Objectivity, retrocausation, and the experiment of Englert, Scully, and Walther

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In a recent contribution to this journal [Am. J. Phys. **64**, 1468–1475 (1996)] I wrongly asserted that retrocausation in the Englert, Scully, and Walther (ESW) experiment (a double-slit interference experiment with atoms) can occur only until the atom arrives at the screen. In their response, Englert, Scully, and Walther [preceding paper] point out my fallacy but give an incomplete analysis of its origin. In this paper I trace this fallacy to a deep-seated preconception about time and reality. I show that among the two possible realistic interpretations of standard quantum mechanics, the reality-of-states view and the reality-of-phenomena view, only the latter is viable. It follows that retrocausation is a necessary feature of any realistic account of the ESW experiment based on standard quantum mechanics. Finally I eludicate the sense in which the spatial properties of quantum systems are objective, and show that they are extrinsic rather than intrinsic.

I. INTRODUCTION

In a recent article[1] I analyzed the thought experiment of Englert, Scully, and Walther[2,3] (ESW) from two ''metaphysical'' perspectives, the reality-of-states view and the reality-of-phenomena view. In that article I arrived at a wrong conclusion, for which I wish to express my sincere apologies to the readers of this journal. I compounded my mistake by attributing my views to Englert, Scully, and Walther. My apologies also to these authors! It ought to be mentioned, however, that I was argued into misrepresenting their views by the anonymous referee of my article. He/she not only agreed with my erroneous conclusion but also thought that ESW would likewise agree with it. For this the referee cannot be blamed, however, for it is only in their paper[4] on my article that ESW's own views are clearly stated.

In the present paper I review the ESW experiment in light of the aforesaid interpretations (Sec. II), paying particular attention to the source of my fallacy (Sec. III). I believe that there is something to be learned from this fallacy, or from the fact that it is so readily accepted. (The reaction of the anonymous referee is a case in point.) Once the source of the fallacy is removed, nothing stands in the way of a realistic interpretation of the quantum-mechanical treatment of the ESW experiment. This interpretation features an objective and temporally unrestricted retroactive causality. The objectivity of retrocausation, however, entails that the objective spatial properties of material objects are extrinsic (that is, they are contingent on what happens or is the case in the rest of the world). This is discussed in Sec. IV. Section V shows that, in a relativistic context, essentially the same fallacy leads to a denial of the objectivity of the temporal modes of being. In Sec. VI I briefly discuss objectivity and retrocausation in the context of the Einstein, Podolsky, and Rosen (EPR) experiment.

II. REALITY OF STATES VS REALITY OF PHENOMENA

The ESW experiment is a double-slit experiment in which a micromaser cavity is placed in front of each slit. Excited atoms are sent, one at a time, through the cavities and the slits. The cavities are designed to force each atom to emit a microwave photon. They are separated from each other by a pair of shutters between which a photosensor is placed (see Fig. 1). Each atom leaves a mark where it hits the screen. If one simply looks at the distribution of marks created by a large number of atoms, no interference pattern is seen. But quantum mechanics predicts that if the experimenters open the shutters (this can be done well after the corresponding atom has reached the screen) and consider separately the cases in which the sensor responds and the cases in which it does not respond, they will be able to discern two complementary interference patterns. Alternatively, they can leave the shutters closed and ascertain the cavity that contains the photon. They thus appear to have a choice between either measuring the phase relation with which the atom has emerged coherently from both slits or determining the particular slit from which it has emerged. And the possibility of this choice appears to entail some form of retroactive causality.

Does standard quantum mechanics imply the reality of retrocausation? Or is retrocausation a necessary feature of every *realistic* interpretation of its formalism? Is the reality-of-phenomena view the only consistent such interpretation? Or is the reality-of-states view a viable alternative without retrocausation? In this section I will show that the answers to these questions are No, Yes, Yes, and No. To begin with, consider a state of the atom–photon system that is proportional to

$$|\psi_x\rangle\otimes(|1\rangle\langle\psi_x|\psi_1\rangle+|2\rangle\langle\psi_x|\psi_2\rangle). \quad (1)$$

Such a state is also proportional to

$$|\psi_x\rangle\otimes(|+\rangle\langle\psi_x|\psi_+\rangle+|-\rangle\langle\psi_x|\psi_-\rangle), \quad (2)$$

where $|\psi_+\rangle$ and $|+\rangle$ ($|\psi_-\rangle$ and $|-\rangle$) are equiprobable symmetric (antisymmetric) superpositions of the atom states $|\psi_1\rangle$ and $|\psi_2\rangle$ and the photon states $|1\rangle$ and $|2\rangle$, respectively.

