannot simply be streams of photons because a purely mechanical treatment of the refraction phenomenon leads to a false prediction on this basis *is therefore not justified*. On the other hand, if it is assumed not only that light consist of particles but also that their collective motion conforms to a definite statistical distribution, a different result is obtained from the refraction analysis [20].

Snell's Law of Sines established the relationship between the angles of incidence and refraction of light rays as they pass between two different transparent media:
 $n_1 \sin\theta_1 = n_2 \sin\theta_2 \dots\dots\dots (1)$

Where n_1 and n_2 are the refractive indices of the two media. Newton argued that the light consists of particles that are subject to his Second Law. It was assumed that the light rays travel in straight lines within each medium and therefore that there are no unbalanced forces in either region. By further assuming that the light refraction is caused by a force $\mathbf{F}=\mathbf{dp}/dt$ normal to the interface, he concluded that the momentum p of the particles in a tangential direction must be conserved and therefore that the following equation must be satisfied:
 $p_1 \sin\theta_1 = p_2 \sin\theta_2 \dots\dots\dots (2)$

Which is obviously similar in form to eq. (1). Comparison of the two equations thus leads to the following proportionality between the momentum of the particles and the index of refraction of the corresponding light rays:
 $p_1/p_2 = n_1/n_2 = \sin\theta_2/\sin\theta_1 \dots\dots\dots (3)$

Although eq. (3) only deals with momentum (a term not used in Newton's *Opticks* [21]), it was used by Newton to make his famous prediction about the speed of light in water. He concluded that since the index of refraction for water is greater than that for air, it must follow that the speed of light must be larger in water as well. This conclusion gained increased significance at the time because it placed his corpuscular theory of light in direct conflict with the wave theory of Huygens and others on this question.

In the wave theory of light it was assumed that Snell's Law of Sines implies that the speed of light decreases as it passes from air into water. The change in angle could be explained [22] by assuming that the distance separating spherical wave fronts decreases as the light passes into a region of higher index of refraction. According to this model, the wavelength $\lambda =$

$2\pi/k$ of the light waves changes in direct proportion to $\sin\theta$, with the result:
 $\lambda_2/\lambda_1 = k_1/k_2 = n_1/n_2 = \sin\theta_2/\sin\theta_1 \dots\dots\dots (4)$

At the same time, it was assumed that the frequency $\nu = \omega/2\pi$ is completely independent of the refractive index for a given medium, so that the corresponding speed of light c_i must be inversely proportional to n_i , i.e.:
 $c_i = \lambda_i \nu = \omega/k_i = c/n_i \dots\dots\dots (5)$

Where c is the speed of light in free space (for which $n=1$ by definition).

In 1850 Foucault measured the speed of light in water and it was clear that his results stood in irreconcilable contradiction to Newton's prediction. This was quite generally accepted as a complete victory for the proponents of the wave theory of light, but in later years more accurate experiments [23-25] showed that its prediction in eq. (5) is not completely verified either. Instead, the following dependence of the light speed v_g on the derivative of the refractive index with respect to wavelength was indicated:
 $v_g = c/n_g = c/n + (\lambda c/n^2) dn/d\lambda \dots\dots\dots (6)$

The presence of the correction term on the right-hand side of this equation has been justified [26] in terms of dispersion effects that are expected to occur when light enters a different refractive medium. Application was made of Rayleigh's theory of sound [27] and its explanation of how beats arise when waves of slightly different wavelength are allowed to interfere.

It is important to examine the question of the assumed dispersion effects, as has been done in Ref. [20], but before doing so, it is instructive to consider how Newton could have so misjudged the effects of light refraction on the speed of light. Such a discussion becomes all the more relevant when it is realized that 55 years after Foucault's experiments had been reported, Einstein [8] effectively resurrected the particle theory of light by virtue of his interpretation of the photoelectric effect.

