A Case for Local Realism

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Abstract

The "Schrödinger cat" states supposed by quantum mechanics need not be considered intrinsically probabilistic or otherwise inconsistent with the existence of the particle in the physically real state assumed by classical physics. The further states contemplated by the formalism of standard quantum mechanics could be states, not of the particle itself, but of the apparatus - oscillatory disturbances induced by reaction as the particle is measured and mimicking the wave characteristics of a particle. If quantum states are understood in this way, much of what has seemed mysterious in quantum behaviour becomes consistent with local realism.

Keywords: Quantum mechanics - Local realism – Self interference - Entanglement - Born rule - Double-slit experiment - Mach-Zehnder interferometer

I. INTRODUCTION

The central problem of quantum mechanics or, as Feynman memorably told his students, "the only mystery" [1] is illustrated in a compelling manner by the Mach-Zehnder interferometer of Fig. 1. The mystery is this: How does a particle that follows a single path through the interferometer project its influence along both paths so as to "self interfere" as those paths rejoin?

We explore here the possibility that it is merely an illusion, induced by the response of the apparatus, that the particle takes both paths. It can hardly be doubted that in some formal sense the alternative "Schrödinger cat" states supposed by standard quantum mechanics (SQM) must exist. But it will be assumed in this paper that the particle is in a single physically real state at all times, albeit that this state may be unknown or transitional or capable of expression as a superposition with respect to the modes of some apparatus.

What might seem to be a further state of the particle will be, not a state of the particle itself, but a state of the apparatus - an oscillatory excitation in the fields of the apparatus induced by reaction as the particle is scattered (for instance at the surface of discontinuity within a beam splitter). Insisting upon the strict operation of laws of conservation, it will be argued that the response of the scattering medium must match exactly the change in the wave characteristics of the particle, and must therefore take the form of a secondary wave propagating through the experiment in the same manner as a particle.

Understood in this way, quantum states become consistent with local realism and the measurement problem disappears. Self interference is then the interference of real not probabilistic states, and it also becomes possible to resolve a threshold problem in the local realistic modelling of a Bell's experiment - the presence in each arm of the experiment of orthogonal waves associated with the same particle.

This paper will concentrate on the self interference and measurement of photons. The complications of the de Broglie wave, avoided here, have been discussed elsewhere [2]. The argument will be presented in a general way in the next section, and developed in Secs. III and IV by reference to measurement apparatus operating by refraction. Secs. V and VI will then consider in turn, a local realistic approach to the Born rule and possible refutations of that approach. After a preliminary discussion of beam splitting in Sec. VII, self interference will be considered in Sec. VIII using as illustrations, the double-slit effect and the Mach-

Zehnder interferometer. A local realistic treatment of Bell's experiments will be presented in Sec. IX, followed by some brief concluding remarks in Sec. X.

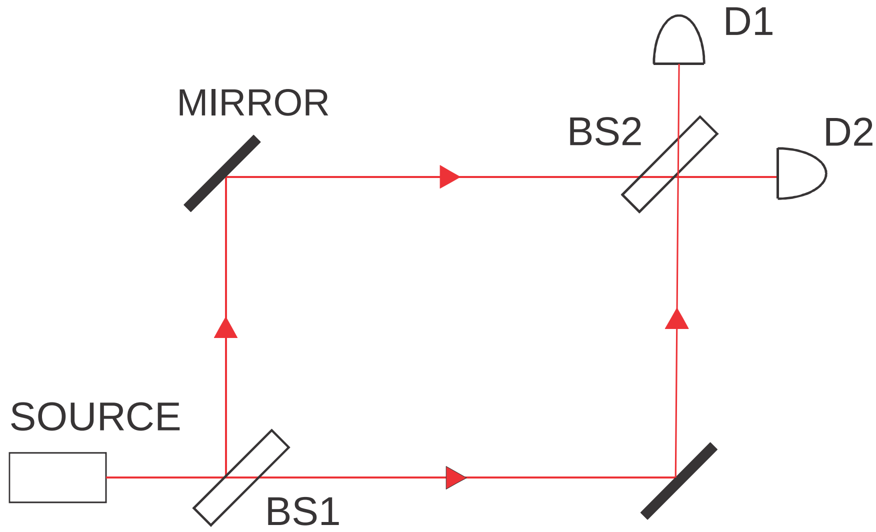

FIG. 1: *A Mach-Zehnder interferometer: In standard quantum mechanics, a probability wave associated with the photon divides at beamsplitter $BS1$. Self interference then occurs as the partial probability waves recombine at $BS2$. In the local realistic explanation here, the scattering of the photon into one or other arm at $BS1$ induces by reaction secondary radiation precisely anticorrelated with the change in the photon and capable of interference with the photon at $BS2$.*

II. QUANTUM STATES

There is nothing mysterious in the proposition that the scattering of a particle in one direction must result in a wave-like influence propagating in another direction. From Newton's third law, or equivalently conservation, the scattering of the particle is accompanied by a transfer of momentum of equal but opposite effect to the change in the particle. If at the same time there is a change in some other property of the particle - spin perhaps or polarization - a transfer of that property accompanies the transfer of momentum.

It is also known that every particle, whether massive or massless, has wave characteristics commensurate with its dynamic properties. These are, from the Planck-Einstein relation,

$$E = \hbar\omega, \tag{1}$$

a frequency ω, and from the de Broglie relation,

$$\mathbf{p} = \hbar\kappa, \tag{2}$$

a wave number κ, where E and $\mathbf{p}$ are respectively the energy and momentum of the particle, and $\hbar$ is the reduced Planck's constant. Thus what is imparted by particle to scatterer is never simply an undifferentiated amount of four-momentum, but an oscillatory disturbance of equal but opposite effect to the change in the wave characteristics of the particle.

All that need be explained then is why the reaction that occurs as a particle is measured (the response of the apparatus) should so mimic the presence of a particle as to create the illusion that the particle has somehow divided between available paths.