From a purely operationalist (or instrumentalist, or antirealist) point of view, (1) tells us the following story: The atom was prepared in such a way that it would have been detected with equal probability in either cavity 1 or cavity 2 had suitable detectors been in place, which was not the case. Instead the atom was detected at x (the position of a mark on the screen). And presently the odds for detecting a photon in

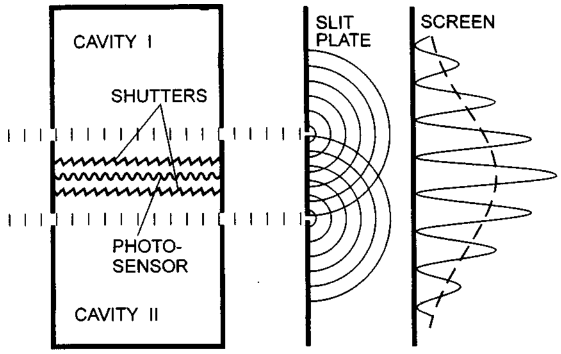

Fig. 1. A plane atom wave split into two coherent collimated beams enters the microwave cavities from the left. Its passage through the cavities forces the previously excited atom to emit a microwave photon. As long as the electro-optic shutters remain closed, which-way information can be obtained, and no interference is observed. Once the shutters are opened, the possibility of obtaining which-way information no longer exists. Atoms associated with photons that are subsequently detected by the photosensor give rise to the same interference pattern that would be observed without the cavities. The remaining atoms give rise to the complementary interference pattern (not shown).

cavity i are proportional to $|\langle\psi_i|\psi_x\rangle|^2$ $(i=1,2)$. End of story. The ''complementary'' story told by (2) goes like this: The atom would also have been detected with equal probability in either of the states $|\psi_+\rangle$ and $|\psi_-\rangle$ had a suitable measuring device been in place, which was not the case. Instead the atom was detected at x, and presently the chances that the sensor will or will not respond (when the shutters are opened) are proportional to $|\langle\psi_+|\psi_x\rangle|^2$ and $|\langle\psi_-|\psi_x\rangle|^2$, respectively. End of story.

The question of retroactive causality arises when one sorts the marks on the screen according to the cavity in which the photon is detected or according to the behavior of the sensor when the shutters are opened. The marks made by atoms whose photons are found in the first (second) cavity are distributed exactly like the marks that one sees if the second (first) slit is closed. And the marks made by atoms whose photons are detected by the sensor are distributed exactly like the marks that one sees in a simple double-slit experiment without micromaser cavities (that is, without the possibility of obtaining which-way information). It thus appears as if every atom whose photon is found in the first cavity has been retroactively caused to have passed through the first cavity. For operationalists, however, the statement that the atom has passed through the first cavity is synonymous with the statement that the atom has been observed to pass through the first cavity, and this is not the case. Hence for them the question of retroactive causality does not arise.

Adopting the reality-of-phenomena point of view, we obtain a different pair of narratives. (1) tells us that the atom has passed through the cavity in which the photon is found whenever this is found in a particular cavity, and (2) tells us that the atom has emerged from both cavities with the corresponding de Broglie waves in phase (out of phase) whenever the shutters are opened and the sensor responds (does not respond). A phenomenon, as understood by Bohr, is a story about a quantum system rather than a story about an experimental arrangement, but nevertheless a story that cannot be told without ''an account of the whole experiment,''[5] and particularly not before the experiment is concluded. The experimental arrangement is needed to define the terms of the story,[6] but this in no way detracts from the objectivity of the story. Each of the bra-kets in (1) and (2) represents part of a possible story. Which of these possible stories turns out to be the true story depends on both the chosen experiment and its particular outcome. Thus, contrary to what in Ref. 1 I claimed to have shown, on the reality-of-phenomena view retroactive causality occurs even if the shutters are opened, or the photon is detected in either cavity, *after* the atom has reached the screen.

Next, the reality-of-states point of view. Implicit in the concept of an instantaneous state (the state of a system at a particular time) is the belief that it is causally determined by the past but not by the future, and that it is causally determinative of the future but not of the past. And implicit in this belief is the seemingly tautological notion of the sole reality of the present: The past is no longer (real), the future is not yet (real). These notions and beliefs imply that the (not yet real) future cannot influence the (real) present, and that the past can influence the present only by persisting through time (that is, by the persistence right up to the present of something that was real, however it may have changed in the meanwhile). Causal influences can reach from the past into the future because they are ''carried'' by the real present, which ''moves'' from past to future. Such, in essence, are the deep-seated and largely unreflected-upon preconceptions that induce us to take for granted, first, that there is such a thing as an instantaneous state, and second, that the state of a system S at a time t encapsulates not only the properties that S possesses at t (in the case of a quantum system its probabilistic dispositions) but also the entire past of S (relative to t) insofar as that is causally relevant to the future of S. (What, for instance, is the electromagnetic field if not an encapsulation in the present of the still causally relevant past of a system of interacting charges?)

