A case for local realism

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Abstract

The "Schrödinger cat" states supposed by quantum mechanics need not be considered 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 quantum mechanics could be states, not of the particle itself, but of the apparatus - oscillatory disturbances induced by reaction as the particle is scattered and mimicking the wave characteristics of a particle state. If quantum states are understood in that way, much of what has seemed mysterious in quantum behaviour becomes consistent with local realism.

I. INTRODUCTION

The members of the Royal Society of London, who were at Somerset House on November 24, 1803 to hear Thomas Young's account of his experiments with light, would have been astonished to learn of the explanations that would later emerge for the "double-slit" interference that Young described that evening [1].

According to what is now orthodox or "standard" quantum mechanics (SQM), an interfering particle exists in a superposition of intrinsically probabilistic "Schrödinger cat" states. And while Schrödinger's paradox of the probabilistic cat who is at once dead and alive [2] may have been fanciful, we may also contemplate in Everett's treatment of the measurement problem [3], the intriguing possibility that the cat may not only be dead and alive, but up to all sorts of mischief in the wider multiverse.

This paper will explore the rather less interesting possibility that the particle only *seems* to be in more than one state. From the success of SQM, and the example of self interference, it can hardly be doubted that in some formal sense the alternative states supposed by SQM must exist. But it will be assumed, consistently with the local realism of classical physics, 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 induced by reaction as the particle is scattered (for instance at the surface of discontinuity within a beamsplitter). Assuming the exact and locally causal 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 or waves 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 Bell's experiments, namely the presence in each arm of the experiment of orthogonal waves associated with the same particle.

The argument will be presented in a general way in the next section, and developed in

Sect. 3 by reference to the phenomenon of refraction. Following sections will discuss in turn: a local realistic approach to the Born rule (Sect. 4), possible refutations of that approach (Sect. 5), beamsplitting (Sect. 6), self interference (Sect. 7) and entanglement (Sect. 8). Sect. 9 will provide a brief conclusion.

II. QUANTUM STATES

The central problem of quantum mechanics, or as Feynman memorably told his students, "the only mystery" [4], though best known from Young's experiment, is illustrated in a particularly compelling manner by the Mach-Zehnder interferometer of Fig. 1.

Interference is observed between the recombining partial beams even when the original beam is incoherent or is so attenuated that only one particle is in flight at a time [5] - or as was said in the context of neutron interferometry - when the next neutron along is yet to be born in the nuclear furnace [6]. The problem then is this: How does a particle that is indivisible and constrained to follow one or other path through the interferometer project its influence along both paths so as to "self interfere" as those paths rejoin?

Notice, however, that there is nothing at all mysterious in the proposition that the scattering of a particle must result in wave-like influences propagating in two directions. From Newton's third law, or equivalently conservation, the scattering of the particle in one direction is accompanied by a transfer of momentum in another direction of equal but opposite effect to the change in the particle.

It is also known, from Einstein and de Broglie, that every elementary particle, whether massive or massless, has wave characteristics commensurate with its dynamic properties, namely 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.