Notice firstly that there is nothing novel in the suggestion that the behaviour of a particle might be simulated by what is not a particle. Such "quasi-particles" are well know to condensed matter physics. There is the "hole" - the absence of an electron mimicking the presence of a positron - as well as various other disturbances of a medium, such as excitons, phonons and plasmons, that like the excitations of the apparatus to be considered below propagate and interfere in the manner of particles.

In general, we would expect the response of a distributed medium to be dissipated in some incoherent manner through the medium. That would be so at least for an impact with a macroscopic object. Consider, for instance, that well known macroscopic object, the cat of Schrödinger, and imagine that it has now collided with a semi-reflective wall. The collision will transfer momentum to the wall, perhaps even leave an impression on the wall, but the oscillatory changes thus induced in the surface molecules of the wall are unlikely to coalesce into some cat-like wave propagating through the wall.

But things at the microscopic level are rather different. The elementary particles exist and combine in characteristic and well defined forms. They may be compelled by the wave-like nature of those forms and the regularity of an array of scatterers to propagate in particular directions of constructive interference. In quantum measurement, where the trajectories and characteristics of incident and transmitted particles are closely constrained by the circumstances of the experiment, so also must be the response of the medium. Trivially, we might thus write,

$$\psi_{in} - \psi_{out} = \psi_{resp}, \tag{3}$$

where ψ_{in} and ψ_{out} are incoming and outgoing wave and ψ_{resp} is the response of the medium, and where in the spirit of an S-matrix formulation, nothing has been said of mediating influences or the delay between the excitation of those influences and their relaxation by reradiation.

It is that delay that explains the refractive index, but we assume nonetheless that in any local realistic explanation of the electromagnetic interaction between particle and medium, the process of excitation and relaxation develops in a causal and continuous manner and in accordance with Maxwell's equations. Where the interaction is electromagnetic, Eqn. (3) follows indeed from the symmetry under time-reversal of those equations. If the process could be run in reverse, the measured particle and the reaction of the medium would recombine to redeliver the unmeasured particle, now propagating in reverse [3]. But this could occur only if the reaction were itself of a wave-like nature capable of interference with the returning particle. In the mode of the apparatus adopted by the particle, the end effect would be to reverse by destructive interference the increase in energy that occurred in that mode. In the orthogonal mode, it would reinstate the energy lost in that mode.

As a simple example, consider the interaction of a photon linearly polarized at θ to the horizontal, that is,

$$\psi_{in} = H\cos\theta + V\sin\theta, \tag{4}$$

with an HV polarizing beam splitter, where H and V are eigenstates of horizontal and vertical polarization respectively.

As this photon is forced into one or other mode, let us say the V mode, a reaction of equal but opposite effect occurs in the apparatus. Thus,

$$\psi_{out} = V, \tag{5}$$

and,

$$\psi_{resp} = H'\cos\theta - V'\cos\theta, \tag{6}$$

where the prime denotes, not a state of the particle, but a state of the apparatus, having in this case the effect of a torsional wave propagating through the beam splitter.

In terms of energy transfers, if the incident photon had the energy,

$$E = E_H + E_V,$$

and adopted the V mode of the apparatus, its energy in that mode would increase by E_H while decreasing by the same amount in the H mode. Conservation of energy would require equal but opposite changes in the corresponding modes of the scattering medium.

According to SQM, a probability wave associated with the photon separates into partial probability waves with amplitudes $H\cos\theta$ and $V\sin\theta$. It remains in this probabilistic limbo until a step is taken to ascertain from which channel the photon has emerged, at which point (which could in principle be years later or not at all) the photon acquires physical reality as an H or V photon. What is now contemplated is that the photon remains at all times in a physically real state, but as it adopts the V mode of the beam splitter, the torsional response of the medium exactly balances the gain by the photon in its V component and the complete loss of its H component. In the mode not adopted by the photon we have the reaction,

$$H'\cos\theta \equiv H\cos\theta,$$

and in the orthogonal mode, a composite disturbance,

$$V - V'\cos\theta \equiv V\sin\theta,$$

these being physically realistic waves formally equivalent to the probabilistic states supposed by SQM.

The response of the medium thus comprises a fleeting imbalance of a wave-like form peculiarly apt to couple with an accompanying or following particle of similar provenance. This disturbance will be referred to compendiously as the "secondary wave" [4]. We will find in the tendency of the apparatus to regain equilibrium by the reacquisition by interference of the resulting imbalance, a local and realistic explanation of measurement. By following the evolution of this secondary wave through the experiment it will be possible to offer a local realistic explanation of self interference.

Crucial to this argument is a reliance upon conservation of a quality not realizable in SQM. It is no longer suggested, as once it was [5], that conservation is merely approximate or "statistical" in quantum processes. Yet in conceding roles to chance and nonlocality SQM is necessarily careless of the conserved properties of physics. Eqn. (3) could not be an equation of SQM. According to SQM, Ψ_f is reached from Ψ_i by a reduction or collapse that may be discontinuous and nonlocal and is certainly non-deterministic. Along with continuity and causality, conservation fails at the instant of measurement, as also in consequence must Maxwell's equations.

In what follows, we assume (in accordance with local realism) the continued validity at the microscopic level of Maxwell's equations, as well as the local and causal operation of laws of conservation.

III. THE SECONDARY WAVE

The secondary wave now proposed is in essence a fluctuation in the reradiation that is well recognized as the origin of refraction [6]. There is a curious inconsistency between the recognition in both classical and quantum physics that this reradiation is the cause of refraction, and the disregard in SQM of all possibility that fluctuations in this reradiation could influence the fate of the refracting photon.

Whether in measurement or otherwise, the interaction of photon with medium is solely with the charged particles of the medium. In a dielectric, these are bound charges, and the process of refraction is thus mediated by moments, primarily electric dipole moments, induced in the molecules of the material. Reradiation from these moments interferes constructively in the direction of the photon flux, and the composition of this induced "polarization field" with the field of the photon causes the change in phase velocity that is the origin of the refractive index.