If we just go by the quantum formalism, a measurement both detects and prepares a unitarily evolving state, a state that can be calculated for times both after and before the time of the measurement.[7] For the purpose of calculating a transition amplitude (a bra-ket), we unitarily propagate to the same time t (mentally or on paper) both the prepared state represented by the ket and the detected state represented by the bra. t may be any time between the preparation and the detection, and it may even be a time before the preparation or after the detection. Thus the prepared and detected states may be (mentally) propagated toward the future and the past, respectively, or both states may be propagated toward the future or toward the past.

From the reality-of-states point of view, what *really* happens is that the prepared state unitarily evolves toward the future until it ''collapses'' into a freshly prepared state, the detected state. The story of the ESW experiment, accordingly, goes like this: First an excited atom is prepared in a unitarily evolving pure state proportional to $|\psi_1\rangle+|\psi_2\rangle$. After the atom has emitted a microwave photon (a unitary development in the atom–photon system), the atom–photon system is described by a unitarily evolving entangled state proportional to

$$|1\rangle\otimes|\psi_1\rangle+|2\rangle\otimes|\psi_2\rangle=|+\rangle\otimes|\psi_+\rangle+|-\rangle\otimes|\psi_-\rangle. \qquad (3)$$

If at this point the photon is detected, say, in the first cavity, the atom will subsequently be in the unitarily evolving state $|\psi_1\rangle$, but it will not have been in this state prior to the detection of the photon at the time t. If by this time the atom has already left the cavities, we are not entitled to conclude that the atom has passed through the first cavity. It is only from t onward that the atom behaves *as if* it had done so. On the other hand, if the photon is left alone until the atom hits the screen at x, nothing that is subsequently done to the photon can affect the contemporary atomic state, for the atom is no longer entangled with the photon. Nor, on this view, can anything done subsequently affect the atom's past. The atom's state is $|\psi_x\rangle$, the photon's state is proportional to

$$|1\rangle\langle\psi_x|\psi_1\rangle+|2\rangle\langle\psi_x|\psi_2\rangle=|+\rangle\langle\psi_x|\psi_+\rangle+|-\rangle\langle\psi_x|\psi_-\rangle,$$

and both states are pure. If at this point the shutters are opened and the sensor responds, we are not entitled to conclude that the atom's individual state prior to its hitting the screen was $|\psi_+\rangle$. That state was an equiprobable mixture of $|\psi_+\rangle$ and $|\psi_-\rangle$ as well as of $|\psi_1\rangle$ and $|\psi_2\rangle$. Nevertheless, for the runs of the experiment in which the sensor responds, the distribution of marks on the screen is the same as that produced by atoms prepared in the state $|\psi_+\rangle$. The observable correlations between the positions of marks and the behavior of the sensor are exactly *as if* the atom had been retroactively put into either of the states $|\psi_+\rangle$ and $|\psi_-\rangle$.

Adherents to the reality-of-states view thus find themselves faced with a dilemma. If they stick to the aforementioned preconceptions about time and reality, or simply deny the possibility of retrocausation, they must insist that it is only *as if* the atom had traveled through the first cavity or only *as if* it had been retroactively furnished with a definite phase relation. They cannot say that the atom *really* was in the state $|\psi_1\rangle$ (or $|\psi_2\rangle$, or $|\psi_+\rangle$, or $|\psi_-\rangle$, as the case may be). And so they find themselves compelled to foreswear realism and embrace operationalism. And if they stick to realism, they will have to drop the *as if*'s and accept the reality of retrocausation. But this means that the story as told from the reality-of-states point of view is not a viable realistic account. Before the story ends, either it turns into a purely operationalistic account or it ends up being told from the reality-of-phenomena viewpoint. The upshot is that only the reality-of-phenomena view yields a viable realistic account of the ESW experiment, and that retrocausation is a necessary feature of *any* realistic interpretation of the quantum formalism.

III. THE ROOT OF THE FALLACY

What made me think that a measurement on the photon can have an effect on the atom's past only if at the time of the measurement the state of the atom–photon system still has the entangled form (3)? In their comment,[4] ESW attribute this erroneous conclusion to my going beyond the ''minimalistic [operationalist] interpretation of state vectors and their reduction.'' I don't see the pertinence of this analysis. It is like saying that the reason for my getting a ticket is that I parked my car. Surely, the pertinent reason is that I parked it *in the wrong place*. The conclusion that ought to be drawn from my fallacy is not that the operationalist interpretation is the only viable one, but that between the two realistic points of view—reality-of-states versus reality-of-phenomena—the latter is the only viable one.