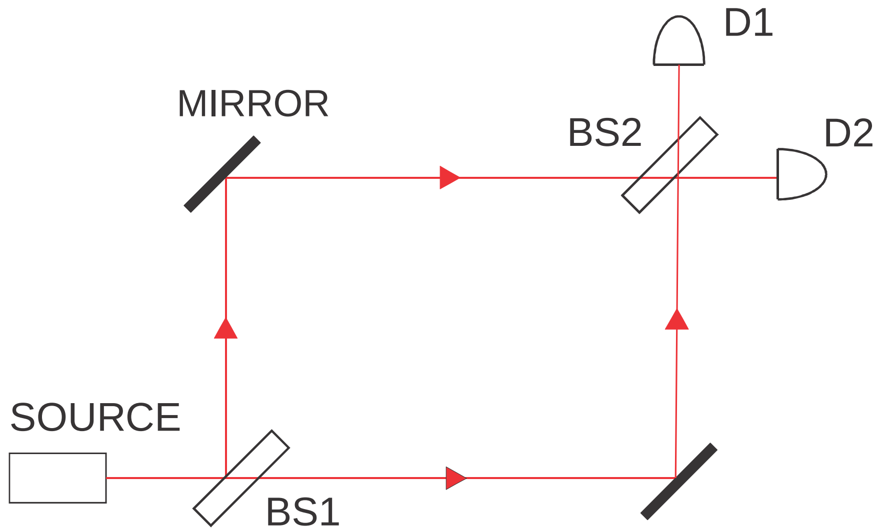

FIG. 1: *A Mach-Zehnder interferometer: In standard quantum mechanics, the probability wave of the photon divides at beamsplitter $BS1$. Self interference then occurs as the partial probability waves recombine at $BS2$. In the local realistic explanation here, the scattering of the photon into one or 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 $BS2$.*

Thus what is imparted by particle to scattering agency is never simply undifferentiated energy or momentum. It is an oscillatory or wave-like disturbance of equal but opposite effect to the change in the wave characteristics of the particle. In general, we should expect this reaction (the response of the scattering medium) to be dissipated in some incoherent manner through the medium. The macroscopic cat who bounces from a wall will impart momentum to the wall, perhaps even leave an impression on the wall, but the oscillatory changes induced in the 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, and are compelled by the wave-like nature of those forms to propagate in 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, but nonetheless precisely, we might write,

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

where ψ_{in} and ψ_{out} are incoming wave and outgoing wave respectively, and ψ_{resp} is the response of the medium.

Let us suppose that ψ_{in} (which we assume to be normalized) has components c_i in the two modes of a beamsplitter, that is,

$$\psi_{in} = \sum_{i=1,2} c_i \, u_i, \tag{4}$$

where u_i is the (here physically real) eigenfunction for the i^{th} mode. If ψ_{in} takes the channel corresponding to say mode 2, we then have

$$\psi_{out} = u_2,$$

and thus a reaction in the medium,

$$\psi_{resp} = c_1 u_1^{'} - c_1 u_2^{'} \tag{5}$$

(where the prime denotes a state of the apparatus).

As a simple example, consider the interaction with an HV polarizing beamsplitter of a photon linearly polarized at θ to the horizontal, that is,

$$\psi_{in} = H \cos\theta + V \sin\theta \tag{6}$$

where H and V (the eigenfunctions) are states 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,

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

and,

$$\psi_{resp} = H' \cos\theta - V' \cos\theta, \tag{7}$$

where the prime again 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 beamsplitter.

According to SQM, the probability wave of the photon separates at the beamsplitter into partial probability waves (Schrödinger cat states) with amplitudes $H\cos\theta$ and $V\sin\theta$. It then 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 (this being one of the oddities of SQM that have encouraged several well considered reinterpretations of quantum mechanics).

What is contemplated in this paper is that the photon is at all times in a physically realistic state, but as it adopts the V state within the beamsplitter, the torsional response (7) of the medium exactly balances the gain by the photon in its V component and the 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,

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

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

Eqn. (3) is simply Newton's third law, but implies that the immediate response of the medium 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". 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 also be possible to offer a local realistic explanation of self interference.

Crucial to the argument will be a reliance upon conservation to a degree not contemplated in SQM. It is no longer suggested, as once it was [7], that conservation is merely approximate or "statistical" in quantum processes, but an interpretation of quantum mechanics that concedes roles to chance and nonlocality is necessarily careless of the conserved properties of physics. Eqn. (3) could not be an equation of the standard interpretation. According to that interpretation, 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 must fail 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 quantum level of Maxwell's equations, as well as the local and causal operation at that level of laws of conservation. We stress that the waves we are describing - the particle itself, which might be thought of as the *primary* wave, and the *secondary* induced by reaction as the primary is scattered - are at all times real waves. They are not the probabilistic waves of SQM. Nor, are they to be equated, for instance, with the two waves of de Broglie's double solution.