So much is well accepted. But consider refraction as it occurs in measurement, as when a photon encounters the birefringence of a polarizing beam splitter or the partially reflective surface of a non-polarizing beam splitter. There are now alternative paths of constructive interference available, and at this point the continuous wave of classical physics would divide. But not so the photon, which (at these energies) is indivisible and thus forced (projected) in its entirety into one or other path.

As the photon "chooses" its path, its dynamic and wave characteristics change, and there must be an equal but opposite reaction to this change. In a nonlocal theory, the location of this reaction may be ill-defined (a possibility to which we will return in Sec. VI), but in any local realistic theory it must take effect in the charged particles from which the photon is scattered. The response of the medium must therefore comprise changes in induced moments of equal but opposite effect to the change in the photon, and a resulting fluctuation in the reradiation from those moments .

It is important to notice that this reradiation inherits its frequency and spatial distribution of phase from the photon driving the interaction. Phase matching, that is to say the requirements of waveform continuity (for example, at the boundary between media of differing index) will thus ensure that the reradiation is constrained to those directions of constructive interference available to the photon itself.

We distinguish now two parts of this fluctuating polarization field. One is the field that would have been generated had the photon been as free to divide as was the classical wave. The other is the departure from the first field induced by reaction as each photon is forced to adopt one or other path from the site of scattering. The first field will define that notional point of equilibrium about which the system must fluctuate as the beam divides. It is the second part, the fluctuation in the polarization field, that is the secondary wave of interest.

Consistently with Eqns. (5) and (6), the secondary wave (or properly, *waves*) must comprise,

(a) a wave propagating in the direction *not* taken by the photon and having the energy and wave characteristics of the wave that would have propagated in that direction had the photon been able to divide, and

(b) a wave propagating in the direction that the photon does take, but of opposite phase to the photon and having the effect of reducing the energy in that mode to that which would have propagated in that direction had the photon been able to divide.

IV. THE EXTINCTION THEOREM OF EWALD AND OSEEN [7] [8].

Let us consider this induced polarization field a little more closely. In the semi-classical modelling of refraction - in which the incident wave is continuous and the medium is quantized - each induced moment is approximated as an harmonic oscillator, essentially an oscillating electron constituting a small electric dipole,

$$\mathbf{p} = -\frac{q^2}{m\omega^2}\mathbf{E} = \epsilon_0 \alpha \mathbf{E}, \tag{7}$$

where $\mathbf{E}$ is the incident electric field, q and m are the charge and mass of the electron respectively, and α is the mean molecular polarizability of the medium (it being assumed that the frequency ω of the incident wave is not near the resonant frequency ω_o of the oscillator) [9].

At the i^{th} dipole, the field $\mathbf{E}_i(\mathbf{r}_i, t)$ comprises the vacuum (externally sourced) field $\mathbf{E}_{vac}(\mathbf{r}_i, t)$ plus the reradiation from every other dipole, that is,

$$\mathbf{E}_i(\mathbf{r}_i, t) = \mathbf{E}_{vac}(\mathbf{r}_i, t) + \sum_{j \neq i} \mathbf{E}_{ji}(\mathbf{r}_i, t), \tag{8}$$

where the field at $\mathbf{r}_i$ from the k^{th} dipole is,

$$\mathbf{E}_{ji}(\mathbf{r}_i, t) = \nabla \times \nabla \times \frac{\mathbf{p}_j(t - R_{ij}/c)}{R_{ij}}, \tag{9}$$

and $R_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$.

The further modelling of the process could continue from here at the molecular level by supposing (as in [10]) an idealized array of dipoles. However, the argument to follow will turn not on the particular form of the medium, but on the assumption that whatever its form, its response to the scattering of a photon must always be equal but opposite to the change induced in that photon. Thus, it will suffice to consider a model that is in effect the converse of the semi-classical model - a model in which a quantized wave (a flux of photons) interacts with an idealized macroscopic medium.

In modelling this medium, we proceed to the continuous limit by assuming a uniform polarization density

$$\rho = N\alpha,$$

where N is the number density of molecules. Eqns. (8) and (9) then become,

$$\mathbf{E}_{trans}(\mathbf{r}, t) = \mathbf{E}_{vac}(\mathbf{r}, t) + \int \nabla \times \nabla \times [N\alpha \frac{\mathbf{E}_{trans}(t - R'/c)}{R'}] \, dV', \tag{10}$$

where $R' = |\mathbf{r} - \mathbf{r}'|$.

Eqn. (10) is an integro-differential equation in which the transmitted field $\mathbf{E}_{trans}$ is due in part to fields that it has itself induced. The equation is solved (in well-known manner [11]) by stipulating that the polarization field (the integral in Eqn. (10)) comprises the transmitted field of velocity c/n, and a field that extinguishes exactly the vacuum field of velocity c, that is

$$\mathbf{E}_{pol}(\mathbf{r},t) = -\mathbf{E}_{vac}(\mathbf{r},t) + \mathbf{E}_{trans}(\mathbf{r},t), \tag{11}$$

where for a dielectric the refractive index n relating the two velocities is given by the Lorentz-Lorenz relation (which need not concern us here).

That the polarization field has these two discernible parts - the transmitted field and a field that extinguishes by interference the incident field - is known to classical physics as the extinction theorem of Ewald and Oseen [12]. The theorem holds identically at all points of space, supposes the local and causal development of the process of scattering, and implies that if the process could be run in reverse it would return the original incident wave (now propagating in reverse). As we noticed in Sec. II, this is also implicit in Maxwell's equations, from which the theorem may be derived [13].

Being a consequence of classical electromagnetic theory, and thus of local realism, the theorem must fail in SQM because of the discontinuous and probabilistic nature of wave function collapse. But by excluding chance and non-locality and asserting the theorem at the level of the quantum, we will now a convenient bridge from the classical to the quantized wave. In so doing, we depart from both the classical approach, which supposes a continuous incident field, and from SQM, which supposes a photon that chooses its path by pure chance.