As I now see it, the root of my fallacy was an unreflecting acceptance of the notion that the present is the sole ''moment of reality.'' What makes it possible for the detected state of the photon to causally determine the state of the atom is the objective entanglement of the two systems, regardless of whether the entanglement is of simultaneous states, as in (3), or between the present state of the photon and the past state of the atom, as in (1) and (2). On the view that the present alone is real, however, this causal influence of the detected photon state has to be exerted either on the simultaneous state of the atom or, if the influence is somehow mediated, on a later state of the atom. It cannot be exerted on an earlier state of the atom. Thus, on the one hand, since the influence is made possible by the entanglement of the two systems, it can affect the atom only while this is entangled with the photon [that is, while (3) obtains]. And on the other hand, it cannot affect an earlier state of the atom. But once the atom has reached the screen, only its earlier state is entangled with the photon—hence my fallacy.

IV. UNTANGLING ENTANGLEMENT: THE EXTRINSIC NATURE OF OBJECTIVE PROPERTIES

Properties that can be influenced retroactively, however, cannot be *intrinsic*. A property p of a physical system S is intrinsic if neither the truth nor the meaning of the proposition $\mathbf{p}=$''S is p'' is contingent on what happens or is the case in ''the rest of the world'' R. If p is intrinsic to S, it is always well-defined, and $\mathbf{p}$ always makes sense and is always either true or false. The truth value of $\mathbf{p}$ can change from ''true'' to ''false'' and vice versa, but it cannot be indefinite (''neither true nor false''). It is possible for $\mathbf{p}$ to be neither true nor false (and thus meaningless) only if p is an *extrinsic* property that cannot be defined without reference to R. In this case the respective criteria for the truth and the falsity of $\mathbf{p}$ must be sought in R, and it may be the case that neither criterion is satisfied (that is, neither the truth nor the falsity of $\mathbf{p}$ is warranted by what happens or is the case in R).

If the position of an atom were an intrinsic property, the proposition $\mathbf{a}_1=$''the atom went through the first slit'' would be either true or false irrespective of the goings-on in R. The detection of the photon in the first cavity would indicate that the atom went through the first slit, but it would not retroactively cause the atom to have taken the first slit. That the position of an atom cannot be an intrinsic property is amply demonstrated by the interference patterns that are observed when there exists neither any matter of fact about the slit taken by the atom nor the possibility of creating such a matter of fact. The occurrence (or existence) of an event (or state of affairs) that implies the atom's passage through the first slit is not only sufficient but also *necessary* for the atom's passage through the first slit. If there isn't any matter of fact from which the atom's passage through a particular slit can be inferred, $\mathbf{a}_1$ is meaningless, and the attribute ''went through the first slit'' is undefined. To my mind, this is why Bohr insisted on the necessity of describing quantum phenomena in terms of experimental arrangements,[8] and why he stressed that quantum systems should not be thought of as possessing properties independently of experimental arrangements.[9] For ''experimental arrangements'' read: the totality of matters of fact about the properties of quantum systems, or the totality of events and states of affairs from which the possession at a time t of a property p by a quantum system S can be inferred.

The possibility of retrocausation hinges on the fact that the event that, for an atom, defines the attribute ''went through the first slit,'' may occur after the atom went through the slit plate and even after the atom has reached the screen. The detection of the associated photon in the first cavity is such a delayed defining event. It deserves to be emphasized, however, that this event does not cause any change in the properties that the atom possessed prior to the detection of the photon. The truth value of a proposition that refers to a given moment or period of time cannot be changed, retroactively or otherwise. The truth value of a proposition may be said to change (whether from ''true'' to ''false'' or from ''neither true nor false'' to ''either,'' or vice versa) only if it refers to different times (that is, if it is actually a pair of propositions referring to different times). Saying that the properties of a system *S* change is the same as saying that the properties of *S* at an earlier time differ from the properties of *S* at a later time. Here we are concerned only with the properties of a particular atom at the time of its passing through the slit plate. A true statement about these properties is a timeless truth. If the associated photon is eventually detected in the first cavity, then $\mathbf{a}_1$ always has been and always will be true. The detection of the photon does not cause any change in the properties that the atom possessed at earlier times; it contributes to *define* these properties.[10] It is nevertheless appropriate to speak of retrocausation since the decision either to ascertain the cavity containing the photon or to open the shutters determines what kind of property-defining event may occur and thus exerts a determining influence on the properties that the atom possessed before the decision was carried out or even taken.