III. THE SECONDARY WAVE

The secondary wave now proposed is in essence the secondary wave that is well recognized as the cause of refraction (see, for instance, Born and Wolf, [8], chap. 2.4.3). In a region of a dielectric remote from discontinuity, the interaction of photon with medium is solely with the charged particles of the medium, which in a dielectric are bound charges. The process is thus mediated by moments, primarily electric dipole moments, induced in the molecules of the material. (If there were no charges in the medium, the photon would pass through entirely unaffected). Reradiation from these moments interferes constructively in the direction of the photon flux. The composition of this reradiation (the 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 beamsplitter or the partially reflective surface of a non-polarizing beamsplitter (of which more will be said in Sect. 6). Here also the interaction of photon with medium is solely with the charges of the medium and mediated entirely by moments induced in the molecules of that medium. However, there are now alternative paths of constructive interference available to the photon, 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.

SQM asserts that the path then taken is determined by *intrinsic* probability, or as von Neuman described it *irreducible quantum randomness* [9], that is to say, pure chance. On this view, the measurement of any one particle in a stream of particles can have no bearing on the measurement of any other, which would seem to imply that the measuring apparatus is entirely unaffected by what it measures.

Yet as the photon "chooses" its path, its dynamic and wave characteristics must 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, but in local realism it must take effect in the charged particles from which the photon is scattered. It must therefore result in changes in associated moments, and a fluctuation in the secondary radiation from those moments.

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 (as will be discussed in Sects. 4 and 6) 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.

The form taken by this fluctuation is determined by the change in the photon. Let us suppose that the incident photon had the energy,

$$E = E_a + E_b,$$

(where for the polarizing beamsplitter, a and b might denote the H and V modes of the beamsplitter). If the photon were to take say the a mode, its energy in that mode would increase by E_b while decreasing by the same amount in the b mode. Conservation would require equal but opposite changes in the corresponding modes of the medium.

Assuming, as we do, the validity at the quantum level of Maxwell's equations, we can be more precise. If the interaction of photon and apparatus could be run in reverse, it would follow from the symmetry under time-reversal of those equations that the measured photon and the reaction of the medium would recombine to return the unmeasured photon, now propagating in reverse. But this could occur only if the reaction were itself of a wave-like nature capable of interference with the returning photon. In the mode adopted by the photon, it would have the effect of reversing 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.

We come now to a significant point. The induced secondary wave acquires both its frequency and its 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 within a beamsplitter) will thus ensure that the secondary wave is constrained to those directions of constructive interference available to the photon itself.

Consistently with Eqn. (5), the secondary wave (or properly, *waves*) must therefore 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.

This fluctuation in the polarization field is not 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.

IV. THE BORN RULE

In SQM, measurement is governed by the Born rule [11], according to which (in a simple form),

$$prob(a_i) = |u_i \, |\psi\rangle|^2 \tag{8}$$

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 have been criticized as circular (see, for instance, Refs [12] to [15]). It has been said of such derivations that it is necessary "to put probabilities in to get probabilities out" [15]. 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 a linear Hermitian operator, and stipulate that the wave function is to evolve in accordance with the time-dependent Schrödinger equation. These postulates are essentially deterministic. They neither preclude the local realistic approach preferred here nor suggest the probabilistic approach of SQM.