With centuries of hindsight, however, it is not difficult to find other indications that Newton was on the right track after all. Primary among these is the conclusion that results when eq. (3) of the particle theory is brought into connection with eq. (4) of the wave theory. As already discussed above, the latter predicts that the wavelength λ of light is inversely proportional to the refractive index n of the medium, whereas the former concludes that the momentum of the associated particles of light is directly proportional to n . Combination of these two theoretical relationships leads directly to another, namely:
 $p_1/p_2 = \lambda_2/\lambda_1 = k_1/k_2 \dots\dots\dots (7)$

Which in turn can be reformulated in terms of a specific proportionality constant:

$$p = h/\lambda = (h/2\pi) k \dots\dots\dots (8)$$

Stark [28] was apparently the first to arrive at eq. (8). He was influenced by a meeting in which Planck's radiation law was a key topic of discussion [29]. The proportionality constant h in eq. (8) is the same as Planck [30] used eight years earlier to introduce his quantum hypothesis and the corresponding relation between energy E and frequency ν :

$$E = h\nu = (h/2\pi) \omega \dots\dots\dots (9)$$

Its present-day value is 6.625×10^{-34} Js.

It is a matter of historical fact that the proponents of the corpuscular and wave theories of light did not obtain eq. (8) on the basis of their studies of light refraction, but that does not change the conclusion that this goal could readily have been achieved over 200 years earlier by simply combining eq. (3) with eq. (4). The reason that Newton and Huygens did not make this connection is most probably because they did not recognize the validity of the other's model for the composition of light and thus were not disposed to making use of any of its respective predictions. The fact that eq. (8) can be derived in a straightforward manner from the two "opposing" theories of light refraction is nonetheless a key observation in theoretical physics. It shows that Stark's recognition [28] of the relation between the momentum of particles of light and the wavelength of the corresponding radiation actually serves as an important confirmation of both theories, in particular that of Newton, since the latter has often been claimed to have been contradicted by the experimental data for light refraction.

None of the above changes the fact that Newton did make a critical error in predicting that the speed of light is greater in water than in air. The reason was not his corpuscular theory, however. Rather, it was his inability to compute the light speed in a manner which was consistent with his Second Law. The decisive impulse in this direction was provided by Hamilton and his canonical equations of motion, published 130 years after Newton's *Opticks*. The key equation in the present context is:

$$dE/dp = v \dots\dots\dots (10)$$

Perhaps ironically, eq. (10) can be derived in a straightforward manner [31,32] on the basis of the Second Law and the definition of work/energy as $\mathbf{F} \cdot d\mathbf{r} = d\mathbf{p} \cdot (d\mathbf{r}/dt)$.

The first step in arriving at the correct dependence of the speed of light in refractive media is to apply eq. (10) to obtain the relation between the energy and momentum of the particles of light in free space. Newton had shown in *Opticks* that white light is

decomposed into its component colors when it passes through a glass prism. He concluded that this phenomenon is caused by the varying accelerations experienced by the particles of light associated with different colors when they enter a refractive medium. Since white light travels great distances from the sun without undergoing an analogous decomposition, it follows by the same reasoning that the speed of light has the same constant value c for all corpuscles/photons in free space. As a result, the desired relation can be obtained by integration of eq. (10) for the special case of $v=c$ while setting the constant of integration to zero, namely as:

$$E = pc \dots\dots\dots (11)$$

The same equation was used by Stark [28, 29] to derive eq. (8) from Planck's radiation law in eq. (9).

The next step is to generalize eq. (11) for the case of photons in a medium of refractive index n . Because p is proportional to n in Newton's particle theory, it follows that p can be replaced by p/n without changing the original equality relationship. Furthermore, because of its association with the color of the light, the energy E of the photons can reasonably be assumed to be unaffected as they pass between different refractive media. Consequently, the most straightforward choice for the generalized version of eq. (11) is:

$$E = pc/n \dots\dots\dots (12)$$

The speed v of the photons is then obtained from eq. (10) as:

$$v = c/n_g = dE/dp = c/n - (pc/n^2)dn/dp \dots\dots\dots (13)$$

Substitution of the $p=h/\lambda$ relation of eq. (8) then leads directly to the observed expression for the velocity of light given in eq. (6). The corresponding formula for the group refractive index n_g in eq. (13) can be obtained directly as:

$$n_g = d(pc)/dE = d(nE)/dE = n + E(dn/dE) \dots\dots\dots (14)$$

It is also worth noting that Planck's radiation law [14, 30] in eq. (9) is obtained by combining eq. (5) of the wave theory of light with eq. (12):

$$E/p = c/n = \omega/k = \lambda\nu \dots\dots\dots (15)$$

Substitution of the relation between momentum and wavelength in eq. (8) gives:

$$E/p = E\lambda/h = \lambda\nu \dots\dots\dots (16)$$

Which upon cancellation and rearrangement yields eq. (9). Planck based his discovery on a statistical treatment of the entropy of blackbody radiation [30], but the same result is seen to be obtained from Newton's corpuscular theory [21] and its treatment of light refraction when used in conjunction with Hamilton's canonical equations.