The following objection may be raised. Suppose we place a detector right behind each slit. If the atom is detected behind the first slit, we are entitled to infer that it went through the first slit. What if we now open the shutters? Suppose the photosensor responds. Aren't we entitled to infer from this that the atom went through both slits with the corresponding de Broglie waves in phase?—in which case the two inferences would contradict each other and the legitimacy of making inferences about the past would be refuted. The second inference, however, is legitimate only if there isn't any matter of fact about the slit taken by the atom. If we prevent the atom from entering the second cavity, the atom cannot but emerge from the first slit, while the sensor cannot but do either of two things: respond or not respond. Yet whatever the sensor does in this case is perfectly irrelevant as far as the atom is concerned. Likewise, if a matter of fact about the cavity traversed by the atom is created, the behavior of the sensor tells us nothing whatever about the atom. Least of all does it ''erase'' the matter of fact about the cavity traversed by the photon, or undo its creation.[11] It is only when there isn't any matter of fact about the cavity traversed by the atom that the behavior of the sensor can yield information about the atom's relative phase. (A relative phase presupposes two interfering alternatives.)

In their paper,[4] ESW maintain that retrodiction of the slit taken by an atom implies that the attribute ''went through the first slit'' is an *objective* property possessed by the atom to begin with, a property that we merely *recognize* when we find the photon in the first cavity. They then point out that this notion flies in the face of the fundamental quantum-mechanical indeterminacy. As should be obvious from the above, I fully agree with them that the atom's transverse position at the time of its passing the slit plate is not an *intrinsic* property the possession of which is merely revealed when the photon is detected in the first cavity. By no means, however, does this imply that $\mathbf{a}_1$ is not an *objectively* true statement, and ''went through the first slit'' an *objectively* possessed property, whenever the associated photon is detected in the first cavity. A property does not have to be intrinsic in order to be objective. The property of passing through a particular slit is extrinsic, objective, and retroactively determined by the experimenters' decision to ascertain the slit taken by the atom.

ESW[4] state that ''finding the photon in the first resonator implies *always* that the atom went through the first slit,'' but insist that ''[t]he '...went through...' is not a statement about the atom's past.'' For them saying ''this atom went through the first slit'' is ''tantamount to saying 'this atom belongs to a subensemble whose statistical properties are correctly accounted for by $\psi_1(x)$' ''—the same wave function that accounts for the statistical properties that are observed when the second slit is blocked. In other words, whenever the photon is detected in the first cavity, it appears *as if* the associated atom went through the first slit, but the atom did not *really* go through the first slit. ESW go on to point out that physics is always about ''as-if-realities:'' ''Physics deals with the phenomena that we perceive and which we can communicate about. An imagined reality beyond our perception (in which the critics [of ESW's position] see the atom 'really' going through the first slit) is the business of philosophers.''

It is not that easy to disengage physics from philosophy. The belief that physics deals only with perceived and communicable phenomena is a philosophical notion, as is the belief that physics can legitimately aspire to describe reality *as it is*. Of these two beliefs the latter appears to me to be the less philosophical (or metaphysical) as it does not presuppose the problematic notion that we live in two worlds, one consisting of subjectively perceived but intersubjectively coherent phenomena, and another causing us to perceive those phenomena—a mind-constructed ''internal''[12] or ''empirical''[13] reality, and a mind-independent ''external'' or ''veiled''[13] reality. This dichotomy is a philosophers' invention if ever there was one. I don't see what good it can do to science. Science is driven by the desire to know how things *really* are. It owes its immense success in large measure to the belief that this can be discovered. This powerful ''sustaining myth''[14] should not be lightly thrown overboard.

Moreover, if physics is *always* about ''as-if-realities'' and *never* about the ''imagined reality beyond our perception,'' it has no need of the latter, and there is no reason why we should downgrade our knowledge of the world (acquired, no doubt, through perception) to a knowledge about ''as-if-realities.'' There are, however, two misconceptions that prevent acceptance of the true objectivity of extrinsic properties and the reality of retrocausation, viz., the said notion of the present as the sole ''moment of reality,'' and the notion that some properties are more objective than others—the notion, in other words, that ''went through'' means different things for different objects, or the notion that there are two kinds of past.