In excluding by definition extraneous considerations, intrinsic probability allows no bridge from the deterministic "Schrödinger phase" in the evolution of the state vector to the catastrophic (discontinuous, acausal and nonlocal) reduction or collapse that is assumed to occur on measurement. (The coexistence of these deterministic and non-deterministic phases, or rather the difficulty of saying when or 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 reproduce the division that was expected (from conservation) of the continuous but divisible wave of classical physics. That this is so is hardly surprising for these probabilities are not prescribed by the Born rule, but determined experimentally or acquired from the same essentially classical rules of conservation. For example, a beam of photons, linearly polarized at θ to the horizontal, divides at an HV polarization beamsplitter, approximately in the proportions:

$$\frac{N(H)}{N(V)} \approx \frac{\cos^2\theta}{\sin^2\theta}, \tag{9}$$

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 stream. It is only necessary to assume that the fluctuating polarization field is reacquired by interference by the stream (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 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 approximate and seemingly probabilistic nature of that conservation. Because there is no longer an intrinsically probabilistic phase in the evolution of the state vector, the measurement problem cannot 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. (9), the reason is easily seen. The energy of a wave is proportional to the square of its amplitude [16], 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)).

V. 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 such fluctuations in the polarization field are simply passed on to the wider environment;

(b) that by the uncertainty principle these fluctuations 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.

The problem with (a) is that 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 [17] and the exploitation of the Beth effect in optical traps and the like [18] 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 in the target. These experiments evidence the operation of Newton's third law (or equivalently conservation) 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 in effect 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 [19].

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 beamsplitter 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 is the more obvious possibility. But the logical difficulties are considerable. One is that the nonlocal transfer 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.

Other curious effects would result from the displacement of the reaction from the point of scattering. 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.

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, not at all temporary, 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.

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 (Sect. 6)) partial reflection is conventionally explained by assuming that Maxwell's equations do remain valid across such boundaries. That some of these difficulties may be well known does not make them any less embarrassing to the notion of nonlocality.

It should also be noticed that a division determined by chance would be an inferior, indeed unreliable, way of approximating conservation. The measurement of any one particle would as likely increase as decrease any pre-existing imbalance in the medium. Indeed, the variance of a distribution based on chance (that of the random walk) increases with run-time, and in the tails of such a distribution an excursion from balance could be substantial [20]. By comparison, excursions from a system in equilibrium tend to be self-limiting, whatever the run-time.

Finally, another difficulty is worthy of mention. Between measurements the system evolves, as we have seen, in the so-called "Schrödinger phase", which is to say, deterministically and 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 Sect. 4.

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 that is assumed by SQM.

VI. BEAMSPLITTING

In the next section (Sect 7.), we discuss the Mach-Zehnder interferometer. As a necessary preliminary, we consider now the local realistic operation of a simple non-polarizing beamsplitter based on partial reflection from a polished dielectric surface.

In SQM, the balancing of field components that determined the division of the classical wave is disrupted on measurement by the discontinuous nature of reduction or collapse. With this disruption, conservation fails locally, as also must Maxwell's equations. Here we suppose no such failure, and need to consider how balancing might be continued and conservation maintained when what is scattered arrives episodically in a flux of indivisible photons. The answer is to be found in the response of the medium.

The continuous wave of classical physics was assumed to divide (in accordance with the Fresnel relations [21]) in such a way that the forces on the charges of the medium, whether arising from incident or induced fields, remain in a state of balance. This implied in turn 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,

$$
\begin{aligned}
(\epsilon_0\mathbf{E}_1+\mathbf{P}_1)_z &= (\epsilon_0\mathbf{E}_2+\mathbf{P}_2)_z\,, \\
(\mathbf{E}_1)_{xy} &= (\mathbf{E}_2)_{xy}\,, \\
\mathbf{B}_1 &= \mathbf{B}_2.
\end{aligned}
\tag{10}
$$

$\mathbf{E}$, $\mathbf{B}$ and $\mathbf{P}$ being the macroscopic electric, magnetic and polarization fields, respectively (See, for instance, Feynman [4], vol. II, chap. 33).

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 (10) themselves, but of the manner in which those conditions are satisfied. Consider, 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 (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.