Of the photon, it need only be supposed that (as all experiment indicates [14]) it is, or acts as if it is, a small electromagnetic waveform having the notable property that it is (usually) indivisible. Being indivisible, it follows that there exists some internal constraint ensuring that indivisibility. We do not know the nature of that force, but some inkling of its strength is provided by the intensities needed to disrupt the photon in nonlinear processes [15].

To extend the extinction theorem to the flux of photons, we simply express Eqn. (11) as summations over the electric fields $\mathbf{e}_i(\mathbf{r},t)$ of the photons constituting the flux, and over the modes j of the measurement apparatus,

$$\textstyle\sum_j\sum_i \mathbf{e}_{ij\,(pol)}(\mathbf{r},t) \;=\; -\sum_j\sum_i \mathbf{e}_{ij\,(vac)}(\mathbf{r},t) + \sum_j\sum_i \mathbf{e}_{ij\,(trans)}(\mathbf{r},t), \qquad (12)$$

where as measurement proceeds (observed or otherwise) all except one mode of the $\mathbf{e}_{ij\,(trans)}$ must go to zero as the photon is forced (projected) into a single mode of the apparatus.

The summations over each of the modes j must satisfy independently equality (12). This is clearly so where, as in the case of a polarizing beam splitter, the modes are orthogonal. It is also demanded by conservation when in effecting a balancing of forces within a non-polarizing beam splitter (as discussed in Sec. VII) the modes follow differing trajectories.

But within each mode, the summation over transmitted photons fluctuates as photons become projected into or from that mode. For Eqn. (12) to hold identically for each mode, each such fluctuation in the transmitted field must therefore be anticorrelated exactly with the corresponding fluctuation in the polarization field, that is to say, for all i and j, we must have,

$$\mathbf{e}_{ij\,(resp)}(\mathbf{r},t) = \mathbf{e}_{ij\,(vac)}(\mathbf{r},t) - \mathbf{e}_{ij\,(trans)}(\mathbf{r},t),$$

which is the response of the medium described in words at the conclusion of the preceding section.

The fluctuation in the polarization field is not of course a photon. Nor could any assemblage of such fluctuations constitute a cat. But the fluctuation is in a sense the alter ego of the photon. It is anticorrelated with the change in the photon, has wave characteristic matching those of following or accompanying photons, and is thus in a form precisely adapted to influence by interference the measurement of those photons, or to (self) interfere with the inducing photon itself if returned to the same path.

Nor is this fluctuation strictly a quasi-particle for it propagates in more than one channel of the apparatus. But its existence explains why it might seem that the particle has divided between available paths.

V. THE BORN RULE

In SQM, measurement is governed by the Born rule [16], which asserts (in a simple form) that,

$$prob(a_i) = |u_i\,|\psi\rangle|^2 \tag{13}$$

where $prob(a_i)$ is the intrinsic probability that a particle in the state ψ will have the eigenvalue a_i for which the corresponding eigenfunction is u_i.

Attempts to derive the Born rule from first principles have been criticized as circular (see, for instance, Refs [17] to [20]). It has been said of such derivations that it is necessary "to put probabilities in to get probabilities out" [20]. There is nothing in the other postulates of SQM that suggests intrinsic probability. Those postulates assimilate the particle to a wave (the wave function or state vector), associate each "observable" property of the particle with an Hermitian operator, and stipulate that the wave function is to evolve in accordance with the time-dependent Schrödinger equation. These postulates are deterministic. They neither preclude the local realistic approach preferred here nor suggest the probabilistic approach of SQM.

In excluding all extraneous considerations, the notion in SQM that probability is intrinsic allows no bridge from the deterministic "Schrödinger phase" in the evolution of the state vector to the discontinuous, acausal and nonlocal reduction or collapse that is assumed to occur on measurement. The coexistence of both deterministic and non-deterministic phases, or rather the difficulty of saying how the one ends and the other begins, is also the source of the "measurement problem" that has so confounded SQM.

In the limit of large numbers, the probabilities assumed by SQM do reproduce the division that was expected (from conservation) of the continuous but divisible wave of classical physics. But this is hardly surprising. These probabilities are not generated by the Born rule, but "added by hand" - determined experimentally or adopted from (essentially classical) rules of conservation. For example, a beam of photons, linearly polarized at θ to the horizontal, divides at an HV polarization beam splitter, approximately in the proportions:

$$\frac{N(H)}{N(V)} \approx \frac{\cos^2\theta}{\sin^2\theta}, \tag{14}$$

thus conserving (to the same approximation) the beam's energies of horizontal and vertical polarization.

But in the context of SQM, it is not at all obvious why the quantized wave should divide in this way. If the measurement of one particle is independent of that of the next, it might be asked why each does not simply adopt that mode for which it has the greater incident component or, even more reasonably, take the energetically more favorable path through the apparatus. If measurement were governed by intrinsic probability, the division of a beam in accordance with conservation would seem a fortuitous coincidence.

In this paper, it is the response of the apparatus that ensures that the beam divides in accordance with conservation. Induced in the paths of following and accompanying photons, and sharing their frequency and trajectories, the secondary wave is well adapted to couple with and influence the measurement of the ensuing flux. It is only necessary to assume that the fluctuating polarization field is reacquired by interference by the beam (as is known to occur with refraction in a uniform medium) to see that the apparatus must itself fluctuate about a state of equilibrium defined by conservation.

The approximate conservation observed in the measured stream may then be seen as merely incidental to this process of relaxation or recovery in the medium. What is exactly conserved is the sum of the measured property in medium and measured stream together.