There is no evidence of any sort that anything in the universe is exempt from the laws of quantum mechanics. (The universe as a whole is a different matter, for there exists no ''rest of the world'' from which anything about it can be inferred.) In other words, physics lends no support to the notion that ''went through'' means something different for particles and atoms than it means for footballs and cats. It seems to me that one of the things that quantum mechanics is trying to tell us about the world is that no object ever passes through a particular opening ''all by itself,'' without the creation of a fact in the rest of the world from which that opening can be inferred, whether the object is an atom and the opening a slit or the object is a cat and the opening a door.

The relevant difference between the behavior of atoms in double-slit experiments and the behavior of cats in ''double-door experiments'' is this: There exist conditions in which the creation of a matter of fact about the slit taken by the atom may be delayed, may never happen, or may be forestalled by the creation of a matter of fact about the phase relation with which the atom emerged coherently from both slits. On the other hand, there are no possible conditions in which a living cat can enter a house, and in which the creation of a matter of fact about the particular door taken by the cat may be delayed, may never happen, or may be similarly forestalled. In any conditions in which a cat can betake herself into a house, myriads of facts are created from which the door taken by the cat can be inferred—what with the telltale effects of all the photons emitted or reflected by the cat, or the effects of the motion of the cat on the positions or the motion of air molecules and dust particles. In either case the meaning of ''went through (a given slit/door)'' hinges on the creation of facts from which the particular slit/door taken can be inferred. If no such facts are created, ''went through (a given slit/door)'' is undefined. In the atom's case few such facts or none are created; hence ''went through (a given slit)'' is sometimes meaningless. In the cat's case inevitably innumerable such facts are created; hence ''went through (a given door)'' is never undefined. It therefore appears as if the cat's position at the time of her entering the house was an intrinsic property of the cat, even though in reality it is as extrinsic as is the atom's position at the time of its passing the slit plate.

That is to say, there is only one kind of past. The past is what matters of fact—once created or yet to be created—imply about the past; or else it is the totality of all matters of fact created in the past plus what can be inferred about the past from the totality of all matters of fact, including those yet to be created.

V. SPECIAL RELATIVITY AND THE REALITY OF TIME

To be able to accept the reality of retrocausation, we also have to reject the notion that the present is the only ''moment of reality.'' As it happens, special relativity too is inconsistent with this notion. Since any two events in spacelike separation are simultaneous in some reference frames, they must be regarded as coexisting. And if two events are not in spacelike separation, there are nevertheless events that are each in spacelike separation from both of them. It follows that all events must be regarded as coexisting. This conclusion has given rise to the misconception that only an atemporal mode of being has objective reality: ''Subjective time with its emphasis on the now has no objective meaning'' (Einstein[15]). In the well-known words of Weyl:

> The objective world simply *is*; it does not *happen*. Only to the gaze of my consciousness, crawling upward along the life line of my body, does a section of this world come to life as a fleeting image in space which continuously changes in time.[16]

As usual, what the theoretical account fails to accommodate is swept under the rug of subjectivity. Like the notion that the present alone is real, the notion that the temporal modes of being have no objective reality has its roots in an unreflecting identification of ''being as such'' with present being. In one instance this leads to the denial of the reality of past and future being, in the other it leads to the denial of the reality of the temporal modes of being. If one visualizes the ''block universe'' of special relativity, one cannot help visualizing its temporal parts simultaneously. If one also thinks of them as existing simultaneously, special relativity becomes self-contradictory. To get rid of the contradiction, Einstein and Weyl throw the baby out with the bath water: they get rid of the temporal modes of being themselves. Yet to save the consistency of the theory, it suffices to draw a distinction between a generic mode of being (''being as such'') and the temporal modes of being (past being, present being, and future being). Coexistence in the generic, atemporal sense of ''existence'' does not imply simultaneity.

VI. OBJECTIVITY, RETROCAUSATION, AND THE EPR EXPERIMENT

In the Appendix to their comment[4] ESW point out a formal analogy between their thought experiment and (Bohm's version[17] of) the EPR[18] experiment. This formal analogy, however, must not blind one to the semantic differences between the two scenarios.

Consider two spin-1/2 particles. Suppose that at t_1 we measure the spin of particle 1 with respect to a certain axis, and that at a later time t_2 we manage to entangle the spin of particle 1 with that of particle 2 in such a way that a singlet state is created. At this point the measurement at t_1 loses its predictive power. From t_2 onward, its outcome can no longer be regarded as a matter of fact about the spin of particle 1. The analogous ESW scenario (to the extent that it is analogous) goes as follows. At t_1 the atom is ''prepared'' in the state $|\psi_+\rangle$ (possibly by sending atoms through a first pair of microwave cavities and selecting those atoms that made the photosensor between these cavities respond). At t_2 the atom deposits a photon somewhere inside the two microwave cavities of the original setup (the second pair of cavities of the modified setup). And from this point onward, the atom's ''preparation'' (the response of the sensor situated between the first two cavities) can no longer be regarded as a matter of fact about the atom's phase relation.