VII. SELF INTERFERENCE

Self interference will be understood here as the mutual interference of physically real waves, namely the particle in question and secondary radiation induced by the scattering of that particle. As we saw in Sect. 3, the phenomenon of refraction is ample evidence that mutual interference of this nature does occur. When it occurs in refraction or diffraction, such mutual interference may be regarded as 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.

But this mutual interference may instead be delayed. Thus in a beamsplitter, the particle and that part 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 [1], it will be assumed that 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. For a massive particle the de Broglie wave will play the role played for a photon by its transverse electromagnetic wave.

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 (usually 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 photon 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. The interference at $BS2$ is now between real waves, these being the photon (we will concentrate on photons) 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 discussed in Sect. 6, this fluctuation of the polarization field propagates in both channels of the beamsplitter 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 $50:50$ beamsplitters 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 $\Delta + \pi$ [22]. 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,

$$\left|e^{i\chi_1} + e^{i\chi_2}\right|^2 = \left[\left(e^{i(\chi_1+\chi_2)/2}\right)\left(e^{i\Delta/2} + e^{-i\Delta/2}\right)\right]^2, \tag{11}$$

$$\approx \cos^2\frac{\Delta}{2} = \frac{1+\cos\Delta}{2}, \tag{12}$$

where $\Delta = \chi_1 - \chi_2$ (and where the first factor in (11) has been equated with unity).

The photon must maintain its characteristic waveform notwithstanding the disruption threatened by the phase difference between the recombining waves. As the photon is projected into one or other path, the indivisibility of the photon induces by reaction an imbalance mediated by induced moments in the material of the beamsplitter. In the direction of detector $D1$, the recombining waves are able to achieve consistency of phase at $BS2$ by inducing in the moments of that beamsplitter an imbalance,

$$\begin{aligned}\Psi_{D1} &= 1 - e^{i\Delta}, \\ &= e^{i\Delta/2}\left(2\sin\frac{\Delta}{2}\right).\end{aligned} \tag{13}$$

The coherent merger of photon and secondary thus induces an imbalance of amplitude $2\sin\frac{\Delta}{2}$ and of phase $\Delta/2$. Such an imbalance will tend to bias by interference a following photon toward detector $D2$. Conversely, coherence in the direction of $D2$ induces an imbalance,

$$\Psi_{D2} = e^{i\Delta/2}\left(2\cos\frac{\Delta}{2}\right), \tag{14}$$

tending to bias a following photon toward $D1$. For equilibrium within $BS2$, we have, from Eqns. (13) and (14), a division in the proportions,

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

which corresponds to prediction (12) 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. 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 considered only photons, neutron interferometry involves similar considerations, with the strong nuclear force replacing the electromagnetic force. Thus it has been said that in the context of neutron interferometry, the use of the word "optical " is by no means metaphorical (Rauch and Werner [23], p.1).

VIII. ENTANGLEMENT

In modelling 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 cannot be dismissed as an extravagance of SQM that might be abandoned in a physically realistic interpretation of quantum mechanics. The presence of two waves in each arm is 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 [24]). The presence of the additional wave is also implied by the interference that is evidently responsible for the differing behaviour of the four Bell states. This has been a significant problem for local realism, but as will now be shown, the additional waves (one in each arm) may be explained, as in self interference, as states of the apparatus - secondary waves induced by reaction as the entangled particle pair is created.

Consider photon pairs sourced, as in recent Bell's experiments (for instance, the important Weihs experiment [25]), 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,

$$\omega_p = \omega_1 + \omega_2, \ \textit{and} \ \ \mathbf{k}_p = \mathbf{k}_1 + \mathbf{k}_2, \tag{15}$$

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 Sect. 3, 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 propagating to Alice and an H-polarized daughter photon to Bob. The phase matching conditions (15) are consistent with the conservation of energy and momentum, but do not exhaust the requirements of that conservation. Writing,

$$V(\omega_p) \longrightarrow V(\omega_V, \theta_V)_A + H(\omega_H, \theta_H)_B, \tag{16}$$

(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 propagating to one side of the crystal at one frequency and vertical to the other at (usually) another frequency.