In summary, when one uses the correct definition for velocity (Hamilton's equation), Newton's corpuscular theory is found to be in quantitative agreement with experiment, including most especially with Foucault's determination of the speed of light in water. Newton's error is seen to be his implied assumption that the inertial mass $m = p/v$ of the corpuscles/photons is the same in all media. By contrast, the value obtained from eq. (12) for p and eqs. (6,13) for v is:

$$m = p/v = (nE/c)/(c/n_g) = n_g E/c^2 = n_g h\nu/c^2 \dots\dots\dots (17)$$

The mass of Newton's corpuscles increases as the square of the refractive index, which means it is roughly 1.7 times larger in water than in air, causing him to overestimate the corresponding speed of light in the former medium by this factor (note that eq. (17) stands in contradiction to Einstein's famous $E=mc^2$ relation [8], thereby demonstrating that the latter is *not* of completely general validity).

Dicke and Wittke [33] have also used the de Broglie relation to derive the sine law of refraction explicitly, thereby showing that wave optics and Newton's classical mechanics are consistent in this respect as well. From the standpoint of Newton's dispute with Huygens, however, there is an important distinction between regarding light as a stream of particles moving in accord with a particular statistical distribution law instead of as an intrinsically wavelike substance. In the first case, one can still speak of the individual units of light as particles which are always perfectly localized in space, whereas in the second, a delocalization is implied which is inconsistent with the concept of a particle.

IV. PROBABILITY ADDITION LAW AND INTERFERENCE PHENOMENA

As remarked in Sect. II., one does not really come to the crux of the wave-particle duality question until interference phenomena are considered. The most frequently analyzed experiment is that performed by Young [34, 35] in 1802, in which light from a single source is allowed to pass through two narrow slits separated from one another by some distance. The interference pattern which results is not the same as what is obtained by superimposing the results of two similar experiments in which only one of the slits is open for the same period of time. This result is generally interpreted as follows [36]. If the light emitted from the source were to consist of particles which are always localized, then each of them would have to pass through *either* one hole or the other. It is safe to say that Newton would have agreed with this statement. Since the holes are relatively far apart, it is impossible that particles going through one of them would be affected by those going through the other. Experimentally one can show that the interference pattern does not result because of collisions between individual photons because the intensity of the light can be decreased to the

point that it is impossible that more than one such particle be in the apparatus at any one time. Dirac summarized this situation [37] by saying that it is as if each photon "interferes with itself."

Since particles cannot interact with themselves but waves (or anything that is extended through space) can, the conclusion that light units (and everything else) somehow behave as both particles and waves depending on the set of governing conditions seems inescapable. For a stream of particles to give a different distribution on a screen depending on whether the two slits through which they pass are always open or whether they alternate in being open and closed in a complementary manner seems tantamount to ascribing some sort of intelligence to them. How can the photons at the source know which holes are going to be open and when?

Yet the solution to this dilemma of attributing both wave and particle properties to matter is also not without its ambiguities. Once the decision is made that a photon (or electron) must pass through both slits [38] in the Young experiment before reaching the screen, a simple variation presents itself. Send a single photon through the apparatus and replace the screen by a photographic plate [36]. The experiment mentioned above approaches this in principle, namely by letting a maximum of one photon through the apparatus at any one time. The fact that the usual intensity pattern still develops *after a sufficiently long time* proves that the photons do not collide with one another, but as long as *more than one particle is involved, it is impossible to be certain that any one of them has passed through both slits* on its way to the photographic plate.

The lack of a suitably sensitive photographic plate renders such an experiment impractical [36], but its conceptualization at least illustrates that the principle of wave-particle duality implies a definite result of an experiment which has actually never been carried out. The possibility that a single photon makes more than one impact on the screen of the Young apparatus, or that it somehow recombines after passing through each of the slits so as to make only one indentation, is sufficiently improbable as to warrant skepticism in the absence of a means of positively verifying its occurrence. In recognition of the conceptual problems inherent in its logical structure, the wave-particle duality principle is typically described as a paradox [39].