The key difference between the two scenarios is that the EPR one is insensitive to the direction with respect to which the spin of particle 1 is measured at t_1, and hence invariant under both a rotation in physical space and the corresponding coordinate transformation in the Hilbert space of (the spin of) particle 1, while the ESW scenario becomes nonsensical upon analogous coordinate transformations in the atom's (two-dimensional) Hilbert space. Here is what one of the transformed scenarios would amount to: At t_1 the atom is ''prepared'' in the state $|\psi_1\rangle$. In other words, there is a matter of fact about the cavity that the atom is going to traverse. (The atom may be prevented from entering the second cavity.) At t_2 the atom deposits a photon somewhere inside the two cavities; and from this point onward, the atom's ''preparation'' can no longer be regarded as a matter of fact about the cavity traversed by the atom. This is patently absurd. As has been pointed out in Sec. IV, the creation of a matter of fact about the cavity traversed by the atom cannot be undone. Consequently, the entangled state (3) cannot be created. It can only be created if (as yet) there isn't any matter of fact about the cavity traversed by the atom.

Let's proceed with the analogy, assuming as we must that there isn't yet any such matter of fact. Suppose that at t_3 ($>t_2$) the spin of particle 1 is measured with respect to the x axis, and that at t_4 ($>t_2$) the spin of particle 2 is measured with respect to the y axis. (Nothing is said about the temporal relation between t_3 and t_4.) And suppose that the results of these measurements are x_1+ and y_2+, in obvious shorthand. The ESW analogue involves (i) opening the shutters and (ii) a direct determination of the slit taken by the atom (e.g., by placing a detector right behind each slit). Suppose that the sensor responds and the detector behind the first slit clicks. The clicking of the detector warrants the conclusion that the atom went through the first cavity, while the response of the sensor does not warrant any conclusion concerning the atom. (For the behavior of the sensor to provide information about the atom's phase relation, it must make sense to attribute a phase relation to the atom, and this presupposes two interfering alternatives.)

The EPR–Bohm scenario requires further analysis. Let $t_3>t_b>t_a>t_2$. Suppose that at the respective times t_a and t_b the y component y_1 and the x component x_1 of the spin of particle 1 are measured (in this order), that the measurements at t_3 and t_4 yield the specified results (x_1+ and y_2+), and that no further measurement is performed on particle 1 (particle 2) prior to $t_3(t_4)$. Under these conditions the measurements at t_a and t_b are certain to yield the respective results y_1- and x_1+. Why? The obvious answer would seem to be: because the value of y_1 at t_a *is* (or was) ''$-$'' and the value of x_1 at t_b *is* (or was) ''$+$''. It is well-known, however, that this answer cannot be construed in the sense that y_1- and x_1+ are *intrinsic* properties of particle 1, possessed at the respective times t_a and t_b independently of the goings-on elsewhere and at other times. Instead these properties are *extrinsic* as well as objective, that is, they are both defined and (retroactively) determined by the results of the measurements at t_3 and t_4. This objective retroactive determination is warranted because the following conditions are satisfied: Between t_2 and t_4 no observable that does not commute with y_2 has been measured on particle 2; between t_2 and t_a no observable that does not commute with y_1 has been measured on particle 1; and between t_b and t_3 no observable that does not commute with x_1 has been measured on particle 1. The past, recall, is the totality of all matters of fact created in the past plus what can be inferred about the past from the *totality* of all matters of fact, including those yet to be created. The word ''totality'' is emphasized to stress that account must also be taken of the possible matters of fact that are never created.[19]

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[1]Ulrich Mohrhoff, ''Restoration of interference and the fallacy of delayed choice: Concerning an experiment proposed by Englert, Scully and Walther,'' Am. J. Phys. **64**, 1468–1475 (1996).

[2]Berthold-Georg Englert, Marlan O. Scully, and Herbert Walther, ''The duality in matter and light,'' Sci. Am. (Int. Ed.) **271** (6), 56–61 (December 1994).

[3]Marlan O. Scully, Berthold-Georg Englert, and Herbert Walther, ''Quantum optical tests of complementarity,'' Nature (London) **351** (6322), 111–116 (1991).

[4]Berthold-Georg Englert, Marlan O. Scully, and Herbert Walther, ''Quantum erasure in double-slit interferometers with which-way detectors,'' Am. J. Phys. **67** (1999).