The forgoing is not of course a derivation of the Born rule. Intrinsic probability has become subjective probability - the probability accorded from ignorance of underlying deterministic processes (as when a card player attributes a chance of 1/52 to the next card being the ace of spades when it is certainly in fact the six of hearts). However, the connection with conservation is now explained, as also the seemingly approximate and probabilistic nature of that conservation. Because there is no longer an intrinsically probabilistic phase in the evolution of the state vector, the measurement problem does not arise.

It remains to consider why the Born rule should depend on the square of an amplitude. In the measurement of photons, as in Eqn. (14), the reason is easily seen. The energy of a wave is proportional to the square of its amplitude [21], and the energy of orthogonal components of the wave must be independently conserved. That this same dependence should hold for massive particles is implicit in the postulates of SQM, which as we have seen, describe the behaviour of a particle in terms of the development and interference of a wave function. More significantly, and this seems to be the true basis of the rule, it is also consistent with the common underlying wave nature of matter and radiation suggested by the Planck-Einstein and de Broglie relations (Eqns. (1) and (2)).

VI. COUNTER-ARGUMENTS

To refute this explanation of measurement, it would seem necessary to identify some mechanism by which the local and causal consequences of the response of the medium might be suppressed. An interpretation of quantum mechanics that is nonlocal and acausal and has an uncertainty principle is not without such "defence mechanisms". It will be argued that their invocation here would lack logical consistency.

Three possibilities might seem worth considering:

(a) that the response of the apparatus is simply passed on to the wider environment;

(b) that by the uncertainty principle the fluctuations in the polarization field are virtual rather than real; and,

(c) that the reaction of the medium is displaced nonlocally to some time or place sufficiently remote that it plays no further part in measurement.

We have already noticed the problem with (a). It is the interference of the polarization field with the photon stream that explains refraction. It is implausible that fluctuations in this same field should escape unnoticed by the photon stream.

Indeed it is known from the experiment of Beth in 1935 [22] and the exploitation of the Beth effect in optical traps and the like [23] that photons refracted by a dielectric target, not only impart linear and angular momentum to that target, but may do so to the extent of causing observable movement of the target. These experiments evidence the operation of Newton's third law in the scattering of photons, they show the torsional nature of the force between photon and target, and they provide ample demonstration that momentum imparted by photon to medium is not simply passed without local effect to the wider environment.

The suspended wave plate of Beth was what might be termed a single-mode device. Allowed no possibility of maintaining equilibrium by a division of the beam, the device was ultimately forced to move in response to the beam. But a measuring apparatus is a multi-mode device that is able to minimize disequilibrium by returning by interference to one particle the imbalance acquired from another.

In support of possibility (b), the argument would be that these fluctuations in the polarization field occur only within those brief periods when (according to SQM) energy may exist in a virtual state. This would not be a novel application of the uncertainty principle. It has been invoked to excuse the similar fluctuations that occur in a nonlinear crystal during a process such as down-conversion [24].

As contemplated by the uncertainty principle, a fluctuation in energy δE may exist in a virtual state for a time interval of order,

$$\delta t = \hbar/\delta E,$$

where for a 50:50 beam splitter and a photon of frequency ω, the permitted fluctuation δE would be $\hbar\omega/2$ in each mode per photon, and could thus endure only for a time,

$$\delta t = 2/\omega,$$

which is of the order of the period of oscillation of the photon. But such a discrepancy in energy would be temporary only if corrected, presumably in this case by the measurement of a following photon or photons. The uncertainty principle could not suppress a fluctuation induced by a lone photon or by any sufficiently attenuated stream of photons.

In SQM, it is (c) that might seem the more obvious possibility, but would entail the displacement non-locally of conserved quantities (including energy, momentum and polarization). This would introduce an arbitrariness inconsistent with the symmetries contemplated by Noether's theorem, and would seem to deny the local conservation and continuity supposed by the gauge principles of modern field theories [25].

The logical difficulties are indeed considerable. The reaction would take effect, not in the charges that have caused the change in the photon, but in remote and otherwise uninvolved charges and moments. Relative phase would then be indefinable, notably the relative phase that should determine the manner in which the nonlocally displaced field fluctuation is to interfere with whatever is already occupying the space that it will now inhabit. This is a large problem for any interpretation of quantum mechanics that supposes nonlocality.

In the absence of a locally causal response from the medium, fields would be discontinuous and, as noted above, Maxwell's equations would fail at a boundary of discontinuity. But (as discussed in the next section) partial reflection is conventionally explained by assuming that Maxwell's equations do remain valid across such boundaries.

Moreover, a nonlocal transfer can be instantaneous in but one frame of reference. In any other frame the transfer would cause a temporary surplus or deficit of energy and momentum. A related difficulty would arise for conservation of angular momentum. Linear momentum lost (or acquired) at one point might be eventually conserved by its emergence (or disappearance) elsewhere, but the angular momentum associated with that linear momentum would not be conserved.

And as we have already discussed, the nonlocality would be curiously selective. It does not suppress that part of the polarization field responsible for the birefringence or partial reflection that causes the beam to divide, but would suppress fluctuations in that same field that are consequent upon that division. That some of these difficulties may be well known does not make them any less embarrassing to the notion of nonlocality.

Finally, it might be argued that if the response of the apparatus is allowed due effect, the collapse supposed by SQM becomes redundant to the deterministic "Schrödinger phase" in the evolution of the state vector. Between measurements it is assumed in SQM that the system evolves as it would classically. Thus in an as yet unmeasured system (and for unobserved Nature generally) the response of the medium is local and causal, must generate by reaction a fluctuating polarization field as discussed above, and must lead through the composition of that fluctuating field with following particles to the division in accordance with conservation discussed in Sec. III.

This process would thus achieve, unmeasured and unobserved, the division predicted by conservation (and quantum mechanics), leaving neither opportunity nor necessity for the discontinuous jump supposed by SQM.

VII. BEAM SPLITTING

As a preliminary to the discussion of the Mach-Zehnder interferometer in the next section, we consider briefly a simple non-polarizing beam splitter based on partial reflection from a polished dielectric surface. Partial reflection can be treated by the extinction theorem of Sec. IV, but we consider it here, as is more usual, in terms of boundary conditions.