It will be recalled, however, that the argument against an exclusively corpuscular (Newtonian) description for the photons in the Young experiment rests on the conclusion that at the time they leave the emitting source, there is no way they could be aware of the status of the two slits of the apparatus. If nothing occupies the space between the source and the slits, there is no reason to doubt this position, but in the course of examining the creation-annihilation

hypothesis, a different picture has emerged. Instead it has been assumed that there is a high density of massless particle-antiparticle systems existing throughout all space [1, 2]. It also has been argued that such a model is consistent with the virtual photon formalism of quantum electrodynamics. If such entities need to be taken into account in the form of radiative corrections in order to obtain a highly accurate description of the fine structure of atomic systems, *it is not obvious that their influence can be entirely neglected in the present context either.*

Particularly if such massless species exist in the numbers required to explain emission processes without invoking the creation-annihilation hypothesis, it would seem to follow that there is a direct line of communication between the source and the two slits of the Young experimental apparatus, one that could cause the photons to distribute themselves differently on the screen depending on the nature of the environment that exists a relatively large distance away. The fact that the single-hole intensity distributions do not satisfy an additivity law [38] to give the corresponding two-hole result is not in itself incompatible with the particle concept. Rather it reinforces the key assumption of the Born interpretation [3] that the wavefunction in quantum mechanical treatments needs to be multiplied with its complex conjugate to obtain a physically meaningful distribution function for the system being treated. An accurate computation of this wavefunction *requires a complete specification of the physical system at hand, which in the Young experiment would mean not only the photons and the apparatus, but everything in between.*

In this connection it is well to recall that the interference effects under discussion have never been observed when photons deriving from different sources are involved [36]. This implies that a very delicate balance is involved which leads to a mixing of the two wavefunction parts corresponding to the different slits of the Young apparatus *only when a perfect symmetry exists.* From this result it is clear that an extremely small perturbation is enough to destroy the constructive interference pattern. Closing one of the holes in the Young experiment might constitute such a small perturbation, the occurrence of which, *if transmitted by a suitable medium to the source,* would be sufficient to “inform” the photons located there that the symmetry required for the production of interference phenomena is no longer present.

The advantage of the above interpretation is that it does *not* require [17] a modification of the fundamental definitions of particles and waves to make the experimental results understandable. Streams of particles of the same properties obey statistical laws embodied in the de Broglie [7] and Bohr/Planck frequency [14, 30] relations. The individual particles are localized at all times, but *the quantum mechanical*

formalism is only able to provide a statistical distribution function from which expectation values for their various properties can be computed. For this purpose an accurate description of the forces acting on the individual components of the system is necessary. In certain instances for which the results are very sensitive to the choice of experimental conditions, this requirement includes taking into account neighboring systems such as massless photons. They are always present, but their influence can usually (but not always) be safely excluded from the theoretical treatment without greatly altering the quality of the ensuing predictions.

V. THE EINSTEIN-PODOLSKY-ROSEN PARADOX

The last topic to be considered is the Einstein-Podolsky-Rosen paradox [40]. Since it was first presented in 1935 there has been great interest in the question of what it implies about the role of quantum mechanical theory in describing general physical processes. The experiment on which this paradox is based is the same one with which the present study began [1, 2], namely positronium decay. To properly appreciate the significance of the EPR paradox, it is important to first consider the essential features of the quantum mechanical theory of measurement known as the Copenhagen Interpretation [41]. The guiding principle of this formalism is that one can only predict the result of a given experiment in terms of a probability distribution. The corresponding quantum mechanical wavefunction describing a given state of a system can always be expanded in terms of the eigenfunctions ϕ_i of a hermitean operator P corresponding to a property which is to be measured. i.e. $\Psi = \sum_i c_i \phi_i$, where $P\phi_i = p_i \phi_i$. The probability that

a given eigenvalue p_i will be obtained in the measurement is expected to be $|c_i|^2$ when Ψ is normalized to unity. The most controversial aspect of the Copenhagen interpretation is the question of whether such a probabilistic theory can be considered to give a complete description of physical reality (essentially the title of the original EPR publication), or whether a more detailed theory exists which is capable of giving more definite predictions of experimental results.