[5]Niels Bohr, Dialectica **2**, 312 (1948); quoted in Abraham Pais, *Niels Bohr's Times, In Physics, Philosophy, and Polity* (Clarendon, Oxford, 1991), p. 433.

[6]Michael Redhead, *Incompleteness, Nonlocality and Realism* (Clarendon, Oxford, 1987), Sec. 2.3.

[7]Yakir Aharonov, Peter G. Bergmann, and Joel L. Lebowitz, ''Time symmetry in the quantum process of measurement,'' Phys. Rev. B **134**, 1410–1416 (1964); reprinted in John Archibald Wheeler and Wojciech Hubert Zurek, *Quantum Theory and Measurement* (Princeton U.P., Princeton, NJ, 1983), pp. 680–686.

[8]Niels Bohr, *Essays 1958–62 on Atomic Physics and Human Knowledge* (Wiley, New York, 1963), p. 3.

[9]Bernard d'Espagnat, *Conceptual Foundations of Quantum Mechanics* (Benjamin, Reading, MA, 1976), 2nd ed., p. 251.

[10]''I must discard here a disastrous, but very frequent, misunderstanding concerning advanced causality. Many people think that advanced causality would imply the possibility of *reshaping* the past—for example, killing one's grandfather in his cradle. This is sheer nonsense. The world history is one, and cannot be rewritten. Advanced causality does not mean reshaping, but it does mean *shaping* the past from the future.''—Olivier Costa de Beauregard, ''Space–time and probability: Classical and quantal,'' in *The World View of Contemporary Physics*, edited by Richard F. Kitchener (SUNY Press, New York, 1988), pp. 104–124 (original emphasis). For further publications on retrocausation prior to 1988 see the references in this article.

[11]ESW's ''quantum erasure'' terminology is potentially misleading. The photon does not carry information about the atom but only enables us to obtain such information. In this respect it is like a telescope which does not by itself carry information about the moon but only enables us to obtain such information. To obtain information about the moon, we must point it at the moon, and to obtain information about the atom, we must subject the photon to a measurement. What is ''erased,'' accordingly, is not *existing* information but merely the *possibility* of obtaining (a particular type of) information. The creation of a matter of fact cannot be undone.

[12]Hilary Putnam, *Representation and Reality* (MIT, Cambridge, MA, 1988), p. 113.

[13]Bernard d'Espagnat, *Veiled Reality* (Addison–Wesley, Reading, MA, 1995).

[14]N. David Mermin, ''What's wrong with this sustaining myth?'' Phys. Today 11–13 (March 1996).

[15]Albert Einstein, quoted by Wolfram Schommers, ''Space-time and quantum phenomena,'' in *Quantum Theory and Pictures of Reality*, edited by Wolfram Schommers (Springer, Berlin and Heidelberg, 1989), p. 230.

[16]Hermann Weyl, *Philosophy of Mathematics and Natural Science* (Princeton U.P., Princeton, NJ, 1949), p. 116.

[17]David Bohm, *Quantum Theory* (Prentice-Hall, Englewood Cliffs, NJ, 1951).

[18]Albert Einstein, Boris Podolsky, and Nathan Rosen, ''Can quantum-mechanical description of physical reality be considered complete?'' Phys. Rev. **47**, 777–780 (1935); reprinted in John Archibald Wheeler and Wojciech Hubert Zurek, *Quantum Theory and Measurement* (Princeton U.P., Princeton, NJ, 1983), pp. 138–141.

[19]Particle 1 thus provides an example of an ensemble that is both pre- and postselected: postselected (determined backward in time) by being eventually found in the state x_1+, and preselected (determined forward in time) by being initially prepared in the state y_1-—a ''preparation'' that capitalizes on the entanglement of the two particles and is effected by the postselection of particle 2 in the state y_2+. Yakir Aharonov and Lev Vaidman [''Complete description of a quantum system at a given time,'' J. Phys. A **24**, 2315–2328 (1991)] proposed that pre- and postselected ensembles be represented by a two-state vector. The two-state vector is to time-symmetrized quantum theory (TSQT) what the state vector is to standard quantum theory [Lev Vaidman, ''Time-symmetrized quantum theory,'' invited lecture, Fundamental Problems in Quantum Theory workshop, University of Maryland Baltimore County, 4–7 August 1997 (unpublished); R. E. Kastner, ''Time-symmetrized quantum theory, counterfactuals, and 'advanced action,' '' forthcoming in Stud. Hist. Phil. Mod. Phys.). TSQT is based on the seminal paper by Y. Aharonov, P. G. Bergmann, and J. L. Lebowitz (Ref. 7). It takes due account of the fact that the maximally specified state of a system contains information based not only on initial but also on final measurements.