The continuous wave of classical physics was assumed to divide (in accordance with the Fresnel relations) in such a way that the forces on the charges of the medium, whether arising from incident or induced fields, were in a state of balance. This implied the continuity of Maxwell's equations across the inter-medial boundary, requiring (assuming a wave passing from medium 1 to medium 2 through a boundary in the xy-plane) that,

$$\begin{aligned}
(\epsilon_0\mathbf{E}_1+\mathbf{P}_1)_z &= (\epsilon_0\mathbf{E}_2+\mathbf{P}_2)_z\,,\\
(\mathbf{E}_1)_{xy} &= (\mathbf{E}_2)_{xy}\,,\\
\mathbf{B}_1 &= \mathbf{B}_2.
\end{aligned} \tag{15}$$

$\mathbf{E}$, $\mathbf{B}$ and $\mathbf{P}$ being the macroscopic electric, magnetic and polarization fields, respectively [26].

Consider now the quantized wave. For the microscopic fields to remain continuous (and Maxwell's equations to hold) as photons are variously reflected or transmitted, there must be a continuing readjustment, not of the boundary conditions (15) themselves, but of the manner in which those conditions are satisfied. Take, for example, the first of these conditions, which is obtained by asserting, in the z-direction, Coulomb's law, which in dielectric form is,

$$\nabla\cdot\mathbf{E} = -\frac{\nabla\cdot\mathbf{P}}{\epsilon_0}.$$

On the side of the boundary to which a photon departs, there will be (as compared with the steady state supposed classically) a fleeting increase in the photon field, and on the other side of the boundary, a corresponding decrease in that field. This fluctuation in fields will induce by reaction a compensating fluctuation in the dispositions of moments and in the direction and strength of the polarization field. Whether the photon is reflected or transmitted, the fields at the boundary will thus remain continuous and consistent with the boundary conditions.

Why then should these excursions from the steady state be self-correcting? The fields remain continuous because moments change in response to fluctuations in the photon field. Each such change in the disposition and strengths of moments involves an exchange of momentum concentrated upon a particular distribution of molecules that will be to that extent in disequilibrium with the surrounding dielectric. Return to equilibrium should be expected on conventional thermodynamic grounds - the minimization of energy and maximization of entropy - but will here be facilitated by the nature of the induced imbalance, which is eminently qualified in its wave characteristics to couple with the ensuing photon stream.

In this process, each photon "chooses" its path, not by chance, but as determined by its own particular circumstances, including the local state of imbalance in which it finds the medium.

VIII. SELF INTERFERENCE

Self interference is to be understood here as the interference of a particle with secondary radiation that has been induced by the scattering of that same particle. As we saw in Sec. III, the phenomenon of refraction is ample evidence that mutual interference of this kind does occur. When it occurs in refraction or diffraction, such mutual interference may be regarded as a form of self interference in which the secondary wave is reacquired immediately by the particle flux. This immediate self interference will explain the diffraction observed at the slits of a Young's experiment [27].

But such interference may instead be delayed. Thus in a beam splitter, the particle and that component of the secondary wave that has taken the alternative channel part company, and it is their later reunion that will explain the Mach-Zehnder and similar interferometers.

Although illustrating differing forms of self interference, the double-slit effect and the Mach-Zehnder interferometer will be seen to have this in common - that they demonstrate the preference of the particle for that path through the experiment that best preserves its characteristic transverse waveform.

Young's experiment:

To explain the double-slit effect, it will be assumed that the wave associated with the particle has sufficient lateral extension to influence the material of the screen, directly or indirectly, in the vicinity of both slits. In this, we suppose of the particle no more than the lateral influence supposed of the corresponding probability wave of SQM.

The particle passes through the screen provided the centre of the wave (which is also its centre of momentum and influence) finds one or other slit. As this occurs, outlying reaches of the wave will interact with the scattering elements (charges) of the screen, and become modified by interference with reradiation from those elements, but the wave will nonetheless be carried through the screen.

There is nothing novel in the notion that a particle, for instance a photon or electron, constitutes an extended wave form that may pass nonetheless through even the smallest of pinholes. Except in an inelastic encounter, the field of one particle may pass through that of another or through the fields of a distribution of particles such as those constituting a screen. Although changed by the encounter, the particle will tend toward its free space form as it departs.

Even if a particle cannot pass through a barrier, its field will be "felt" by a test charge on the other side. That influence is indirect being relayed through changes induced in the fields of the screen. Nonetheless the field of the particle, modified in phase by the response of the screen, can be considered to penetrate the screen. If the charge is moving the analysis becomes more complicated but the principle is the same.

As the particle interacts with the slitted screen, it suffers varying degrees of dephasing from interaction with the screen, but those regions of its waveform encountering one or other slit remain relatively unchanged and mutually coherent. The available paths of constructive interference - the trajectories that will least disrupt the continuity and coherence of the particle - are thus determined by the slits. From the geometry of the setup, we then have in well known manner, but on the basis of local realism, Young's condition for constructive interference.

$$d \sin \theta = n\lambda$$

where d is the slit separation, θ the angle of deflection of the photon, n the order of the interference fringe, and λ the wavelength.

In following such a path, the particle is taking, as it were, the path of least resistance - the path that will least disrupt its waveform - and to which it is compelled by whatever internal force or effect is ensuring its indivisibility. Its preference for that path will be affected by transient moments and currents, whether induced by the particle itself or by accompanying or preceding particles, as well by any intervention, such as the seeking of "which way" information, that diminishes (or enhances) the possibility of constructive interference.