The positronium decay experiment represents a paradoxical situation *vis-a-vis* the Copenhagen interpretation because it shows that the value of a property of one of the two emitted photons (in the singlet decay) is always completely predictable based on knowledge of the outcome of the analogous measurement carried out for the other [40]. From this interpretation it would seem to follow that if a property is measured for which the photon wavefunction is not an eigenfunction of the corresponding quantum mechanical operator, the result obtained can never be predicted with certainty, regardless of what other

information is available. Since there are a variety of different measurements possible whose quantum mechanical operators cannot all be compatible (mutually commuting), the experimental evidence indicates that, *at least in the form given above, this principle is violated in practice*. While one can only speculate how two particles can always give complementary results when subjected to the same experiment, it seems certain that such a mechanism does exist on the basis of the above measurements [39,41].

In a broader sense the Einstein-Podolsky-Rosen paradox suggests that particles such as electrons, which are taken to be perfectly *indistinguishable* in a quantum mechanical treatment, actually enjoy a unique existence. For example, in a collection of a large number of hydrogen atoms, which are all in the $^2P_{1/2}$ state, there may be a mechanism by which an observer can know with certainty which of them will undergo radiative emission at a particular time. What is clear and indisputable is that quantum mechanical theory as we know it is incapable of providing such information. It is important to note in this context, however, that there really would be no way to *verify such theoretical predictions* for the outcome of the above experiment. This is for the simple reason that *it is impossible to tell the individual particles apart*. One cannot put a label on an individual hydrogen atom and then determine precisely when this particular system undergoes radiative emission. So in that sense, it is impossible to devise a practical means of testing such a hypothetical extension of quantum mechanical theory.

The positronium decay experiment described above nonetheless succeeds in providing a type of photon labelling which satisfies the basic condition described in the last paragraph for hydrogen atoms. Accordingly, two otherwise indistinguishable objects are identified by virtue of their special relationship to one another. Under these circumstances, it is still impossible to predict the outcome of every conceivable experiment on one of the two photons (i.e. that measured first), in accord with the Copenhagen interpretation. The knowledge of its relationship to the other product of a given positronium decay, however, is sufficient to allow for complete predictability of every complementary measurement subsequently carried out for the second photon.

There is no immediate justification for extrapolating this result to the much more sweeping proposition that the outcome of every experiment is completely predictable according to some unspecified theory, but this possibility is at least left open on such a basis. The required extension of quantum mechanical theory to achieve this goal might still involve the wavefunction for each of a given set of indistinguishable particles. This assertion follows from the fact that the definition of such functions is not

uniquely provided in the existing theory. It is always possible to introduce a *finite discontinuity* in such functions which leads to no change in any of its operator expectation values. Since its predictions are always in terms of expectation values [3], it is clear that different functions can give identical results for all properties.

One of the more frequently mentioned examples of this nature involves the evaluation of the Darwin term for atoms when a *point-charge nuclear charge distribution* is assumed [42]. Because this operator is singular at the origin, the value of the wavefunction there affects its expectation value, contrary to all other Hamiltonian terms (for example, those in Table I of Ref.) [2]. If one excludes such physically unrealistic operators from the Hamiltonian that do depend on the value at the origin, it is possible to vary the value of the wavefunction at the origin over an arbitrary range of finite values without affecting the associated total energy expectation value. It can be argued that no property which can be measured in practical experiments will depend on the value of the wavefunction at the origin either, so in this sense there is no *unique* definition for any physically meaningful quantum mechanical wavefunction.

In summary, there are an infinite variety of functions whose overlap with one another is exactly unity. This being the case, one could use this ambiguity to store any conceivable amount of distinctive information regarding individual particles without affecting the equality of their quantum mechanical expectation values in any case. Under the circumstances, it seems only prudent to at least hold open the possibility that the result of each experiment ever to be carried out upon it *is* uniquely specified. Presented with a set of such wavefunctions, we would only verify that they lead to identical probability distributions, and consequently to the same expectation values for any conceivable measurable property. In other words, the very structure of quantum mechanical theory suggests a level of ambiguity which allows *no definitive conclusion* as to whether its probabilistic character is a signal of an intrinsic element of unpredictability of naturally occurring phenomena or not.

Since a possible higher level of theory would not be subject to verification because of the impossibility of labelling otherwise indistinguishable objects, it might well be argued that there is no point in even looking for its concretization. From a purely scientific point of view this position is tenable. Nonetheless, the belief that the outcome of physical experiments is often just a matter of probability can lead to the generalization that almost everything is simply a matter of chance, and as a consequence, that causality is a proven impossibility in the natural course of events. The Einstein-Podolsky-Rosen paradox is an

indication that such a judgment is at best premature. It is important to know if anything happens by chance or not, even if it is clear that in many situations it must remain effectively impossible to predict the (conceivably) inevitable outcome of a given experiment.