The asymmetry in Eqn. (16) would be redressed by the inclusion, in the direction of Alice, of a fluctuation in the polarization field, of form,

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

and in the direction of Bob, of form,

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

where reaction is again identified by a prime, and the negative implies a diminution in the relevant mode of the polarization field. On including these secondary waves, Eqn. (16) becomes,

$$\begin{aligned} V(\omega_p) \Longrightarrow & [V(\omega_V, \theta_V) + \frac{1}{2}H^{'}(\omega_H, \theta_H) - \frac{1}{2}V^{'}(\omega_V, \theta_V)]_L \\ + & [H(\omega_H, \theta_H) - \frac{1}{2}H^{'}(\omega_H, \theta_H) + \frac{1}{2}V^{'}(\omega_V, \theta_V)]_R, \end{aligned} \tag{17}$$

which remains consistent with the phase matching conditions (15), 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. (17) as follows,

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

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

so that, as is assumed in SQM, H- and V- polarized waves are propagating to both Alice and Bob.

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 anticorrelation.

It is not suggested that the mere existence of these waves avoids Bell's theorem [26], but it may allow a more plausible modelling of the data sets of reported dynamic Bell's experiments than has been possible hitherto. Certainly, the conclusions reached in those experiments are not beyond dispute, as recent analyses [29] [30] of deficiencies in the data sets of the Weihs experiment [25] have shown. The antithesis between special relativity and nonlocality would itself be reason enough to scrutinize very carefully the claims of these experiments.

IX. CONCLUSION

Various reinterpretations of quantum mechanics have sought to avoid the measurement problem and the excesses of probabilistic collapse. But confronted by self interference and entanglement, all 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 of course a theory of quanta, but it is also theory of waves. As we saw in Sect. 4, 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 an essentially 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 between interfering waves.

There is thus a tension between the continuity of underlying wave forms and the nonlocality 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, and with it the problems of measurement and collapse. While local realism has had its own problems, the interpretation of "Schrödinger cat" 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 local realistic modelling of Bell's experiments.

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[1] T. Young, Experiments and calculations relating to physical optics, Phil. Trans. Roy. Soc. **94,** 1 (1804).

[2] E. Schrödinger, Die gegenwärtige Situation in der Quantenmechanik, Naturwissen. **23**, 807 (1935), translated in, J. A. Wheeler, W. H. Zurek, (eds.): *Quantum Theory and Measurement* (Princeton University Press, New Jersey, 1983).

[3] H. Everett, Relative state formulation of quantum mechanics, Rev. Mod. Phys. **29**, 454 (1957).

[4] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley, Reading, 1963).

[5] G. I. Taylor, Interference fringes with feeble light, Proc. Cambridge Philos. Soc. **15**, 114 (1909).

[6] H. Rauch, Neutrons, Schrödinger Waves and Cats, 6th Schrödinger Lecture, Trinity College, Dublin, 27 Oct. 2000.

[7] N. Bohr, H. A. Kramers, and J. C. Slater, The quantum theory of radiation, Philos. Mag. **47,** 785 (1924), reprinted in B. L. van der Waerden, (ed.), *Sources of quantum mechanics* (North-Holland Publishing, Amsterdam, 1967).

[8] M. Born, and E. Wolf, *Principles of optics*, 7th edn. (Cambridge University Press, Cambridge, 1999).

[9] J. Von Neuman, *Mathematical foundations of quantum mechanics* (Princeton University Press, Princeton, 1958).

[10] E. Hecht, *Optics,* 4th edn. (Addison Wesley, San Francisco, 2002).