The Mach-Zehnder Interferometer

Consider again Fig. 1. It will be convenient to concentrate now on photons, it being assumed nonetheless that for a massive particle the de Broglie wave will play the role played for a photon by its transverse electromagnetic wave [2].The interference at $BS2$ is now between real waves, these being the photon and the secondary wave that was generated by reaction at $BS1$ as the photon was forced to adopt one or other path through the interferometer. As was discussed in Sec. VI, this fluctuation of the polarization field propagates in both channels of the beam splitter maintaining microscopically the continuity of fields supposed classically by Maxwell's equations and the Fresnel relations.

As in SQM, each set of waves recombining at $BS2$ has originated from the scattering of the same photon at $BS1$. The phase difference Δ between the two paths is thus the same from one photon to the next, and it follows that no matter how attenuated or incoherent is the original beam, the recombining beams will be mutually coherent.

Let us suppose that $BS1$ and $BS2$ are non-polarizing lossless $50:50$ beam splitters so constructed and aligned that when the upper and lower optical paths to detector $D1$ differ by Δ, the corresponding paths to detector $D2$ will differ by $\Delta + \pi$ [28]. If $\Delta = 0$, the waves propagating in the two arms will interfere constructively in the direction of $D1$, but destructively in that of $D2$. The photon will favour the path that better preserves the integrity of its waveform. Photons scattered at $BS2$ will thus register only at $D1$.

Suppose instead that the waves are neither exactly in nor out phase as they arrive at

$BS2$. In SQM, the probability of detection where superposed probability waves of equal amplitude have differing phases χ_1 and χ_2 is,

$$\left|e^{i\chi_1} + e^{i\chi_2}\right|^2 = \left[\left(e^{i(\chi_1+\chi_2)/2}\right)\left(e^{i\Delta/2} + e^{-i\Delta/2}\right)\right]^2, \tag{16}$$

$$\approx \cos^2\frac{\Delta}{2} = \frac{1+\cos\Delta}{2}, \tag{17}$$

where $\Delta = \chi_1 - \chi_2$ (and where the first factor in (16) has been equated with unity).

The photon must maintain its characteristic transverse waveform notwithstanding the disruption threatened by the differing phases of the recombining waves. As the photon is projected into one or other path, the indivisibility of the photon thus induces by reaction an imbalance mediated by induced moments in the material of the beam splitter. If the recombining waves differ in phase by Δ, they will consistency of phase will be achieved in the direction of detector $D1$ by inducing in the moments of $BS2$, a reaction of energy,

$$\sin^2(\Delta/2). \tag{18}$$

The coherent merger of photon and secondary thus induces an imbalance in $BS2$ that will tend to bias by interference a following photon toward detector $D2$. Conversely, coherence in the direction of $D2$ must induce an imbalance,

$$\cos^2(\Delta/2), \tag{19}$$

tending to bias a following photon toward $D1$. For equilibrium within $BS2$, we thus have, from Eqns. (18) and (19), a division in the proportions,

$$\frac{N(D1)}{N(D2)} \approx \frac{\cos^2(\Delta/2)}{\sin^2(\Delta/2)},$$

which corresponds to prediction (17) of SQM, but is derived now on the basis of local realism.

It has been assumed in this treatment that secondary wave and photon propagate in similar manner. It might be thought that since the induced moments are confined to the dielectric, so also must be the reradiation from those moments. However the moments are merely the sources of the polarization field, and such sources may extend their influence far beyond the medium containing those sources. Thus in the conventional modelling of refraction, the field at a point remote from the dielectric is the sum at that point of the fields from all sources, including those from dipole reradiation. It is true that as a photon departs the medium, it regains its earlier wave length, but it carries with it nonetheless the continuing influence of the polarization field in an altered phase and (usually) a change of trajectory.

Again, there is no suggestion that the secondary wave is in any sense a photon or part of a photon. It is a fluctuation in the polarization field capable of survival over the time frame of the experiment because it is equal but opposite in effect to the change occurring in the photon, and capable therefore of propagating in like manner.

Although we have concentrated on photons, neutron interferometry involves similar considerations, with the strong nuclear force playing the part played by the electromagnetic in photonic interferometry. It has been indeed said that in the context of neutron interferometry, the use of the word "optical " is by no means metaphorical [29].

IX. ENTANGLEMENT

In the modeling of a Bell's experiment, local realism has been handicapped by an inability to replicate the orthogonal or conjugate waves that are assumed in SQM to be propagating simultaneously in each arm of the experiment. In SQM, these are alternative probabilistic states of the particle, but local realism can supply only one particle per arm per pair.

The extra wave is not to be dismissed as an extravagance of SQM that might be abandoned in a physically realistic reinterpretation of quantum mechanics. The presence of two waves in each arm is clearly evidenced by the need for compensation for birefringent "walk-off" in the generation of entangled photons by down-conversion (see, for example, Kwiat et al [30]). The additional wave is also implied by the interference that is evidently responsible for the differing behaviour of the various Bell states.

Even without the additional wave, the detection loophole can be invoked with some plausibility to explain the correlations observed in Bell's experiments at particular analyzer settings including those at the important T'sirelson bound. But such modelling is far less successful in explaining the correlations observed at other settings, in particular those in the $45° : -45°$ basis (in the case of polarization-entangled photons) where SQM predicts 100% correlation for photons in the Ψ^+ Bell state and complete anti-correlation for those in the Ψ^- state. At the same settings, classical physics contemplates 50% correlation whatever the Bell state under consideration, and it is here that the prospect of local realistic modelling has seemed unlikely, sufficiently unlikely perhaps as to discourage any robust evaluation of the claims of reported Bell's experiments.

However, as will now be shown, the additional wave in each arm may be explained, as in self interference, as a state of the apparatus - a secondary wave induced by reaction as the entangled particle pair is created. We will take as illustration polarization- entangled pairs sourced, as in recent Bell's experiments (for instance, the important Weihs experiment [31]), from type II spontaneous parametric down-conversion (SPDC).