VI. CONCLUSIONS

With the above line of argumentation, one can summarize the situation, at least tentatively, as follows: the wave properties of a given system only arise when *large numbers of such particles are observed under similar conditions over the entire duration of an experiment*. By contrast, the characteristic properties of a localized system exhibit themselves even if attention is restricted to the behavior of a single particle. There is a crucial contention which needs to be carefully examined. For if the wave properties commonly associated with particles only arise because of the collective motion of large numbers of them, as suggested by the above statistical argument, *there is really no need to speak of a wave-particle duality* to describe the relevant experimental findings. Instead, the de Broglie wavelength [7] and the Bohr/Planck frequency [14, 30] can simply be characterized as statistical parameters needed to specify an appropriate distribution function for a large sample of indistinguishable particles, each of which possesses the same momentum and energy. In short, if waves are nothing but streams of individual particles, then Newton was right when he argued in favor of his corpuscular theory of light [5].

The main treason that physicists have rejected Newton's particle theory of light was that it failed to predict that the speed of light is slower in water than in free space. Closer examination of his arguments shows, however, that his mistake was actually based on his failure to recognize that the mass of photons is not the same in water as it is in free space. Instead, it varies as in eq. (17), namely as the product of n and n_g . This is a case where the $E=mc^2$ formula is not correct. Within a medium of refractive index n , the equation of state for light is $E=pc/n$. On this basis, one can use Hamilton's relation $dE=vdp$ to obtain the correct variation of the speed of light given by eq. (13), which to a good approximation is nothing more than Huygens' expression $v=c/n$. One is left with the realization that both the corpuscular and wave theories of light have basic elements of truth in them.

It is pointed out that the *wavelike* properties of photons and other material objects can only be observed when a *stream of such particles* is allowed to interact with the measuring device, even though no more than one such particle may be in the apparatus at any one time. In this view there is simply a connection between the temporal and spatial distributions of a collection of particles of the same type having the same translational energy and momentum, as given by the de Broglie and

Bohr/Planck frequency relations. It is this systematic character of the motion of particles under the same conditions which produces the experimental results generally interpreted as being consistent with wavelike behavior.

The Born interpretation of the absolute square of the wavefunction as a probability distribution is compatible with such a view, especially when the effects of the system's translation are taken explicitly into account. The main question which has raised doubts about such a purely statistical interpretation has revolved around the finding that probabilities themselves are not additive in the theory, but rather only the wavefunctions which are used to compute the pertinent distribution function. In the Young interference experiment *with coherent radiation*, it has been consistently argued that photons at the source have no means of "knowing" whether one or both slits of the apparatus are open. The key observation is that the intensity distribution observed for the case when both slits are open is not simply obtained by adding the corresponding distribution which results when one of the slits is open and the other closed to that resulting for the complementary arrangement. It has often been argued that this result is only understandable *if a given particle can pass through both openings* on the way to the screen, i.e. that it possess the delocalized character generally only associated with wavelike substances.

By rejecting the assumption that space can be free of material particles and replacing it instead with the concept of ubiquitous photons everywhere in the universe, a mechanism presents itself, however, which does allow particles at the source of the Young apparatus to be aware of the condition at the slits allowing passage to the screen beyond (Sect. IV). As a consequence, the need to redefine the original meanings of particle and wave in order to explain the Young interference phenomenon *is eliminated*. Thus even the paradox of wave-particle duality is seen to be intimately tied up with the hypothesis that material elements can be created and destroyed in physical transformations. By rejecting this position and holding instead that indestructible elements do exist in nature, it is found that there really is no proof that massless particles cannot exist in sufficient density throughout the universe and thus produce the observed results of the Young interference experiment.

Finally, a mechanism is suggested whereby the definition of the quantum mechanical wave function can be extended to enable it to contain more information about a given system than could be deduced on the basis of expectation values of dynamical variables. The possible relevance of this subject to the understanding of the Einstein-Podolsky-Rosen paradox has been discussed (Sect. V), particularly from the point of view of whether the results of experiments involving individual particles might not in fact be generally

predictable. In cases where no physical means exists to distinguish one particle from another, however, it is clear that even such additional theoretical information would not be sufficient to allow an assignment of different outcomes of experiments to specific members of the ensemble.

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