[11] M. Born, Quantenmechanik der Stoßvorgänge, Z. Phys. **37**, 863 (1926), translated in J. A. Wheeler, and W. H. Zurek, (eds.), *Quantum Theory and Measurement,* (Princeton University Press, New Jersey, 1983).

[12] E. J. Squires, On an alleged proof of the quantum probability law, Phys. Lett A **145**, 67 (1990).

[13] A. Cassinello, J. L. Sánchez-Gómez, On the probabilistic postulate of quantum mechanics, Found. Phys. **26**, 1357 (1996).

[14] H. Barnum, C. M. Caves, J. Finkelstein, C. A. Fuchs, and R. Schack, Quantum probability from decision theory? Proc. Roy. Soc. London. **A456**, 1175 (2000).

[15] M. Schlosshauer, and A. Fine, On Zurek's derivation of the Born Rule, Found. Phys. **35**, 197 (2005).

[16] But this is not quite true. The amplitude of an electromagnetic wave, and *semble* a photon, is index dependent, changing with wave length and the consequent stretching or compression of the wave. See for example F. A. Jenkins, and H. E. White, *Fundamentals of Optics.* 4th ed. (McGraw-Hill, Singapore, 1981), Chap. 25.2.

[17] R. A. Beth, Mechanical detection and measurement of the angular momentum of light, Phys. Rev. **50**, 115 (1936).

[18] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, Observation of a single-beam gradient force for dielectric particles, Opt. Lett. **11,** 288 (1986).

[19] R. W. Boyd, *Nonlinear Optics,* 2nd edn., (Academic, San Diego, 2003).

[20] L. Mandel, and E. Wolf, *Optical coherence and quantum optics* (Cambridge University Press, Cambridge, 1995).

[21] The relative amplitudes of reflected and refracted beams were derived by Fresnel from an elastic wave theory in 1823 and by Lorentz in 1875 by insisting that Maxwell's equations be satisfied across the boundary of discontinuity, see H. A. Lorentz, Dissertation, University of Leiden (1875), in *Collected Papers* (Nijhoff, The Hague, 1935).

[22] K. P. Zetie, S. F. Adams, and R. M. Tocknell, How does a Mach-Zehnder interferometer work?, Phys. Educ. **35(1)**, 46 (2000).

[23] H. Rauch, and S. A. Werner, *Neutron interferometry* (Clarendon Press, Oxford, 2000).

[24] P. G. Kwiat, K. H. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih, New high-intensity source of polarization-entangled photon pairs, Phys. Rev. Lett. **75,** 4337 (1995).

[25] G. Weihs, T. Jennewein, C. Simon, H. Weinfurter, and A. Zeilinger, Violation of Bell's inequality under strict Einstein locality conditions, Phys. Rev. Lett. **81,** 5039 (1998).

[26] J. S. Bell, On the Einstein-Podolsky-Rosen paradox, Physics, **1**, 195-200 (1964), reprinted in J. S. Bell, *Speakable and unspeakable in quantum mechanics*, revised edn. (Cambridge University Press, Cambridge, 2004).

[27] In a dynamic Bell's experiment, measurements at space-like intervals are contrived by the rapid and random switching of analyzer settings. The important experiments are A. Aspect, J. Dalibard, and G. Roger, Experimental test of Bell's inequalities using time-varying analyzers, Phys. Rev. Lett. **49,** 1804 (1982); and Weihs et al [25], and in particular the latter, which

avoided in its method a number of weaknesses in the earlier experiment.

[28] A. Aspect, J. Dalibard, G. Roger, Experimental test of Bell's inequalities using time-varying analyzers, Phys. Rev. Lett. **49,** 1804 (1982).

[29] G. Adenier, and Y. A. Khrennikov, Is the fair sampling assumption supported by EPR experiments? J. Phys. B **40(1**), 131 (2007).

[30] J. H. Bigelow, Explaining counts from EPRB experiments: Are they consistent with quantum theory? e-print arXiv:1112.3399v1 (2011).