In a nonlinear crystal, induced moments and reradiation from those moments have a quadratic component, which in a intense pump laser may find its release in down-conversion (the division of a pump photon into two "daughter" photons), subject for optimal efficiency to the phase matching conditions,

$$\omega_p = \omega_1 + \omega_2, \ and \ \mathbf{k}_p = \mathbf{k}_1 + \mathbf{k}_2, \tag{20}$$

where ω and $\mathbf{k}$ designate, respectively, angular frequencies and wave vectors, while the suffix p identifies a pump photon and 1 and 2 the daughter photons.

In the nonlinear crystal, as in any dielectric, the interaction between beam and medium is mediated solely by induced moments. Assuming local realism, and as discussed in Sec. III, any imbalance induced in the photon field must be accompanied by an equal but opposite reaction in those moments and a resulting fluctuation in the polarization field.

Let us suppose a typical type II SPDC event in which a pump photon (V-polarized) down-converts to a V-polarized daughter photon going to Alice and an H-polarized daughter photon going to Bob. The phase matching conditions (20), though consistent with the conservation of energy and momentum, do not exhaust the requirements of that conservation. Writing,

$$V(\omega_p) \longrightarrow V(\omega_V, \theta_V)_A + H(\omega_H, \theta_H)_B, \tag{21}$$

(where θ_V and θ_H are the angles at which the photons diverge from the pump beam), it becomes evident, not only that horizontal polarization has been gained at the expense of vertical polarization, but that horizontal polarization is now propagating to one side of the crystal at one frequency and vertical to the other at (usually) another frequency.

The asymmetry in Eqn. (21) would be redressed by the inclusion, in the direction of Alice, of a fluctuation in the polarization field, of form,

$$\frac{1}{2}[H'(\omega_H, \theta_H) - V'(\omega_V, \theta_V)],$$

and in the direction of Bob, of form,

$$\frac{1}{2}[V'(\omega_V, \theta_V) - H'(\omega_H, \theta_H)],$$

where reaction is again identified by a prime, and the negative implies a diminution in the relevant mode of the polarization field (or a phase of π). On including these secondary waves, Eqn. (21) becomes,

$$\begin{aligned} V(\omega_p) \Longrightarrow & [V(\omega_V, \theta_V) + \frac{1}{2}H^{'}(\omega_H, \theta_H) - \frac{1}{2}V^{'}(\omega_V, \theta_V)]_A \\ & + [H(\omega_H, \theta_H) - \frac{1}{2}H^{'}(\omega_H, \theta_H) + \frac{1}{2}V^{'}(\omega_V, \theta_V)]_B, \end{aligned} \tag{22}$$

which remains consistent with the phase matching conditions (20), but waves propagating to Alice are now in balance with those propagating to Bob. The formal equivalence of these waves to the probabilistic waves of SQM may be seen from Eqn. (22) as follows,

$$\begin{aligned} & [V(\omega_V, \theta_V) + \frac{1}{2}H^{'}(\omega_H, \theta_H) - \frac{1}{2}V^{'}(\omega_V, \theta_V)]_A \approx \\ & \qquad \frac{1}{2}[V(\omega_V, \theta_V) + H(\omega_H, \theta_H)]_A \Longrightarrow (V_A + H_A), \end{aligned}$$

$$\begin{aligned} & [H(\omega_H, \theta_H) - \frac{1}{2}H^{'}(\omega_H, \theta_H) + \frac{1}{2}V^{'}(\omega_V, \theta_V)]_B \approx \\ & \qquad \frac{1}{2}[H(\omega_H, \theta_H) + V(\omega_V, \theta_V)]_B \Longrightarrow (H_B + V_B). \end{aligned}$$

so that, as assumed in SQM, H- and V- polarized waves are propagating to both Alice and Bob. Now, however, these are physically real rather than probabilistic waves.

Interference between these waves, occurring independently at each end of a Bell's experiment, suggests immediately the significance of phase to the differing behaviour of the Bell states. It becomes apparent, for instance, that with Alice's and Bob's analyzers at the same setting, phase relationships will determine whether their measurements tend to correlation or anti-correlation.

It is not suggested that the mere existence of these waves avoids Bell's theorem [32], but it will allow a local realistic modelling of the data sets of reported dynamic Bell's experiments [33] that is more plausible than has been possible hitherto. Certainly, the conclusions reached in those experiments are not beyond dispute, as recent analyses [34] [35] of deficiencies in the data sets of the Weihs experiment [31] have shown.

The antithesis between special relativity and nonlocality would itself be reason enough to scrutinize very carefully the claims of these experiments.

X. CONCLUSION

Various well-considered reinterpretations of quantum mechanics have sought to avoid the measurement problem and the anomalies of intrinsically probabilistic collapse. But confronted by self interference and entanglement, such reinterpretations have included, as does SQM, some random or nonlocal step or branching or other discontinuity inconsistent with the wave-like nature of the underlying processes.

Quantum mechanics is a theory of quanta, but it is also theory of waves. As we saw in Sec. V, the wave nature of matter and radiation is implicit in the amplitude dependence of the Born rule and explicit in the deterministic Schrödinger phase of SQM. Schrödinger's wave version of quantum mechanics was prompted indeed by de Broglie's insights concerning the wave nature of matter. But in its evolution and interactions, a wave is a peculiarly causal and local phenomenon. Acausality implies discontinuity, while in the absence of actual physical overlap, it is not apparent how a relationship of phase could be defined for interfering waves.

There is thus a tension between the continuity of underlying wave forms and the non-locality and acausality that has been perceived in self interference and entanglement. It should not be surprising then that it is when introducing nonlocality or intrinsic probability that reinterpretations of quantum mechanics have seemed ad hoc or contrived, or have led, as in SQM, to logical inconsistency.

A return to local realism would avoid this tension, as well as the problems of measurement and collapse. While classical physics has seemed unable to explain Feynman's "only mystery", the interpretation of quantum states proposed here permits a local realistic explanation of self interference, and in the extension of that explanation to entanglement, removes what has been a significant obstacle to the plausible modelling of Bell's experiments.

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